Progress Report on Nuclear Data Research in the Federal Republic of Germany for the Period 2018 – 2020

compiled by

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KARLSRUHE INSTITUTE OF TECHNOLOGY

INSTITUTE OF NUCLEAR PHYSICS

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1. Stellar and thermal neutron capture cross section of ^{9}Be

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The neutron capture cross section of ^{9}Be for stellar energies was measured via the activation technique using the Karlsruhe Van de Graaff accelerator in combination with accelerator mass spectrometry at the Vienna Environmental Research Accelerator. To characterize the energy region of interest for astrophysical applications, activations were performed in a quasistellar neutron spectrum of kT =25 keV and for a spectrum at En =473±53keV. Despite the very small cross section, the method used provided the required sensitivity for obtaining fairly accurate results of 10.4±0.6 and 8.4±1.0 μb, respectively. With these data it was possible to constrain the cross section shape up to the first resonances at 622 and 812 keV, thus allowing for the determination of Maxwellian-averaged cross sections at thermal energies between kT =5 and 100 keV. In addition, we report a new experimental cross section value at thermal energy of σ_{th}=8.31±0.52 mb.

Phys. Rev. C 99:015804 (2019)

2. Der Ursprung der Elemente: Durch Neutroneneinfang zu den schwersten Atomkernen

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Sterne sind kosmische Hochöfen: Sie produzieren die Stoffe, aus denen wir und alle Materie in unserer Umgebung bestehen. Doch die während ihrer Entwicklung ablaufenden Kernfusionen können die Herkunft der schwersten Elemente nicht erklären. Die aktive Forschung im Zusammenspiel von Kern- und Astrophysik hat die explosiven Wege erkundet, denen wir die Hälfte der Elemente von Eisen bis Blei und Wismut und alle noch schwereren Elemente verdanken.

Sterne und Weltraum, Dezember 2018, p. 36

3. The Activation Method for Cross Section Measurements in Astrophysics

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The primary aim of experimental nuclear astrophysics is to determine the rates of nuclear reactions taking place in stars in various astrophysical conditions. These reaction rates are important ingredients for understanding the elemental abundance distribution in our solar system and the galaxy. The reaction rates are determined from the cross sections, which need to be measured at energies as close to the astrophysically relevant ones as possible. In many cases the final nucleus of an astrophysically important reaction is radioactive, which allows the cross section to be determined based on the off-line measurement of the number of produced isotopes. In general, this technique is referred to as the activation method, which often has substantial advantages over in-beam particle- or γ-detection measurements. In this paper the activation method is reviewed from the viewpoint of nuclear astrophysics. Important aspects of the activation method are given through several reaction studies for charged particle-, neutron-, and γ-induced reactions. Various techniques for the measurement of the produced activity are detailed. As a special case of activation, the technique of Accelerator Mass Spectrometry in cross section measurements is also reviewed.

Eur. Phys. J. A 55:41 (2019), doi:10.1140/epja/i2019-12708-4

KARLSRUHE INSTITUTE OF TECHNOLOGY
INSTITUTE FOR NEUTRON PHYSICS AND REACTOR TECHNOLOGY

Improved atomic displacement cross-sections for proton irradiation of aluminium, iron, copper, and tungsten at energies up to 10 GeV

A.Yu. Konobeyev, U. Fischer, S.P. Simakov

Displacement cross-sections for an advanced assessment of radiation damage rates were obtained for a number of structural materials irradiated with protons at energies from threshold up to 10 GeV. The proposed calculation method utilises an athermal recombination-corrected dpa model with corrections obtained from simulations using the binary collision approximation model. Justification of the method was performed using available measured and systematics data.

Nucl. Instr. Meth. Phys. Res. B431, (2018) p.55

Atomic displacement cross-sections for neutron irradiation of materials from Be to Bi calculated using the arc-dpa model

A.Yu. Konobeyev, U. Fischer, S.P. Simakov

Displacement cross-sections for an advanced assessment of radiation damage rates were obtained for a number of materials using the arc-dpa model at neutron incident energies from 10−5 eV to 10 GeV. Evaluated data files, CEM03 and ECIS codes, and an approximate approach were applied for the calculation of recoil energy distributions in neutron induced reactions.
Three sets of displacement cross-sections based on the use of low-energy data from JEFF-3.3, ENDF/B-VIII.0, and JENDL-4.0u were prepared. Files contain also cross-sections calculated using the standard NRT model.
Special efforts were made to estimate the uncertainty of obtained displacement cross-sections.

Nuclear Engineering and Technology, 51 (2019), p.170.

Evaluated data files for neutron irradiation of W-182 and W-186 at energies up to 200 MeV

A.Yu. Konobeyev, U. Fischer, P.P. Pereslavtsev, .S.P. Simakov

New evaluated general purpose nuclear data files were prepared for 182,186 W isotopes at primary neutron energy up to 200 MeV. A special version of the TALYS code implementing the geometry dependent hybrid model (GDH) supplied with models for the non-equilibrium cluster emission was applied for calculations of nuclide production and particle energy distributions. The parameters of the GDH model were properly estimated using measured data for individual tungsten isotopes. The evaluation of cross-sections was performed using results of model calculations, available experimental data, systematics of light charge particle production cross-sections, and obtained covariance information. The BEKED code package developed in KIT was used for numerical calculations. Data were formatted using the TEFAL code and the FOX code from BEKED

Report KIT SWP 108 (2019),

Evaluated data files for n+W-180 and W-183 irradiation at incident neutron energies up to 200 MeV

A.Yu. Konobeyev, U. Fischer, P.P. Pereslavtsev, S.P. Simakov

New evaluation of nuclear data was performed for tungsten isotopes W-180 and W-183 at incident neutron energies up to 200 MeV. Calculations were carried out using a special version of the TALYS code implementing the geometry dependent hybrid model and models for the non-equilibrium light cluster emission. The evaluation was performed using the results of calculations, available measured data, systematics predictions, and covariance information. The TEFAL code and the FOX code from the BEKED package were applied for the formatting of the data.

Report KIT SWP 123 (2019)

New evaluation of general purpose neutron data for stable W-isotopes up to 200 MeV

A.Yu. Konobeyev, U. Fischer, P.P. Pereslavtsev, S.P. Simakov

In the frame of the Power Plant Physics and Technology of EUROfusion, new evaluations of general purpose neutron cross-section data were performed for the 180,182,183,184,186 W isotopes covering the neutron energy up to 200 MeV. A special version of the TALYS nuclear model code implementing the geometry dependent hybrid model supplied with models for the non-equilibrium cluster emission was applied for calculations of the nuclide production and the energy distribution of the emitted particles. The parameters of the GDH model were properly estimated using measured data for individual tungsten isotopes. The neutron cross-sections were evaluated making use of available experimental data, systematics including estimated A-dependence of components of gas production cross-sections, and covariance information produced as part of the evaluation process. The BEKED code package, developed at KIT, was applied for calculations of co-variances using a dedicated Monte Carlo method. The evaluated data were processed into standard ENDF data format using the TEFAL code and the FOX module of the BEKED system. The evaluated data files were checked for errors and inconsistencies, processed with the NJOY code into ACE data format, and benchmarked against available integral experiments with MCNP neutron transport calculations.

EPJ Web of Conferences 239 (2020) 11002

Neutron-induced damage simulations: Beyond defect production cross-section, displacement per atom and iron-based metrics

J.-Ch. Sublet, (...), A.Yu. Konobeyev, (...), S.P. Simakov et al.

Nuclear interactions can be the source of atomic displacement and post-short-term cascade annealing defects in irradiated structural materials. Such quantities are derived from, or can be correlated to, nuclear kinematic simulations of primary atomic energy distributions spectra and the quantification of the numbers of secondary defects produced per primary as a function of the available recoils, residual and emitted, energies. Recoils kinematics of neutral, residual, charged and multi-particle emissions are now more rigorously treated based on modern, complete and enhanced nuclear data parsed in state of the art processing tools. Defect production metrics are the starting point in this complex problem of correlating and simulating the behavior of materials under irradiation, as direct measurements are extremely improbable. The multi-scale dimensions (nuclear-atomic-molecular-material) of the simulation process is tackled from the Fermi gradation to provide the atomic- and

meso-scale dimensions with better metrics relying upon a deeper understanding and modelling capabilities of the nuclear level. Detailed, segregated primary knock-on-atom metrics are now available as the starting point of further simulation processes of isolated and clustered defects in material lattices. This allows more materials, incident energy ranges and particles, and irradiations conditions to be explored, with sufficient data to adequately cover both standard applications and novel ones, such as advanced-fission, accelerators, nuclear medicine, space and fusion. This paper reviews the theory, describes the latest methodologies and metrics, and provides recommendations for standard and novel approaches.

Eur. Phys. J. Plus 134 (2019) 350

Status and benchmarking of the deuteron induced Tritium and Beryllium-7 production cross sections in Lithium

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This report summaries the results of analyses of the available experimental and evaluated d-Li cross section data for the assessment of the tritium and beryllium-7 production in IFMIF-DONES, the International Fusion Materials Irradiation Facility - DEMO Oriented Neutron Source project which is a part of the European Fusion Roadmap. The work comprises the collection and quality assessment of the relevant experimental cross-section data, comparison with available contemporary evaluations FZK-2005, ENDF/B-VIII.0, JEFF-3.3, TENDL-2017/2019, FENDL-3.1 and others. These evaluated cross sections were then used to calculate the radioactive inventories generated in the thick Li target with the help of the own developed code d-Activ and conventional inventory code FISPACT-II. Based on the outcomes of this analysis, we recommend that measurements of the ^{6,7,nat}Li(d,xt) cross sections above 5 MeV and tritium thick target yields in lithium up to 40 MeV as well as the substantial upgrade of ENDF, JEFF, TENDL and FENDL are needed.

Report KIT SWP 147(2020)

Comparative survey of evaluated nuclear data libraries for fusion-relevant neutron activation spectrometry

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The neutron flux-spectrum in a fusion device is frequently determined with activation foils and adjustment of a guess-spectrum in unfolding codes. Spectral-adjustment being a rather complex and uncertain procedure, we are carefully streamlining and evaluating it for upcoming experiments. Input nuclear cross-section data holds a vital position in this. This paper presents a survey of common dosimetry reactions and available data files relevant for fusion applications. While the IRDFF v1.05 library is the recommended source, many reactions of our interest are found missing in this. We investigated other standard sources: ENDF/B-VIII.0, EAF-2010, TENDL-2017, JENDL-4.0 etc. And, we analysed two experiments to ascertain the sensitivity of the spectral adjustment to the choice of nuclear data. One was performed with D-D (approx. 2.5 MeV peak) neutrons at the Joint European Torus (JET) machine and another with a white neutron field (approx. 33 MeV endpoint energy) at Nuclear Physics Institute (NPI) of Řež. Choice of cross-section source has affected the integral fluxes (<5%), reaction rates (<10%), total fluxes in some sensitive energy-regions (>20%) and individual group fluxes (<30%). Based on this experience, essential qualitative conclusions are made to improve the fusion activation-spectrometry.

EPJ Web of Conferences 239, 21003 (2020)

HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF

INSTITUTE FOR RADIATION PHYSICS

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1. Measurement of the prompt fission γ-ray spectrum of ^{242}Pu

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The prompt γ-ray spectrum of fission fragments is important in understanding the dynamics of the fission process, as well as for nuclear engineering in terms of predicting the γ-ray heating in nuclear reactors. The γ-ray spectrum measured from the fission fragments of the spontaneous fission of ^{242}Pu will be presented here. A fission chamber containing in total 37 mg of ^{242}Pu was used as active sample. The γ-quanta were detected with high time- and energy-resolution using $LaBr_3$ and HPGe detectors, respectively, in coincidence with spontaneous fission events detected by the fission chamber. The acquired γ-ray spectra were corrected for the detector response using the spectrum stripping method. About 70 million fission events were detected which results in a very low statistical uncertainty and a wider energy range covered compared to previous measurements. The prompt fission γ-ray spectrum measured with the HPGe detectors shows structures that allow conclusions about the nature of γ-ray transitions in the fission fragments. The average photon multiplicity of 8.2 and the average total energy release by prompt photons per fission event of about 6.8 MeV were determined for both detector types.

EPJ Web of Conferences 169, 00026 (2018)

2. Experimental Signals for Broken Axial Symmetry in Excited Heavy Nuclei from the Valley of Stability

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An increasing number of experimental data indicates the breaking of axial symmetry in many heavy nuclei already in the valley of stability: Multiple Coulomb excitation analysed in a rotation invariant way, gamma transition rates and energies in odd nuclei, mass predictions, the splitting of Giant Resonances (GR), the collective enhancement of nuclear level densities and Maxwellian averaged neutron capture cross sections. For the interpretation of these experimental observations, the axial symmetry breaking shows up in nearly all heavy nuclei as predicted by Hartree–Fock–Bogoliubov (HFB) calculations; this indicates a nuclear Jahn–Teller effect. We show that nearly no parameters remain free to be adjusted by separate fitting to level density or giant resonance data, if advance information on nuclear deformations, radii etc. are taken from such calculations with the force parameters already fixed. The data analysis and interpretation have to include the quantum mechanical requirement of zero point oscillations and the distinction between static vs. dynamic symmetry breaking has to be regarded.

Acta Phys. Pol. B Proc. Suppl. **11**, 37 (2018)

3. On the use of stacks of fission-like targets for neutron capture experiments

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The measurement of neutron induced reactions on unstable isotopes is of interest in many fields, from nuclear energy to astrophysics or applications; in particular transuranic isotopes are essential for the development of innovative nuclear reactors and for the management of the radioactive waste. In such measurements, the quality of the associated radioactive target is crucial for the success of the experiment, but in many cases the geometry, amount of mass and encapsulation of the target are not optimal, leading to limited results. In this work we propose to produce high quality radioactive targets for capture as a stack of thin targets using the techniques usually employed for fission measurements. In particular, we have succeeded in making a 242Pu target of nearly 100 mg by combining seven thin (1 mg/cm2) fission-like targets with 45 mm in diameter achieving a total backing thickness of only of aluminum. The target has been shown to perform successfully in experiments at both a neutron time-of-flight facility (n_TOF at CERN) and a thermal neutron beam (BRR at KFKI), providing the most accurate data from thermal up to 500 keV to date.

Nucl. Inst. Meth. A 925 (2019) 87

4. Improved ^{242}Pu(n, γ) thermal cross section combining activation and prompt gamma analysis

J. Lerendegui-Marco[1], C. Guerrero[1,2], T.Belgya[3], B.Maróti[3], K.Eberhardt[4,5], Ch.E.Düllmann [4,5,6], A.R. Junghans[7], C.Mokry[4,5], J.M. Quesada[1], J.Runke[4,6], and P. Thörle-Pospiech[4,5]

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A good knowledge of the radiative capture cross section of ^{242}Pu is required for innovative nuclear reactor studies, especially for MoX fuel reactors. However, the experimental data available show discrepancies in the energy regions of interest: the thermal point and the keV region. Previous experimental results of the thermal cross section deviate from each other by 20% and these discrepancies are reflected also in the evaluated libraries, each of them giving more credit to different data sets. A recent measurement by Genreith et al. did not succeed to solve the existing discrepancy due to the large uncertainties and correction factors in the analysis. This work presents a new measurement of the thermal capture cross section of ^{242}Pu carried out in the Budapest Research Reactor using the same thin targets of a previous measurement at n_TOF-EAR1, each containing 30mg of 99.995% pure ^{242}Pu. The combined analysis of the full prompt γ-ray spectrum and the ^{243}Pu decay has led to three compatible values for the thermal cross section. Their average value, 18.9(9) b, has an improved accuracy compared to recent measurements. Leaving aside the activation value of Genreith using an

outdated intensity value for the 84 keV decay line of ^{243}Pu , our average result is in very good agreement with the JEFF-3.2 evaluation and all the previous measurements, with the exception of the highest value 22.5(11) b reported by Marie et al., which has a strong influence in the ENDF evaluation.

Eur. Phys. J. A (2019)55:63

5. Fast-neutron-induced fission cross section of ^{242}Pu measured at the neutron time-of-flight facility nELBE

T. Kögler,[1,2], A. R. Junghans,[1], R. Beyer,[1], M. Dietz,[1,2], Ch. E. Düllmann,[3,4,5] K. Eberhardt,[3,4] Ch. Lorenz,[1,2], S. E. Müller,[1] R. Nolte,[6], T. P. Reinhardt,[1,2], K. Schmidt,[1,2], J. Runke,[3,5] R. Schwengner,[1] M. Takacs,[1,2], A. Vascon,[1,3], and A. Wagner[1]

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The fast-neutron-induced fission cross section of ^{242}Pu was measured at the neutron time-of-flight facility nELBE. A parallel-plate fission ionization chamber with novel, homogeneous, large-area ^{242}Pu deposits on Si-wafer backings was used to determine this quantity relative to the IAEA neutron cross-section standard ^{235}U(n,f) in the energy range of 0.5 to 10 MeV. The number of target nuclei was determined from the measured spontaneous fission rate of ^{242}Pu. This helps to reduce the influence of the fission fragment detection efficiency on the cross section. Neutron transport simulations performed withGEANT4, MCNP6, andFLUKA2011 are used to correct the cross-section data for neutron scattering. In the reported energy range the systematic uncertainty is below 2.7% and on average the statistical uncertainty is 4.9%. The determined results show an agreement within 0.67(16)% to recently published data and a good accordance to current evaluated data sets.

PHYSICAL REVIEW C99, 024604 (2019)

6. Development of an Ionization Chamber for the Measurement of the ^{16}O(n, α)^{13}C Cross-Section at the CERN n_TOF Facility

Sebastian Urlass,[1,2,3] Arnd R. Junghans,[2] Andreas Hartmann,[2] Federica Mingrone,[3] Manfred Sobiella,[2] Daniel Stach,[2] Laurent Tassan-Got,[3] David Weinberger,[1] The n_TOF Collaboration[3]

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The ^{16}O(n, α)^{13}C reaction, as the inverse reaction of the astrophysically important ^{13}C(α, n)^{16}O reaction, is proposed to be measured at the neutron time-of-flight (n_TOF) facility of CERN. To this purpose, a Double Frisch Grid Ionization Chamber (DFGIC) containing the oxygen atoms as a component in the counting gas has been developed and a prototype was constructed at Helmholtz-Zentrum Dresden-Rossendorf(HZDR), in Germany. The first in-beam tests of the detector have been performed in November 2017 in the first (EAR1) and in April 2018 in the second (EAR2) experimental areas of the n_TOF at facility.

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https://doi.org/10.1007/978-3-030-13876-9_89

7. Cross section and neutron angular distribution measurements of neutron scattering on natural iron

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New measurements of the neutron scattering double differential cross section of iron were carried out at the neutron time-of-flight facilities GELINA and nELBE. A neutron spectrometer consisting of an array of up to 32 liquid organic scintillators was employed, which was designed to measure the scattering differential cross section at eight scattering angles and to simultaneously determine the integral cross section via numerical quadrature. The separation of elastic from inelastic scattering was achieved by analyzing the time-of-flight-dependent light-output distributions to determine the scattered neutron energy. The method was validated by studying elastic scattering on carbon and it was proved to work well for the determination of the elastic cross section. Here, the possibility to extend it to inelastic scattering was investigated too. For these experiments a sample of natural iron was used and the results cover the incident neutron energy range from 2 to 6 MeV. Both the differential and the integral elastic cross sections were produced for ^{nat}Fe, while for inelastic scattering, partial angular distributions for scattering from the first excited level of ^{56}Fe could be determined.

PHYSICAL REVIEW C99, 024601 (2019)

8. Consequences of broken axial symmetry in heavy nuclei—an overview of the situation in the valley of stability

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An overview on the various effects of axial symmetry breaking is presented for medium heavy and heavy nuclei covering the mass number range $70<A<240$. The discussion includes various observations for nuclei: level densities, spectroscopic features as energies and transition rates, ground state masses and finally the splitting of giant dipole resonances. Quadrupole moments and rates can be derived from models of triaxial rigid rotation or cranking for a given triaxiality parameters γ, but microscopic considerations are needed to predict these for eachnucleus investigated. Respective predictions were adopted from recently made Hartree–Fock–Bogolyubov(HFB)calculations extended to arbitrary triaxiality by a generator coordinate method. In accord to these, various observations as reported in this overview demonstrate the importance of allowing a breaking of axial symmetry for heavy nuclei already in the valley of stability. Considering this breaking as indicated from the HFB approach surprisingly many experimental data are well described globally without the need for local fit parameters. In addition to these comparisons it will be shown that it is advantageous to consider $c_\gamma=\cos(3\gamma)$an indicator of axiality for heavy nuclei independent of their quadrupole moment.

Phys. Scr.94 (2019) 014008

9. Neutron transmission measurements at nELBE

Arnd Junghans[1], Roland Beyer[1], Jürgen Claußner[1], Toni Kögler [1], Sebastian Urlass[1],Daniel Bemmerer[1], AnnaFerrari[1], Ronald Schwengner[1], Andreas Wagner[1], Mirco Dietz[1,2], Axel Frotscher[1,2], Marcel Grieger[1,2], Thomas Hensel[1,2], Martina Koppitz[1,2], Felix Ludwig[1,2],SteffenTurkat[1,2], Ralf Nolte[3], Elisa Pirovano[1,3], Stefan Kopecky[4], Markus Nyman[4], Arjan Plompen[4], Peter Schillebeeckx[4], Erik Borris[5], René Reifarth[5], Daniel Veltum[5], Mario Weigand[5], Jan Glorius[6], Joachim Görres[7], Uwe Oberlack[8], and Daniel Wenz[8]

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Neutron total cross sections are an important source of experimental data in the evaluation of neutron-induced cross sections. The sum of all neutron-induced reaction cross sections can be determined with a precision of a few per cent in a relative measurement. The neutron spectrum of the photoneutron source nELBE extends in the fast region from about 100 keV to 10 MeV and has favourable conditions for transmission measurements due to the low instantaneous flux of neutrons and low gamma-flash background. Several materials of interest (in part included in the CIELO evaluation or on the HPRL of OECD/NEA) have been investigated: ^{197}Au [1, 2], ^{nat}Fe [2], ^{nat}W [2], ^{238}U, ^{nat}Pt, ^{4}He, ^{nat}O, ^{nat}Ne, ^{nat}Xe. For gaseous targets high pressure gas cells with flat end-caps have been built that hold up to 200 bar pressure. The experimental setup will be presented including results from several transmission experiments and the data analysis leading to the total cross sections will be discussed.

EPJ Web of Conferences 239, 01006 (2020)

10. Measurement of the ^{242}Pu(n, γ) cross section from thermal to 500 keV at the Budapest research reactor and CERN n_TOF-EAR1 facilities

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The design and operation of innovative nuclear systems requires a better knowledge of the capture and fission cross sections of the Pu isotopes. For the case of capture on ^{242}Pu, a reduction of the uncertainty in the fast region down to 8-12% is required. Moreover, aiming at improving the evaluation of the fast energy range in terms of average parameters, the OECD NEA High Priority Request List (HPRL) requests high-resolution capture measurements with improved accuracy below 2 keV. The current uncertainties also affect the thermal point, where previous experiments deviate from each other by 20%. A fruitful collaboration between JGU Mainz and HZ Dresden-Rossendorf within the EC CHANDA project resulted in a ^{242}Pu sample consisting of a stack of seven fission-like targets making a total of 95(4) mg of ^{242}Pu electrodeposited on thin (11.5 μm) aluminum backings. This contribution presents the results of a set of measurements of the ^{242}Pu(n, γ) cross section from thermal to 500 keV combining different neutron beams and techniques. The thermal point was

determined at the Budapest Research Reactor by means of Neutron Activation Analysis and Prompt Gamma Analysis, and the resolved (1 eV - 4 keV) and unresolved (1 - 500 keV) resonance regions were measured using a set of four Total Energy detectors at the CERN n_TOF-EAR1.

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11. Measurement of the $^{16}O(n, \alpha)^{13}C$ cross-section using a Double Frisch Grid Ionization Chamber

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The $^{16}O(n, \alpha)^{13}C$ reaction was proposed to be measured at the neutron time-of-flight (n_TOF) facility of CERN. To this purpose, a Double Frisch Grid Ionization Chamber (DFGIC) containing the oxygen atoms as a component in the counting gas coupled with a switch device in order to prevent the charge collection from the so-called γ-flash has been developed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR), in Germany. The first $^{16}O(n, \alpha)^{13}C$ measurement without seeing the charge of the γ-flash at n_TOF has been performed in November 2018. After the electronics did not suffer from the y-flash any more, another huge charge collection was discovered. Due to the high instantaneous flux at the n_TOF facility [1] the amount of that induced charge from neutron induced background reactions was piling up so much that the recognition of $^{16}O(n, \alpha)^{13}C$ reactions from that background was very difficult. For that reason another $^{16}O(n, \alpha)^{13}C$ measurement at the time-of-flight facility nELBE at HZDR which has a low instantaneous flux [2], has been performed in April 2019. Both measurements from n_TOF and nELBE will be presented here.

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12. Fast neutron inelastic scattering from ^{7}Li

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The inelastic scattering of fast neutrons from ^{7}Li nuclei was investigated at the nELBE neutron-time-of-flight facility. The photon production cross section of 478 keV γ-rays from the first excited state of ^{7}Li was determined by irradiating a disc of LiF with neutrons of energies ranging from 100 keV to about 10 MeV. The target position was surounded by a setup of 7 $LaBr_3$ scintillation detectors and 7 high-purity germanium detectors to detect the de-excitation γ-rays. A ^{235}U fission chamber was used

to determine the incoming neutron flux. The number of detected photons was corrected for the detection efficiency, multiple scattering and the time-of-flight dependent data acquisition dead time. The preliminary results show reasonable agreement with some previous measurments but are about 15 % below the recent data taken at the GELINA facility.

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13. Exploring enhanced low-energy magnetic dipole strength in photon scattering

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Strengths of M1 transitions depopulating high-lying 1^+ states and of subsequent transitions in cascades populating the first excited state were determined on the basis of large-scale shell-model calculations for the nuclide ^{54}Fe. The results reveal that the spectra of primary M1 transitions from 1^+ states as well as the subsequent cascades of M1 transitions show an enhancement of strength toward low energy, which is similar to that found for a huge number of transitions between states of a wide spin range as observed in light-ion induced reactions. This allows, in principle, the study of low-energy M1 strength using photon scattering. Based on these results, intensities of M1 transitions under experimental conditions are estimated.

Physical Review C 100, 054320 (2019).

14. Reference database for photon strength functions

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Photon strength functions describing the average response of the nucleus to an electromagnetic probe are key input information in the theoretical modelling of nuclear reactions. Consequently they are important for a wide range of fields such as nuclear structure, nuclear astrophysics, medical isotope production, fission and fusion reactor technologies. They are also sources of information for widely used reaction libraries such as the IAEA Reference Input Parameter Library and evaluated data files such as EGAF. In the past two decades, the amount of reaction gamma-ray data measured to deter-

mine photon strength functions has grown rapidly. Different experimental techniques have led to discrepant results and users are faced with the dilemma of which (if any) of the divergent data to adopt. We report on a coordinated effort to compile and assess the existing experimental data on photon strength functions from the giant dipole resonance region to energies below the neutron separation energy. The assessment of the discrepant data at energies around or below the neutron separation energy has been possible only in a few cases where adequate information on the model-dependent analysis and estimation of uncertainties was available. In the giant dipole resonance region, we adopt the recommendations of the new IAEA photonuclear data library. We also present global empirical and semi-microscopic models that describe the photon strength functions in the entire energy region and reproduce reasonably well most of the experimental data. The compiled experimental photon strengths and recommended model calculations are available from the PSF database hosted at the IAEA (wwwnds.iaea.org/PSFdatabase).

European Physical Journal A 55, 172 (2019)

15. Nuclear level densities and gamma-ray strength functions in ^{147,149}Sm isotopes

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The γ-strength functions and level densities in the quasicontinuum of 147,149Sm isotopes have been extracted from particle-γ coincidences using the Oslo method. The nuclei of interest were populated via (p,d) reactions on pure 148,150Sm targets and the reaction products were recorded by the Hyperion array. An upbend in the low-energy region of the γ SF has been observed. The systematic analysis of the γSF for a range of Sm isotopes highlights the interplay between scissors mode and the upbend. Shell-model calculations show reasonable agreement with the experimental γSFs and confirm the correspondence between the upbend and scissors mode.

Physical Review C 99, 054331 (2019)

16. Dipole strength distribution in ^{206}Pb for the evaluation of the neutron-capture cross section of ^{205}Pb

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The dipole strength distribution of ^{206}Pb was investigated via a nuclear resonance fluorescence experiment using bremsstrahlung produced with an electron beam at a kinetic energy of 10.5 MeV at the linear accelerator ELBE. We identified 88 states resonantly excited at energies from 3.7 to 8.2

MeV. The analysis of the measured γ-ray spectra includes the quasicontinuum of levels at high energy. Monte Carlo simulation of γ-ray cascades were performed to obtain the intensities of inelastic transitions and branching ratios of the ground-state transitions. The extracted photoabsorption cross section shows enhanced dipole strength at the excitation energies around 5.5 and 7 MeV, which may related to a pygmy dipole resonance. The present (γ, γ) data combined with (γ, n) data from the literature were used for confining input parameters of the statistical calculation code CCONE to derive the neutron-capture cross section of the unstable ^{205}Pb nucleus.

Physical Review C 98, 064317 (2018)

17. IAEA Photonuclear Data Library 2019

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Photo-induced reaction cross section data are of importance for a variety of current or emerging applications, such as radiation shielding design and radiation transport analyses, calculations of absorbed dose in the human body during radiotherapy, physics and technology of fission reactors (influence of photo-reactions on neutron balance) and fusion reactors (plasma diagnostics and shielding), activation analyses, safeguards and inspection technologies, nuclear waste transmutation, medical isotope production and astrophysical applications.

To address these data needs the IAEA Photonuclear Data library was produced in 1999, containing evaluated photo-induced cross sections and neutron spectra for 164 nuclides which were deemed relevant for the applications.

Since the release of the IAEA Photonuclear Data Library however, new experimental data as well as new methods to assess the reliability of experimental cross sections have become available. Theoretical models and input parameters used to evaluate photo-induced reactions have improved significantly over the years. In addition, new measurements of partial photoneutron cross sections using mono-energetic photon beams and advanced neutron detection systems have been performed allowing for the validation of the evaluations and assessments of the experimental data. Furthermore, technological advances have led to the construction of new and more powerful gamma-beam facilities, therefore new data needs are emerging.

We report our coordinated efforts to address these data needs and present the results of the new up-to-date evaluations included in the new updated IAEA Photonuclear Data Library consisting of 219 nuclides. The new library includes 188 new evaluations produced by the CRP evaluators, and one evaluation taken from the JENDL/PD-2016 library, while 20 evaluations were retained from the previous 1999 IAEA Photonuclear Data Library. In most of the cases, the photon energy goes up to 200 MeV. A total of 55 nuclides are new in this library reflecting the progress in measurements but also the developing data needs. In this paper we discuss the new assessment method and make recommendations to the user community in cases where the experimental data are discrepant and the assessments disagree. In addition, in the absence of experimental data, we present model predictions for photo-induced reaction cross section on nuclides of potential interest to medical radioisotope production.

Nuclear Data Sheets 163 (2020) 109–162

18. Electric and magnetic dipole strength in ^{54}Fe

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The dipole strength of the N=28 closed-shell nuclide ^{54}Fe was studied in photon-scattering experiments using bremsstrahlung produced with electron beams of kinetic energies of 7.5 and 13.9 MeV at the γELBE facility as well as using quasimonoenergetic and linearly polarized photon beams of 26 different energies within the range from 5.5 to 11.4 MeV at the HIγS facility. About 100 J=1 states were newly identified, out of them 19 with 1^+ and 30 with 1^- assignments. The quasicontinuum of unresolved transitions was included in the analysis of the spectra and the intensities of branching transitions were estimated on the basis of simulations of statistical γ-ray cascades. As a result, the photoabsorption cross section up to the neutron-separation energy was determined and compared with predictions of the statistical reaction model. The experimental M1 strengths from resolved 1^+ states are compared with results of large-scale shell-model calculations.

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19. Dipole response of ^{87}Rb and its impact on the ^{86}Rb(n, γ) ^{87}Rb cross section

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Background: Detailed information on the low-lying dipole response in atomic nuclei along isotonic or isotopic chains is well suited to systematically investigate the structure and evolution of the pygmy dipole resonance (PDR). Moreover, the dipole strength below and around the neutron separation energy Sn has impact on statistical model calculations for nucleosynthesis processes.
Purpose: The photon strength function (PSF) of ^{87}Rb, which is directly connected to the photoabsorption cross section, is a crucial input for statistical model calculations constraining the Maxwellian-averaged cross section (MACS) of the neutron capture of the unstable s-process branching-point nucleus ^{86}Rb. Within this work, the photoabsorption cross section is investigated.
Methods: The photoabsorption cross section of the N = 50 nucleus ^{87}Rb was determined from photon-scattering experiments via the nuclear resonance fluorescence (NRF) technique. Bremsstrahlung beams at the γELBE facility in conjunction with monoenergetic photon beams at the HIγS facility were used to determine the integrated cross sections I_s of isolated states as well as the averaged cross section as function of the excitation energy. Decays to the ground state were disentangled from decays to first low-lying excited states. Statistical and experimental approaches for the γ -decay properties at various excitation energies were applied. The linearly polarized photon beams at HIγS provide information on the ratio of electric and magnetic type of radiation.
Results: Within this work, more than 200 ground-state decays and associated levels in ^{87}Rb were identified. Moreover, transitions below the sensitivity limit of the state-by-state analysis were taken into account via a statistical approach from the bremsstrahlung data as well as model-independently from the HIγ S data. The photoabsorption cross sections at various excitation energies were determined. The dipole response between 6 and 10 MeV of ^{87}Rb is in agreement with assuming contributions of electric multipolarity, only.
Conclusions: The photoabsorption cross section of ^{87}Rb does not contradict with the trend of decreasing E1 strength with increasing proton number along the N = 50 isotonic chain but might also be associated with a constant trend. The experimental γ decay at various excitation energies of the HIγ S data supports the statistical approach but does not provide a stringent proof due to the limited sensitivity in the decay channels. The additional E1 strength observed in the present experiments significantly enhances the MACSs compared only to recent microscopic HFB+QRPA (Hartree-Fock-Bogoliubov plus quasiparticle random-phase approximation) calculations using the D1M interaction. Moreover, theoretical estimations provided by the KADoNiS project could be significantly improved.

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20. High-sensitivity investigation of low-lying dipole strengths in ^{120}Sn

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Background: The term Pygmy Dipole Resonance (PDR) denotes an accumulation of electric dipole excitations below and around the neutron separation threshold. It may be important, e.g., for the nucleosynthesis of heavy nuclei or the symmetry energy in the Equation of State (EoS). For a deeper understanding of the PDR, systematic studies are essential.

Purpose: The tin isotopic chain is a well-suited candidate to investigate the systematics of the PDR, and the (γ,γ′) reactions on ^{112,116,120,124}Sn have already been measured in experiments using bremsstrahlung. It was claimed that the extracted electric dipole transition strengths of these isotopes increase with increasing neutron-to-proton ratio with the exception of ^{120}Sn. Furthermore, previous results from elastic photon scattering experiments on ^{120}Sn are in disagreement with corresponding (p,p′) Coulomb excitation data. To examine this discrepancy an additional high-sensitivity bremsstrahlung experiment on ^{120}Sn was performed.

Method: The Nuclear Resonance Fluorescence (NRF) method is used, which is based on the scattering of real photons. The bremsstrahlung experiment presented in this work was performed with a maximum energy of Eγ,max=9.5MeV at the γELBE facility at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). Besides a state-to-state analysis, the quasicontinuum was investigated as well.

Results: Above Ex=4 MeV 228 dipole transitions were clearly identified; 163 were observed for the first time. Assuming that all identified dipole transitions have electric dipole character the summed electric dipole strength equals $\sum B(E1)\uparrow = 369(49)\times 10^{-3} e^2 fm^2$ [which amounts to 0.58(8)% of the Thomas-Reiche-Kuhn sum rule] for transitions from 4 MeV to Sn=9.1 MeV. This is an enhancement of a factor 2.3 compared to the previously published ^{120}Sn(γ,γ′) results. This increase can be explained by the contribution of many weak, previously not included transitions in the state-to-state analysis. The photoabsorption cross sections deduced from the quasicontinuum analysis exceed those of the (p,p′) experiment in average by about 50% between 5.9 and 8.7 MeV.

Conclusion: The newly extracted summed B(E1) value of the state-to-state analysis is larger than those of ^{112,116}Sn and smaller than that of ^{124}Sn. The difference between the electric dipole transition strengths deduced from isolated peaks of the present (γ,γ′) data and those from the inelastic proton scattering experiment above 6.3 MeV is still striking. The analysis of the photoabsorption cross section including the quasicontinuum of levels overcomes this problem and the results are in the order of magnitude of the (p,p′) data and continue the (γ,n) cross sections at the neutron separation threshold.

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21. Direct measurements of low-energy resonance strengths of the ^{23}Na(p,γ)^{24}Mg reaction for astrophysics

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The NeNa and the MgAl cycles play a fundamental role in the nucleosynthesis of asymptotic giant branch stars undergoing hot bottom burning. The ^{23}Na(p, γ)^{24}Mgreaction links these two cycles and a precise determination of its rate is required to correctly estimate the contribution of these stars to the chemical evolution of various isotopes of Na, Mg and Al. At temperatures of 50 <T<110 MK, narrow resonances at E_p=140 and 251 keVare the main contributors to the reaction rate, in addition to the direct capture that dominates in the lower part of the temperature range. We present new measurements of the strengths of these resonances at the Laboratory for Underground Nuclear Astrophysics (LUNA). We have used two complementary detection approaches: high efficiency with a 4π BGO detector for the 140 keV resonance, and high resolution with a HPGe detector for the 251 keV resonance. Thanks to the reduced cosmic ray background of LUNA, we were able to determine the resonance strength of the 251 keV resonance as ωγ = 482(82) μeV and observed new gamma ray transitions for the decay of the corresponding state in ^{24}Mg at E_x = 11931 keV. With the highly efficient BGO detector, we observed a signal for the 140 keV resonance for the first time in a direct measurement, resulting in a strength of $\omega\gamma_{140}$ = 1.46+0.58 −0.53 neV (68% CL). Our measurement reduces the uncertainty of the ^{23}Na(p, γ)^{24}Mg reaction rate in the temperature range from 0.05 to 0.1GK to at most +50% −35% at 0.07 GK. Accordingly, our results imply a significant reduction of the uncertainties in the nucleosynthesis calculations.

Physics Letters B 795 (2019) 122

22. The baryon density of the Universe from an improved rate of deuterium burning

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Light elements were produced in the first few minutes of the Universe through a sequence of nuclear reactions known as Big Bang nucleosynthesis (BBN)[1,2]. Among the light elements produced during BBN[1,2], deuterium is an excellent indicator of cosmological parameters because its abundance is highly sensitive to the primordial baryon density and also depends on the number of neutrino species permeating the early Universe. Although astronomical observations of primordial deuterium abundance have reached percent accuracy[3], theoretical predictions[4–6] based on BBN are hampered by large uncertainties on the cross-section of the deuterium burning D(p,γ)^{3}He reaction. Here we show that our improved cross-sections of this reaction lead to BBN estimates of the baryon density at the 1.6 percent level, in excellent agreement with a recent analysis of the cosmic microwave background[7]. Improved cross-section data were obtained by exploiting the negligible cosmic-ray background deep underground at the Laboratory for Underground Nuclear Astrophysics (LUNA) of the Laboratori Nazionali del Gran Sasso (Italy)[8,9]. We bombarded a high-purity deuterium gas target10 with an intense proton beam from the LUNA 400-kilovolt accelerator11 and detected the γ-rays from the nuclear reaction under study with a high-purity germanium detector. Our experimental results settle the most uncertain nuclear physics input to BBN calculations and substantially improve the reliability of using primordial abundances to probe the physics of the early Universe.

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INSTITUT FUER KERN- UND TEILCHENPHYSIK TECHNISCHE UNIVERSITÄT DRESDEN

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1. New measurement of the ^{144}Sm(α, γ) ^{148}Gd reaction rate for the γ process

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Background: Most of the heavier *p* isotopes are believed to be produced in the γ process whose reaction path crucially depends on the proton and α-particle penetrability at sub-Coulomb energies. Both nuclei of the samarium *p*-process chronometer, 146Sm and 144Sm, are produced in the γ process, and their initial abundance ratio is very sensitive to the (γ , *n*) and (γ ,α) branching ratio on 148Gd. The 148Gd(γ ,α) 144Sm reaction rate was measured roughly 20 years ago by means of the activation technique and its surprising results triggered adjustments to the global low-energy α+nucleus optical-model potentials (OMPs).
Purpose: We want to take advantage of modern α-particle spectroscopy techniques in order to constrain the controversial previous results on the 148Gd(γ ,α) 144Sm reaction rate.
Method: The 148Gd(γ ,α) 144Sm reaction rate has been determined by measuring the cross section of the reverse reaction 144Sm(α, γ) 148Gd, applying the activation technique to the α decay of 148Gd. Targets have been irradiated at the cyclotron of the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany. The α-particle spectroscopy has been carried out with a state-of-the-art low-background ionization chamber of the Technische Universität Dresden, Germany.
Results: Cross sections for the 144Sm(α, γ) 148Gd reaction have been measured between 10.66 and 12.66 MeV with much higher precision than in the previous measurement. The results agree with earlier results within their uncertainties. The statistical-model analysis has been carried out using the TALYS code on the basis of the latest parametrizations of α-OMPs. The best reproductions of the experimental results within the statistical model have been used to calculate the reaction rates. **Conclusion:** The values presented here suggest a steeper increase in the astrophysical *S* factor towards lower center-of-mass energies. Different parametrizations of the α-OMP were able to describe the experimental values sufficiently. Further measurements at energies below 11.0 MeV are suggested.

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2. Laser-assisted decay spectroscopy and mass spectrometry of ^{178}Au

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A comprehensive study of the isotope 178Au has been made at the CERN-ISOLDE facility, using resonance laser ionization. Two long-lived states in 178Au were identified—a low-spin ground state and a high-spin isomer—each of which were produced as pure beams. Using the ISOLTRAP precision Penning trap, the excitation energy of the isomeric state in 178Au was determined to be $E* = 189(14)$ keV. The α-decay fine structure patterns of the two states were studied using the Windmill decay station, providing information on the low-lying states in the daughter nucleus 174Ir. Nuclear spin assignments of I (178Aug) = (2, 3) and I (178Aum) = (7, 8) are made based on the observed β-decay feeding and hyperfine structure intensity patterns. These spin assignments are used for fitting the hyperfine structures of the two states from which values for the magnetic dipole moments are extracted. The extracted moments are compared with calculations using additivity relations to establish the most probable configurations for 178Aug,m.

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3. Laser-assisted decay spectroscopy for the ground states of ^{180,182}Au

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A study of the ground states of the laser-ionized and mass-separated odd-odd isotopes 180,182Au was performed using the Resonance Ionization Laser Ion Source, Windmill detection setup and ISOLTRAP Multi-Reflection Time-of-Flight Mass Spectrometer at ISOLDE, CERN. A complex fine-structure α-decay pattern of 180Au was deduced, providing insight into the low-lying levels in the daughter nucleus 176Ir. An α-decay branching ratio of $b\alpha$ (180Au) = 0.58(10)% and a half-life of $T1/2$ = 7.2(5) s have also been derived, allowing for the calculation of the reduced α-decay widths and determining the degree of hindrance of respective α-decay branches. From complementary first in-source laser spectroscopy measurements of the hyperfine structure in atomic transitions of 180,182Au, the nuclear magnetic moments of μ(180Au) = −0.83(9) μN and μ(182Au) = 1.66(9) μN were extracted with an inclusion of a correction for the hyperfine anomaly. Based on the observed hyperfine structure patterns, and on the comparison of the measured and calculated μ values, a preferred ground-state spin and parity $I\pi$ ($180Au_{gs}$) = (1+) is proposed, and the earlier assignment of $I\pi$ (182Augs) = (2+) is confirmed. For 180Au, the most probable proton-neutron Nilsson configuration of π3/2−[532]⊗ν5/2−[512] suggests the same protonstate as in the heavier deformed odd-odd nuclei182,184Au.

PHYSICAL REVIEW C 102, 024312 (2020)

4. Examining the $N = 28$ shell closure through high-precision mass measurements of $^{46–48}$Ar

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The strength of the $N = 28$ magic number in neutron-rich argon isotopes is examined through high-precision mass measurements of $^{46–48}$Ar, performed with the ISOLTRAP mass spectrometer at ISOLDE/CERN. The new mass values are up to 90 times more precise than previous measurements. While they suggest the persistence of the $N = 28$ shell closure for argon, we show that this conclusion has to be nuanced in light of the wealth of spectroscopic data and theoretical investigations performed with the SDPF-U phenomenological shell model interaction. Our results are also compared with *ab initio* calculations using the valence space in-medium similarity renormalization group and the self-consistent Green's function approaches. Both calculations provide a very good account of mass systematics at and around $Z = 18$ and, generally, a consistent description of the

physics in this region. This combined analysis indicates that ^{46}Ar is the transition between the closed-shell ^{48}Ca and collective ^{44}S.

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5. Spin-dipole nuclear matrix element for the double beta decay of ^{76}Ge by the (3He, t) charge-exchange reaction

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Nuclear matrix elements (NMEs) for double beta decays (DBDs) are crucial for studying the neutrino mass and other neutrino properties beyond the standard electro-weak model by measuring neutrino-less DBDs. The spin dipole (SD) J π=2− NME is one of the major components associated with the DBD NME. The SD NME for ^{76}Ge was derived for the first time by using the ^{74,76} Ge (^{3}He, t) at RCNP Osaka. The obtained SD NME for the ^{76}Ge→^{76}As ground-state transition is $|M$E-XP(SD)| = 1.5 * 10^{-3} in natural units. This is smaller by a coefficient around k ≈ 0.2 with respect to the quasi-particle model NME $|M$Q-P(SD)|. The impact of the reduced (quenched) SD NME on DBD neutrino studies is discussed.

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6. First Glimpse of the N = 82 Shell Closure below Z = 50 from Masses of Neutron-Rich Cadmium Isotopes and Isomers

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We probe the N = 82 nuclear shell closure by mass measurements of neutron-rich cadmium isotopes with the ISOLTRAP spectrometer at ISOLDE-CERN. The new mass of ^{132}Cd offers the first value of the N = 82, two-neutron shell gap below Z = 50 and confirms the phenomenon of mutually enhanced magicity at 132Sn. Using the recently implemented phase-imaging ion-cyclotron-resonance method, the ordering of the low-lying isomers in 129Cd and their energies are determined. The new experimental findings are used to test large-scale shell-model, mean-field, and beyond-mean-field calculations, as well as the ab initio valence-space in-medium similarity renormalization group.

PHYSICAL REVIEW LETTERS 124, 092502 (2020)

7. Hyperfine anomaly in gold and magnetic moments of $I\pi = 11/2-$ gold isomers

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Hyperfine-structure constants for the 6*s* 2*S*1/2 and 6*p* 2*P*1/2 atomic states of the $I\pi = 11/2-$ gold isomers 177,191,193,195Au*m* have been measured at CERN-ISOLDE, using the in-source laser resonance-ionization spectroscopy technique. From the measured hyperfine constants the differences between hyperfine anomalies for these atomic states have been deduced. These differential hyperfine anomaly values have been used to determine the 6*s*-state hyperfine anomaly relative to the stable 197Au with advanced atomic calculations. Magnetic dipole moments for the gold isomers in question have been deduced, taking into account the corresponding relative hyperfine-anomaly values. It has been shown that the commonly used prescription for the extraction of the magnetic moment values for the gold isotopes should be reconsidered. The magnetic moments calculated by this prescription have been reevaluated by properly accounting for the hyperfine anomaly, which is as large as 10% for several gold isotopes.

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8. **Gamow–Teller strength distributions of ^{116}Sb and ^{122}Sb using the *(*3He, *t)* charge-exchange reaction**

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The Gamow–Teller strength distributions of ^{116}Sb and ^{122}Sb were measured with the ^{116,122}Sn*(*^{3}He*, t)*116*,*122Sb charge-exchange reactions at 140 MeV/u. The measurements were carried out at the Research Center for Nuclear Physics (RCNP) at Osaka University in Osaka, Japan using the Grand Raiden spectrometer. The data were analysed by Multipole-Decomposition Analysis (MDA). The Gamow– Teller strengths summed up to 28 MeV are *(*38 ± 7*)*% and *(*48 ± 6*)*% of the Ikeda sum rule for ^{116}Sb and ^{122}Sb, respectively, if the quasi-free scattering (QFS) contribution is not subtracted. These percentages are *(*29 ± 7*)*%and *(*35 ± 5*)*%, respectively, if theQFS contribution is maximally subtracted. These results were compared to those from previous measurements of the same isotopes, to recent measurements of ^{150}Pm, and to a Quasi-particle Random-Phase Approximation (QRPA) calculation with Quasi-Particle Vibration Coupling (QPVC). The data suggest that the true QFS contribution is small for ^{116}Sb, but are inconclusive about whether the QFS contribution is small or significant for ^{122}Sb. Therefore, these data may provide an interesting test for the general quenching phenomenon of the Gamow–Teller Resonance (GTR). However, more research to reveal the nature of the QFS contribution is still needed on both the experimental and the theoretical side.

Eur. Phys. J. A (2020) 56:51

9. **High-resolution and low-background 163Ho spectrum: interpretation of the resonance tails**

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The determination of the effective electron neutrino mass via kinematic analysis of beta and electron capture spectra is considered to be model-independent since it relies on energy and momentum conservation. At the same time the precise description of the expected spectrum goes beyond the simple phase space term. In particular for electron capture processes, many-body electron-electron interactions lead to additional structures besides the main resonances in calorimetrically measured spectra. A precise description of the 163Ho spectrum is fundamental for understanding the impact of low intensity structures at the endpoint region where a finite neutrino mass affects the shape most strongly. We present a low-background and high-energy resolution measurement of the 163Ho spectrum obtained in the framework of the ECHo experiment. We study the line shape of the main resonances and multiplets with intensities spanning three orders of magnitude. We discuss the need to introduce an asymmetric line shape contribution due to Auger–Meitner decay of states above the auto-ionisation threshold. With this we determine an enhancement of count rate at the endpoint region of about a factor of 2, which in turn leads to an equal reduction in the required exposure of the experiment to achieve a given sensitivity on the effective electron neutrino mass.

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10. Quasi-free neutron and proton knockout reactions from light nuclei in a wide neutron-to-proton asymmetry range

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The quasi-free scattering reactions 11C(p, 2p)and 10,11,12C(p, pn)have been studied in inverse kinematics at beam energies of 300–400MeV/uat the R3B-LAND setup. The outgoing proton-proton and proton-neutron pairs were detected in coincidence with the reaction fragments in kinematically complete measurements. The efficiency to detect these pairs has been obtained from GEANT4 simulations which were tested using the 12C(p, 2p) and 12C(p, pn) reactions. Experimental cross sections and momentum distributions have been obtained and compared to DWIA calculations based on eikonal theory. The new results reported here are combined with previously published cross sections for quasi-free scattering from oxygen and nitrogen isotopes and together they enable a systematic study of the reduction of single-particle strength compared to predictions of the shell model over a wide neutron-to-proton asymmetry range. The combined reduction factors show a weak or no dependence on isospin asymmetry, in contrast to the strong dependency reported in nucleon-removal reactions induced by nuclear targets at lower energies. However, the reduction factors for (p, 2p)are found to be 'significantly smaller than for (p, pn)reactions for all investigated nuclei.

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11. *Q*EC-value determination for ^{21}Na → ^{21}Ne and ^{23}Mg → ^{23}Na mirror-nuclei decays using high-precision mass spectrometry with ISOLTRAP at the CERN ISOLDE facility

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We report on high-precision *Q*EC values of the 21Na → 21Ne and 23Mg → 23Na mirror β transitions from mass measurements with ISOLTRAP at the CERN ISOLDE facility. A precision of $\delta m/m = 9 \times 10^{-10}$ and $\delta m/m = 1.5 \times 10^{-9}$ was reached for the masses of 21Na and 23Mg, respectively. We reduce the uncertainty of the *Q*EC values by a factor of 5, making them the most precise experimental input data for the calculation of the corrected *Ft* value of these mixed Fermi and Gamow-Teller transitions. For the 21Na → 21Ne *Q*EC value, a 2.3σ deviation from the literature *Q*EC value was found.

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12. Mass measurements of neutron-rich isotopes near $N = 20$ by in-trap decay with the ISOLTRAP spectrometer

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The masses of ^{34}Si, ^{33,34}Mg, and ^{34}Al have been measured with the ISOLTRAP Penning-trap spectrometer at ISOLDE/CERN. The results are in agreement with previous mass measurements and uncertainties have been decreased. The mass of ^{34}Al was determined in two configurations, one following direct production by the ISOLDE facility, favoring the 4^- state, expected to be the ground state, second by in-trap decay of ^{34}Mg, followed by recoil-ion trapping, favoring the production of the isomeric 1+ state. A position-sensitive detector was used to clean the ToF-ICR resonance. In addition, the mass of the refractory doubly magic ^{34}Si nucleus was directly measured, using the in-trap decay of ^{34}Mg, following two sequential recoil-ion captures. The approach, challenges and conclusions are discussed.

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13. Evaluation of high-precision atomic masses of A ∼50–80 and rare-earth nuclides measured with ISOLTRAP

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High-precision mass measurements of stable and beta-decaying nuclides 52–57Cr, 55Mn, 56,59Fe, 59Co, 75,77–79Ga, and the lanthanide nuclides 140Ce, 140Nd, 160Yb, 168Lu, 178Yb have been performed with the Penning-trap mass spectrometer ISOLTRAP at ISOLDE/CERN. The new data are entered into the Atomic Mass Evaluation and improve the accuracy of masses along the valley

of stability, strengthening the so-called backbone. The mass of neutron-deficient 168Lu in its isomeric state has been measured directly. The mass of neutron-rich 178Yb indicates a change of nuclear structure approaching the double harmonic oscillator shell closure for $Z = 70$ and $N = 112$.

Eur. Phys. J. A (2019) **55**: 96

14. Inverse odd-even staggering in nuclear charge radii and possible octupole collectivity in ^{217,218,219}At revealed by in-source laser spectroscopy

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Hyperfine-structure parameters and isotope shifts for the 795-nm atomic transitions in ^{217,218,219}At have been measured at CERN-ISOLDE, using the in-source resonance-ionization spectroscopy technique. Magnetic dipole and electric quadrupole moments, and changes in the nuclear mean-square charge radii, have been deduced. A large inverse odd-even staggering in radii, which may be associated with the presence of octupole collectivity, has been observed. Namely, the radius of the odd-odd isotope 218At has been found to be larger than the average of its even-N neighbors, 217,219At. The discrepancy between the additivity-rule prediction and experimental data for the magnetic moment of 218At also supports the possible presence of octupole collectivity in the considered nuclei.

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15. New investigation of half-lives for the decay modes of ^{50}V

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A new search for the decay modes of the fourfold forbidden nonunique decay of ^{50}V has been performed at the Gran Sasso Underground Laboratory (LNGS). In total, an exposure of 197 kg d has been accumulated. The half-life for the electron capture into the first excited state of ^{50}Ti has been measured with the highest precision to date as $2.67^{+0.16}_{-0.18} \times 10^{17}$ yr (68% C.I.) in which systematics uncertainties dominate. The search for the β decay into the first excited state of ^{50}Cr resulted in a lower limit of 1.9×10^{19} yr (90% C.I.), which is an improvement of almost one order of magnitude compared to existing results. The sensitivity of the new measurement is now in the region of theoretical predictions.

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16. Change in structure between the I=1/2 states in ^{181}Tl and ^{177,179}Au

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The first accurate measurements of the α-decay branching ratio and half-life of the $I\pi$=1/2+ground state in 181Tl have been made, along with the first determination of the magnetic moments and I=1/2spin assignments of the ground states in 177,179Au. The results are discussed within the complementary systematics of the reduced α-decay widths and nuclear $g$factors of low-lying, $I\pi$=1/2+states in the neutron-deficient lead region. The findings shed light on the unexpected hindrance of the 1/2+→1/2+, 181Tl$_g$→177Augαdecay, which is explained by a mixing of π3s1/2and π2d3/2configurations in 177Au$_g$, whilst 181Tl$_g$ remains a near-pure π3s1/2. This conclusion is inferred from the $g$factor of 177Augwhich has an intermediate value between those of π3s1/2and π2d3/2states. A similar mixed configuration is proposed for the $I\pi$=1/2+ground state of 179Au. This mixing may provide evidence for triaxial shapes in the ground states in these nuclei.

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17. Characterization of the shape-staggering effect in mercury nuclei

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In rare cases, the removal of a single proton (Z) or neutron (N) from an atomic nucleus leads to a dramatic shape change. These instances are crucial for understanding the components of the nuclear interactions that drive deformation. The mercury isotopes (Z = 80) are a striking example[1,2]: their close neighbours, the lead isotopes (Z = 82), are spherical and steadily shrink with decreasing N. The even-mass (A = N + Z) mercury isotopes follow this trend. The odd-mass mercury isotopes ^{181,183,185}Hg, however, exhibit noticeably larger charge radii. Due to the experimental difficulties of probing extremely neutron-deficient systems, and the computational complexity of modelling such heavy nuclides, the microscopic origin of this unique shape staggering has remained unclear. Here, by applying resonance ionization spectroscopy, mass spectrometry and nuclear spectroscopy as far as ^{177}Hg, we determine ^{181}Hg as the shape-staggering endpoint. By combining our experimental

measurements with Monte Carlo shell model calculations, we conclude that this phenomenon results from the interplay between monopole and quadrupole interactions driving a quantum phase transition, for which we identify the participating orbitals. Although shape staggering in the mercury isotopes is a unique and localized feature in the nuclear chart, it nicely illustrates the concurrence of single-particle and collective degrees of freedom at play in atomic nuclei.

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18. **Structure of ^{13}Be studied in proton knockout from ^{14}B**

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The neutron-unbound isotope 13Be has been studied in several experiments using different reactions, different projectile energies, and different experimental setups. There is, however, no real consensus in the interpretation of the data, in particular concerning the structure of the low-lying excited states. Gathering new experimental information, which may reveal the 13Be structure, is a challenge, particularly in light of its bridging role between 12Be, where the N=8 neutron shell breaks down, and the Borromean halo nucleus 14Be. The purpose of the present study is to investigate the role of bound excited states in the reaction product 12Be after proton knockout from 14B, by measuring coincidences between 12Be, neutrons, and γ rays originating from de-excitation of states fed by neutron decay of 13Be. The 13Be isotopes were produced in proton knockout from a 400 MeV/nucleon 14B beam impinging on a CH2 target. The 12Be−n relative-energy spectrum dσ/dEfn was obtained from coincidences between 12Be(g.s.) and a neutron, and also as threefold coincidences by adding γ rays, from the de-excitation of excited states in 12Be. Neutron decay from the first 5/2+ state in 13Be to the 2+ state in 12Be at 2.11 MeV is confirmed. An energy independence of the proton-knockout mechanism is found from a comparison with data taken with a 35 MeV/nucleon 14B beam. A low-lying p-wave resonance in 13Be(1/2−) is confirmed by comparing proton- and neutron-knockout data from 14B and 14Be.

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19. Precision Mass Measurements of $^{58–63}$Cr: Nuclear Collectivity Towards the N = 40 Island of Inversion

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The neutron-rich isotopes $^{58-63}$Cr were produced for the first time at the ISOLDE facility and their masses were measured with the ISOLTRAP spectrometer. The new values are up to 300 times more precise than those in the literature and indicate significantly different nuclear structure from the new mass-surface trend. A gradual onset of deformation is found in this proton and neutron midshell region, which is a gateway to the second island of inversion around N = 40. In addition to comparisons with density- functional theory and large-scale shell-model calculations, we present predictions from the valence-space formulation of the ab initio in-medium similarity renormalization group, the first such results for open-shell chromium isotopes.

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20. Charge radii and electromagnetic moments of $^{195-211}$At

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Hyperfine-structure parameters and isotope shifts of $^{195–211}$At have been measured for the first time at CERN- ISOLDE, using the in-source resonance-ionization spectroscopy method. The hyperfine structures of isotopes were recorded using a triad of experimental techniques for monitoring the photo-ion current. The Multi-Reflection Time-of-Flight Mass Spectrometer, in connection with a high-resolution electron multiplier, was used as an ion- counting setup for isotopes that either were affected by strong isobaric contamination or possessed a long half-life; the ISOLDE Faraday cups were used for cases with high-intensity beams; and the Windmill decay station was used for short-lived, predominantly α-decaying nuclei. The electromagnetic moments and changes in the mean-square charge radii of the astatine nuclei have been extracted from the measured hyperfine-structure constants and isotope shifts. This was only made possible by dedicated state-of-the-art large-scale atomic computations of the electronic factors and the specific mass shift of atomic transitions in astatine that are needed for these extractions. By comparison with systematics, it was possible to assess the reliability of the results of these calculations and their ascribed uncertainties. A strong deviation in the ground-state mean-square charge radii of the lightest astatine isotopes, from the trend of the (spherical) lead isotopes, is interpreted as the result of an onset of deformation. This behavior bears a resemblance to the deviation observed in the isotonic polonium isotopes. Cases for shape coexistence have been identified in ^{197,199}At, for which a significant difference in the charge radii for ground (9/2−) and isomeric (1/2+) states has been observed.

PHYSICAL REVIEW C **97**, 054327 (2018)

FORSCHUNGSZENTRUM JÜLICH
INSTITUT FÜR NEUROWISSENSCHAFTEN UND MEDIZIN, INM-5: NUKLEARCHEMIE

Nuclear model analysis of excitation functions of α-particle induced reactions on In and Cd up to 60MeV with relevance to the production of high specific activity ^{117m}Sn.

Aslam, M. N.; Zubia, K.; Qaim, S. M.

Excitation functions were calculated for the α-particle induced reactions ^{115}In(α,x)^{117m}Sn, ^{114}Cd(α,n)^{117m}Sn, ^{116}Cd(α,3n)^{117m}Sn and ^{nat}Cd(α,x)^{117m}Sn to analyse the production of the medically important ^{117m}Sn ($T_{½}$ = 13.6 d). For calculations three nuclear model codes (i.e. TALYS, EMPIRE and ALICE-IPPE) were used and the results were compared with the available experimental data. For the most important reaction, ^{116}Cd(α,3n)^{117m}Sn, evaluated data are presented. The yield and radionuclidic purity of ^{117m}Sn from each reaction are discussed.

*Applied Radiation and Isotopes **132** (2018) 181-188*
[10.1016/j.apradiso.2017.12.002]

Isolation of high purity ^{73}Se using solid phase extraction after selective 4,5-[73Se]benzopiazselenol formation with aminonaphthalene

Königs, U. ; Humpert, S. ; Spahn, I. ; Qaim, S. M. ; Neumaier, B.

A fast and efficient process for the production of the PET radionuclide ^{73}Se was developed using ^{75}Se as a surrogate. ^{75}Se was separated from proton irradiated arsenic trioxide by reaction with 2,3-diaminonaphthalene to 4,5-[^{75}Se]benzopiazelenol. This compound was purified using SPE column chromatography and subsequently decomposed with hydrogen peroxide. For further chemical conversions [^{75}Se]selenite was reduced to elemental [^{75}Se]selenium by either using thiosulfate or sulfur dioxide. The recovery yield of ^{75}Se from the target amounted to 43%. The utility of the isolated ^{75}Se for radiosyntheses was demonstrated by the successful preparation of [^{75}Se]selenomethionine. The methodology developed using ^{75}Se was successfully transformed to ^{73}Se.

*Radiochimica Acta **106** (2018) 497–505*
[10.1515/ract-2017-2864]

New developments in the production of theranostic pairs of radionuclides

Qaim, S. M.; Scholten, B. ; Neumaier, B.

A brief historical background of the development of the theranostic approach in nuclear medicine is given and seven theranostic pairs of radionuclides, namely ^{44g}Sc/^{47}Sc, ^{64}Cu/^{67}Cu, ^{83}Sr/^{89}Sr, ^{86}Y/^{90}Y, ^{124}I/^{131}I, ^{152}Tb/^{161}Tb and ^{152}Tb/^{149}Tb, are considered. The first six pairs consist of a positron and a β^--emitter whereas the seventh pair consists of a positron and an α-particle emitter. The decay properties of all those radionuclides are briefly mentioned and their production methodologies are discussed. The positron emitters ^{64}Cu, ^{86}Y and ^{124}I are commonly produced in sufficient quantities via the (p,n) reaction on the respective highly enriched target isotope. A clinical scale production of the positron emitter ^{44g}Sc has been achieved via the generator route as well as via the (p,n) reaction, but further development work is necessary. The positron emitters ^{83}Sr and ^{152}Tb are under development.

Among the therapeutic radionuclides, ^{89}Sr, ^{90}Y and ^{131}I are commercially available and ^{161}Tb can also be produced in sufficient quantity at a nuclear reactor. Great efforts are presently underway to produce ^{47}Sc and ^{67}Cu via neutron, photon and charged particle induced reactions. The radionuclide ^{149}Tb is unique because it is an α-particle emitter. The present method of production of ^{152}Tb and ^{149}Tb involves the use of the spallation process in combination with an on-line mass separator. The role of some emerging irradiation facilities in the production of special radionuclides is discussed.

Journal of Radioanalytical and Nuclear Chemistry ***318*** *(2018) 1493 - 1509*
[10.1007/s10967-018-6238-x]

Development of novel radionuclides for medical applications

Spahn, I.; Qaim, S. M.

Medical radionuclide production technology is well established. There is, however, a constant need for further development of radionuclides. The present efforts are mainly devoted to nonstandard positron emitters (eg, ^{64}Cu, ^{86}Y, ^{124}I, and ^{73}Se) and novel therapeutic radionuclides emitting low-range β^- particles (eg, ^{67}Cu and ^{186}Re), conversion or Auger electrons (eg, ^{117m}Sn and ^{77}Br), and α particles (eg, ^{225}Ac). A brief account of various aspects of development work (ie, nuclear data, targetry, chemical processing, and quality control) is given. For each radionuclide under consideration, the status of technology for clinical scale production is discussed. The increasing need of intermediate-energy multiple-particle accelerating cyclotrons is pointed out.

Journal of Labelled Compounds and Radiopharmaceuticals ***61*** *(2018)126-140*
[10.1002/jlcr.3578]

Positron-emitting radionuclides for applications, with special emphasis on their production methodologies for medical use

Qaim, S. M. ; Scholten, B. ; Spahn, I. ; Neumaier, B.

A survey of the positron-emitting radionuclides over the whole mass range of the Periodic Table of Elements was carried out. As already known, positrons are preferably emitted from light mass neutron deficient radionuclides. Their emission from heavier mass nuclides is rather rare. The applications of positron annihilation in three areas, namely materials research, plant physiology and medical diagnosis, are reported. The methods of production of positron emitters are discussed, with emphasis on radionuclides presently attracting more attention in theranostics and multimodal imaging. Some future perspectives of radionuclide development technologies are considered.

Radiochimica Acta ***107*** *(2019) 1011 - 1026*
[10.1515/ract-2019-3154]

Theranostic radionuclides: recent advances in production methodologies

Qaim, S. M.

Various concepts involved in the quantification of radiation dose while following the theranostic approach in nuclear medicine are outlined. The availability of the relevant radionuclides is discussed. The production methodologies of many of the "matched-pair" of radionuclides were recently reviewed in detail. In this contribution, some additional information on a few positron emitters and therapeutic radionuclides is presented. In addition to generator production of ^{68}Ga ($T_{½}$ = 1.13 h), its direct production at a medical cyclotron is critically discussed. Besides conventional use of reactors and cyclotrons, there is a growing interest in utilizing fast neutrons from a d/Be source and high-energy photons from an electron linear accelerator to produce a few special therapeutic radionuclides. The related new developments are reviewed.

Journal of radioanalytical and nuclear chemistry ***322*** *(2019) 1257 - 1266*
[10.1007/s10967-019-06797-y]

GOETHE UNIVERSITÄT FRANKFURT
EXPERIMENTAL ASTROPHYSICS

1. Electron capture of Xe^{54+} in collisions with H_2 molecules in the energy range between 5.5 and 30.9 MeV/u

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The electron-capture process was studied for Xe54+ colliding with H2 molecules at the internal gas target of the Experimental Storage Ring (ESR) at GSI, Darmstadt. Cross-section values for electron capture into excited projectile states were deduced from the observed emission cross section of Lyman radiation, being emitted by the hydrogen like ions subsequent to the capture of a target electron. The ion beam energy range was varied between 5.5 and 30.9 MeV/u by applying the deceleration mode of the ESR. Thus, electron-capture data were recorded at the intermediate and, in particular, the low-collision-energy regime, well below the beam energy necessary to produce bare xenon ions. The obtained data are found to be in reasonable qualitative agreement with theoretical approaches, while a commonly applied empirical formula significantly overestimates the experimental findings.

Phys. Rev. A 102, 42825 (2020)

2. Measurement of the α ratio and (n,γ) cross section of ^{235}U from 0.2 to 200 eV at n_TOF

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We measured the neutron capture-to-fission cross-section ratio (α ratio) and the capture cross section of 235U between 0.2 and 200 eV at the n_TOF facility at CERN. The simultaneous measurement of neutron-induced capture and fission rates was performed by means of the n_TOF BaF2 Total Absorption Calorimeter (TAC), used for detection of γ rays, in combination with a set of micromegas detectors used as fission tagging detectors. The energy dependence of the capture cross section was obtained with help of the 6Li(n,t) standard reaction determining the n_TOF neutron fluence; the well-known integral of the 235U(n,f) cross section between 7.8 and 11 eV was then used for its absolute normalization. The α ratio, obtained with slightly higher statistical fluctuations, was determined directly, without need for any reference cross section. To perform the analysis of this measurement we developed a new methodology to correct the experimentally observed effect that the probabilities of detecting a fission reaction in the TAC and the micromegas detectors are not independent. The results of this work have been used in a new evaluation of 235U performed within the scope of the Collaborative International Evaluated Library Organisation (CIELO) Project, and are consistent with the ENDF/B-VIII.0 and JEFF-3.3 capture cross sections below 4 eV and above 100 eV. However, the measured capture cross section is on average 10% larger between 4 and 100 eV.

Phys. Rev. C 102, 044615 18 (2020)

3. Neutron Capture on the s-Process Branching Point ^{171}Tm via Time-of-Flight and Activation

C. Guerrero, J. Lerendegui-Marco, M. Paul, M. Tessler, S. Heinitz, C. Domingo-Pardo, S. Cristallo, R. Dressler, S. Halfon, N. Kivel, U. Köster, E. A. Maugeri, T. Palchan-Hazan, J. M. Quesada, D. Rochman, D. Schumann, L. Weissman, O. Aberle, S. Amaducci, J. Andrzejewski, L. Audouin, V. Bécares, M. Bacak, J. Balibrea, A. Barak, M. Barbagallo, S. Barros, F. Bevá, C. Beinrucker, D. Berkovits, E. Berthoumieux, J. Billowes, D. Bosnar, M. Brugger, Y. Buzaglo, M. Caamaño, F. Calviño, M. Calviani, D. Cano-Ott, R. Cardella, A. Casanovas, D. M. Castelluccio, F. Cerutti, Y. H. Chen, E. Chiaveri, N. Colonna, G. Cortés, M. A. Cortés-Giraldo, L. Cosentino, H. Dafna, A. Damone, M. Diakaki, M. Dietz, E. Dupont, I. Durán, Y. Eisen, B. Fernández-Domínguez, A. Ferrari, P. Ferreira, P. Finocchiaro, V. Furman, K. Göbel, A. R. García, A. Gawlik, T. Glodariu, I. F. Gonçalves, E. González-Romero, A. Goverdovski, E. Griesmayer, F. Gunsing, H. Harada, T. Heftrich, J. Heyse, T. Hirsh, D. G. Jenkins, E. Jericha, F. Käppeler, Y. Kadi, B. Kaizer, T. Katabuchi, P. Kavrigin, V. Ketlerov, V. Khryachkov, D. Kijel, A. Kimura, M. Kokkoris, A. Kriesel, M. Krtika, E. Leal-Cidoncha, C. Lederer-Woods, H. Leeb, S. Lo Meo, S. J. Lonsdale, R. Losito, D. Macina, A. Manna, J. Marganiec, T. Martínez, C. Massimi, P. Mastinu, M. Mastromarco, F. Matteucci, E. Mendoza, A. Mengoni, P. M. Milazzo, M. A. Millán-Callado, F. Mingrone, M. Mirea, S. Montesano, A. Musumarra, R. Nolte, A. Oprea, N. Patronis, A. Pavlik, J. Perkowski, L. Piersanti, I. Porras, J. Praena, K. Rajeev, T. Rauscher, R. Reifarth, T. Rodríguez-González, P. C. Rout, C. Rubbia, J. A. Ryan, M. Sabaté-Gilarte, A. Saxena, P. Schillebeeckx, S. Schmidt, A. Shor, P. Sedyshev, A. G. Smith, A. Stamatopoulos, G. Tagliente, J. L. Tain, A. Tarifeño-Saldivia, L. Tassan-Got, A. Tsinganis, S. Valenta, G. Vannini, V. Variale, P. Vaz, A. Ventura, V. Vlachoudis, R. Vlastou, A. Wallner, S. Warren, M. Weigand, C. Weiss, C. Wolf, P. J. Woods, T. Wright, P. Žugec

The neutron capture cross sections of several unstable nuclides acting as branching points in the s process are crucial for stellar nucleosynthesis studies. The unstable 171Tm (t1/2=1.92 yr) is part of the branching around mass A∼170 but its neutron capture cross section as a function of the neutron energy is not known to date. In this work, following the production for the first time of more than 5 mg of 171Tm at the high-flux reactor Institut Laue-Langevin in France, a sample was produced at the Paul Scherrer Institute in Switzerland. Two complementary experiments were carried out at the neutron time-of-flight facility (n_TOF) at CERN in Switzerland and at the SARAF liquid lithium

target facility at Soreq Nuclear Research Center in Israel by time of flight and activation, respectively. The result of the time-of-flight experiment consists of the first ever set of resonance parameters and the corresponding average resonance parameters, allowing us to make an estimation of the Maxwellian-averaged cross sections (MACS) by extrapolation. The activation measurement provides a direct and more precise measurement of the MACS at 30 keV: 384(40) mb, with which the estimation from the n_TOF data agree at the limit of 1 standard deviation. This value is 2.6 times lower than the JEFF-3.3 and ENDF/B-VIII evaluations, 25% lower than that of the Bao *et al.* compilation, and 1.6 times larger than the value recommended in the KADoNiS (v1) database, based on the only previous experiment. Our result affects the nucleosynthesis at the A∼170 branching, namely, the 171Yb abundance increases in the material lost by asymptotic giant branch stars, providing a better match to the available pre-solar SiC grain measurements compared to the calculations based on the current JEFF-3.3 model-based evaluation.

Phys. Rev. Lett. 125, 142701 8 (2020)

4. Probing the Z = 6 spin-orbit shell gap with (p,2p) quasi-free scattering reactions

I. Syndikus, M. Petri, A.O. Macchiavelli, S. Paschalis, C.A. Bertulani and 78 more

The evolution of the traditional nuclear magic numbers away from the valley of stability is an active field of research. Experimental efforts focus on providing key spectroscopic information that will shed light into the structure of exotic nuclei and understanding the driving mechanism behind the shell evolution. In this work, we investigate the spin-orbit shell gap towards the neutron dripline. To do so, we employed (p,2p) quasi-free scattering reactions to measure the proton component of the state of ^{16,18,20}C. The experimental findings support the notion of a moderate reduction of the proton spin-orbit splitting, at variance to recent claims for a prevalent magic number towards the neutron dripline.

Physics Letters B 809, 135748 (2020)

5. Determination of luminosity for in-ring reactions: A new approach for the low-energy domain

Y.M. Xing, J. Glorius, L. Varga, L. Bott, C. Brandau and 58 more

Luminosity is a measure of the colliding frequency between beam and target and it is a crucial parameter for the measurement of absolute values, such as reaction cross sections. In this paper, we make use of experimental data from the ESR storage ring to demonstrate that the luminosity can be precisely determined by modelling the measured Rutherford scattering distribution. The obtained results are in good agreement with an independent measurement based on the x-ray normalization method. Our new method provides an alternative way to precisely measure the luminosity in low-energy stored-beam configurations. This can be of great value in particular in dedicated low-energy storage rings where established methods are difficult or impossible to apply.

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 982, 164367 (2020)

6. A compact fission detector for fission-tagging neutron capture experiments with radioactive fissile isotopes

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In the measurement of neutron capture cross-sections of fissile isotopes, the fission channel is a source of background which can be removed efficiently using the so-called *fission-tagging* or *fission-veto technique*. For this purpose a new compact and fast fission chamber has been developed. The design criteria and technical description of the chamber are given within the context of a measurement of the ^{233}U(n,γ) cross-section at the n_TOF facility at CERN, where it was coupled to the n_TOF Total Absorption Calorimeter. For this measurement the fission detector was optimized for time resolution, minimization of material in the neutron beam and for alpha-fission discrimination. The performance of the fission chamber and its application as a fission tagging detector are discussed.

Nuclear Instruments and Methods in Physics Research A 969, 163981 (2020)

7. Shell-model studies of the astrophysical rp-process reactions ^{34}S(p,γ)^{35}Cl and ^{34g,m}Cl(p,γ)^{35}Ar

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Background: Dust grains condensed in the outflows of presolar classical novae should have been present in the protosolar nebula. Candidates for such presolar nova grains have been found in primitive meteorites and can in principle be identified by their isotopic ratios, but the ratios predicted by state-of-the-art one-dimensional hydrodynamic models are uncertain due to nuclear-physics uncertainties.
Purpose: To theoretically calculate the thermonuclear rates and uncertainties of the 34S(p,γ)35Cl and 34g,mCl(p,γ)35Ar reactions and investigate their impacts on the predicted 34S/32S isotopic ratio for presolar nova grains.

Method: A shell-model approach in a (0+1) $\hbar\omega$ model space was used to calculate the properties of resonances in the 34S(p,γ)35Cl and 34g,mCl(p,γ)35Ar reactions and their thermonuclear rates. Uncertainties were estimated using a Monte Carlo method. The implications of these rates and their uncertainties on sulfur isotopic nova yields were investigated using a postprocessing nucleosynthesis code. The rates for transitions from the ground state of 34Cl as well as from the isomeric first excited state of 34Cl were explicitly calculated.
Results: At energies in the resonance region near the proton-emission threshold, many negative-parity states appear. Energies, spectroscopic factors, and proton-decay widths are reported. The resulting thermonuclear rates are compared with previous determinations.
Conclusions: The shell-model calculations alone are sufficient to constrain the variation of the 34S/32S ratios to within about 30%. Uncertainties associated with other reactions must also be considered, but in general we find that the 34S/32S ratios are not a robust diagnostic to clearly identify presolar grains made from nova ejecta.

Phys. Rev. C 102, 025801 8 (2020)

8. Investigation of the ^{240}Pu(n,f) reaction at the n_TOF/EAR2 facility in the 9 meV-6 MeV range

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Background: Nuclear waste management is considered amongst the major challenges in the field of nuclear energy. A possible means of addressing this issue is waste transmutation in advanced nuclear systems, whose operation requires a fast neutron spectrum. In this regard, the accurate knowledge of neutron-induced reaction cross sections of several (minor) actinide isotopes is essential for design optimization and improvement of safety margins of such systems. One such case is 240Pu, due to its accumulation in spent nuclear fuel of thermal reactors and its usage in fast reactor fuel. The measurement of the 240Pu(n,f) cross section was previously attempted at the CERN n_TOF facility EAR1 measuring station using the time-of-flight technique. Due to the low amount of available material and the given flux at EAR1, the measurement had to last several months to achieve a sufficient statistical accuracy. This long duration led to detector deterioration due to the prolonged exposure to the high α activity of the fission foils, therefore the measurement could not be successfully completed.
Purpose: It is aimed to determine whether it is feasible to study neutron-induced fission at n_TOF/EAR2 and provide data on the 240Pu(n,f) reaction in energy regions requested for applications.

Methods: The study of the 240Pu(n,f) reaction was made at a new experimental area (EAR2) with a shorter flight path which delivered on average 30 times higher flux at fast neutron energies. This enabled the measurement to be performed much faster, thus limiting the exposure of the detectors to the intrinsic activity of the fission foils. The experimental setup was based on microbulk Micromegas detectors and the time-of-flight data were analyzed with an optimized pulse-shape analysis algorithm. Special attention was dedicated to the estimation of the non-negligible counting loss corrections with the development of a new methodology, and other corrections were estimated via Monte Carlo simulations of the experimental setup.
Results: This new measurement of the 240Pu(n,f) cross section yielded data from 9meV up to 6MeV incident neutron energy and fission resonance kernels were extracted up to 10keV.
Conclusions: Neutron-induced fission of high activity samples can be successfully studied at the n_TOF/EAR2 facility at CERN covering a wide range of neutron energies, from thermal to a few MeV.

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9. Measurement of the ^{154}Gd(n,γ) cross section and its astrophysical implications

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The neutron capture cross section of ^{154}Gd was measured from 1 eV to 300 keV in the experimental area located 185 m from the CERN n_TOF neutron spallation source, using a metallic sample of gadolinium, enriched to 67% in ^{154}Gd. The capture measurement, performed with four C_6D_6 scintillation detectors, has been complemented by a transmission measurement performed at the GELINA time-of-flight facility (JRC-Geel), thus minimising the uncertainty related to sample composition. An accurate Maxwellian averaged capture cross section (MACS) was deduced over the temperature range of interest for s process nucleosynthesis modelling. We report a value of 880(50) mb for the MACS at keV, significantly lower compared to values available in literature. The new adopted ^{154}Gd(n,γ) cross section reduces the discrepancy between observed and calculated solar s-only isotopic abundances predicted by s-process nucleosynthesis models.

Physics Letters B 804, 135405 (2020)

10. Fragmentation of Single-Particle Strength around the Doubly Magic Nucleus ^{132}Sn and the Position of the 0 $f_{5/2}$ Proton-Hole State in ^{131}In

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Spectroscopic factors of neutron-hole and proton-hole states in ^{131}Sn and ^{131}In, respectively, were measured using one-nucleon removal reactions from doubly magic ^{132}Sn at relativistic energies. For ^{131}In, a 2910(50)-keV γ ray was observed for the first time and tentatively assigned to a decay from a $5/2^-$ state at 3275(50) keV to the known $1/2^-$ level at 365 keV. The spectroscopic factors determined for this new excited state and three other single-hole states provide first evidence for a strong fragmentation of single-hole strength in ^{131}Sn and ^{131}In. The experimental results are compared to theoretical calculations based on the relativistic particle-vibration coupling model and to experimental information for single-hole states in the stable doubly magic nucleus ^{208}Pb.

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11. Measurement of the ^{70}Ge(n,γ) cross section up to 300 keV at the CERN n_TOF facility

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Neutron capture data on intermediate mass nuclei are of key importance to nucleosynthesis in the weak component of the slow neutron capture processes, which occurs in massive stars. The (n,γ)

cross section on ^{70}Ge, which is mainly produced in the s process, was measured at the neutron time-of-flight facility n_TOF at CERN. Resonance capture kernels were determined up to 40 keV neutron energy and average cross sections up to 300 keV. Stellar cross sections were calculated from kT=5 keV to kT=100 keV and are in very good agreement with a previous measurement by Walter and Beer (1985) and recent evaluations. Average cross sections are in agreement with Walter and Beer (1985) over most of the neutron energy range covered, while they are systematically smaller for neutron energies above 150 keV. We have calculated isotopic abundances produced in s-process environments in a 25 solar mass star for two initial metallicities (below solar and close to solar). While the low metallicity model reproduces best the solar system germanium isotopic abundances, the close to solar model shows a good global match to solar system abundances in the range of mass numbers A=60–80.

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12. Quasi-free proton knockout from ^{12}C on carbon target at 398 MeV/u

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The proton-removal mechanism of the $^{12}C\rightarrow^{11}B$ reaction induced on a carbon target via elementary nucleon-nucleon scattering is investigated in exclusive triple-coincidence measurements. The observed two-nucleon angular correlations are found to be consistent with quasi-free scattering of a projectile-like proton off a target-like nucleon. Exclusive cross sections for one-step ppand pninteractions are determined as σ_{pp}=17.2(12)mb and σ_{pn}=18.2(18), respectively. The extracted quasi-free component amounts up to 58(4)% of the total proton-removal cross section. The results are compared to total proton-removal cross sections obtained from the experiment and eikonal reaction theory.

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13. Quasi-free neutron and proton knockout reactions from light nuclei in a wide neutron-to-proton asymmetry range

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The quasi-free scattering reactions ^{11}C(p,2p) and ^{10,11,12}C(p,pn) have been studied in inverse kinematics at beam energies of 300–400 MeV/u at the R^{3}B-LAND setup. The outgoing proton-proton and proton-neutron pairs were detected in coincidence with the reaction fragments in kinematically

complete measurements. The efficiency to detect these pairs has been obtained from GEANT4 simulations which were tested using the ^{12}C(p,2p) and ^{12}C(p,pn) reactions. Experimental cross sections and momentum distributions have been obtained and compared to DWIA calculations based on eikonal theory. The new results reported here are combined with previously published cross sections for quasi-free scattering from oxygen and nitrogen isotopes and together they enable a systematic study of the reduction of single-particle strength compared to predictions of the shell model over a wide neutron-to-proton asymmetry range. The combined reduction factors show a weak or no dependence on isospin asymmetry, in contrast to the strong dependency reported in nucleon-removal reactions induced by nuclear targets at lower energies. However, the reduction factors for (p,2p) are found to be 'significantly smaller than for (p,pn) reactions for all investigated nuclei.

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14. r-process nucleosynthesis: connecting rare-isotope beam facilities with the cosmos

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This is an exciting time for the study of *r*-process nucleosynthesis. Recently, a neutron star merger GW170817 was observed in extraordinary detail with gravitational waves and electromagnetic radiation from radio to γ rays. The very red color of the associated kilonova suggests that neutron star mergers are an important *r*-process site. Astrophysical simulations of neutron star mergers and core collapse supernovae are making rapid progress. Detection of both electron neutrinos and antineutrinos from the next galactic supernova will constrain the composition of neutrino-driven winds and provide unique nucleosynthesis information. Finally, FRIB and other rare-isotope beam facilities will soon have dramatic new capabilities to synthesize many neutron-rich nuclei that are involved in the *r*-process. The new capabilities can significantly improve our understanding of the *r*-process and likely resolve one of the main outstanding problems in classical nuclear astrophysics. However, to make best use of the new experimental capabilities and to fully interpret the results, a great deal of infrastructure is needed in many related areas of astronomy, astrophysics, and nuclear theory. We place these experiments in context by discussing astrophysical simulations and observations of *r*-process sites, observations of stellar abundances, galactic chemical evolution, and nuclear theory for the structure and reactions of very neutron-rich nuclei. This review paper was initiated at a three-week International Collaborations in Nuclear Theory program in June 2016, where we explored promising *r*-process experiments and discussed their likely impact, and their astronomical, astrophysical, and nuclear theory context.

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15. Galactic Chemical Evolution of Radioactive Isotopes

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The presence of short-lived (~Myr) radioactive isotopes in meteoritic inclusions at the time of their formation represents a unique opportunity to study the circumstances that led to the formation of the solar system. To interpret these observations, we need to calculate the evolution of radioactive-to-

stable isotopic ratios in the Galaxy. We present an extension of the open-source galactic chemical evolution codes NuPyCEE and JINAPyCEE that enable the decay of radioactive isotopes in the interstellar medium to be tracked. We show how the evolution of the isotopic ratio depends on the star formation history and efficiency, star-to-gas mass ratio, and galactic outflows. Given the uncertainties in the observations used to calibrate our model, our predictions for isotopic ratios at the time of formation of the Sun are uncertain by a factor of 3.6. At that time, to recover the actual radioactive-to-stable isotopic ratios predicted by our model, one can multiply the steady-state solution (see Equation ()) by $2.3^{+3.4}_{-0.7}$. However, in the cases where the radioactive isotope has a half-life longer than ~200 Myr, or the target radioactive or stable isotopes have mass- and/or metallicity-dependent production rates, or they originate from different sources with different delay-time distributions, or the reference isotope is radioactive, our codes should be used for more accurate solutions. Our preliminary calculations confirm the dichotomy between radioactive nuclei in the early solar system with *r*- and *s*-process origin, and that ^{55}Mn and ^{60}Fe can be explained by galactic chemical evolution, while ^{26}Al cannot.

ApJ 878, 156 (2019)

16. Measurement of the ^{235}U(n,f) cross section relative to the ^{6}Li(n,t) and ^{10}B(n,α) standards from thermal to 170 keV neutron energy range at n_TOF

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The ^{235}U(n, f) cross section was measured at n_TOF relative to ^{6}Li(n, t) and ^{10}B(n,α) , with high resolution (L=183.49(2) m) and in a wide energy range (25meV-170keV) with 1.5% systematic uncertainty, making use of a stack of six samples and six silicon detectors placed in the neutron beam. This allowed us to make a direct comparison of the yields of the ^{235}U(n, f) and of the two reference reactions under the same experimental conditions, and taking into account the forward/backward emission asymmetry. A hint of an anomaly in the 10-30keV neutron energy range had been previously observed in other experiments, indicating a cross section systematically lower by several percent relative to major evaluations. The present results indicate that the cross section in the 9-18keV neutron energy range is indeed overestimated by almost 5% in the recently released evaluated data files ENDF/B-VIII.0 and JEFF3.3, as a consequence of a 7% overestimate in a single GMA node in the IAEA reference file. Furthermore, these new high-resolution data confirm the existence of resonance-like structures in the keV neutron energy region. The results here reported may

lead to a reduction of the uncertainty in the 1-100keV neutron energy region. Finally, from the present data, a value of 249.7±1.4(stat)±0.94(syst) b·eV has been extracted for the cross section integral between 7.8 and 11eV, confirming the value of 247.5±3 b·eV recently established as a standard.

Eur. Phys. J. A 55, 120 (2019)

17. New test of modulated electron capture decay of hydrogen-like 142Pm ions: Precision measurement of purely exponential decay

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An experiment addressing electron capture (EC) decay of hydrogen-like ions has been conducted at the experimental storage ring (ESR) at GSI. The decay appears to be purely exponential and no modulations were observed. Decay times for about 9000 individual EC decays have been measured by applying the single-ion decay spectroscopy method. Both visually and automatically analysed data can be described by a single exponential decay with decay constants of for automatic analysis and for manual analysis. If a modulation superimposed on the exponential decay curve is assumed, the best fit gives a modulation amplitude of merely 0.019(15), which is compatible with zero and by 4.9 standard deviations smaller than in the original observation which had an amplitude of 0.23(4).

Physics Letters B 797, 134800 (2019)

18. Constraining the Neutron Star Compactness: Extraction of the ^{23}Al(p,γ) Reaction Rate for the rp Process

C. Wolf, C. Langer, F. Montes, J. Pereira, W.-J. Ong, T. Poxon-Pearson, S. Ahn, S. Ayoub, T. Baumann, D. Bazin, P. C. Bender, B. A. Brown, J. Browne, H. Crawford, R. H. Cyburt, E. Deleeuw, B. Elman, S. Fiebiger, A. Gade, P. Gastis, S. Lipschutz, B. Longfellow, Z. Meisel, F. M. Nunes, G. Perdikakis, R. Reifarth, W. A. Richter, H. Schatz, K. Schmidt, J. Schmitt, C. Sullivan, R. Titus, D. Weisshaar, P. J. Woods, J. C. Zamora, R. G. T. Zegers

The ^{23}Al(p,γ)^{24}Si reaction is among the most important reactions driving the energy generation in type-I x-ray bursts. However, the present reaction-rate uncertainty limits constraints on neutron star properties that can be achieved with burst model-observation comparisons. Here, we present a novel technique for constraining this important reaction by combining the GRETINA array with the neutron detector LENDA coupled to the S800 spectrograph at the National Superconducting Cyclotron

Laboratory. The ^{23}Al(d,n) reaction was used to populate the astrophysically important states in ^{24}Si. This enables a measurement in complete kinematics for extracting all relevant inputs necessary to calculate the reaction rate. For the first time, a predicted close-lying doublet of a 2^+_2 and $(4^+_1,0^+_2)$ state in ^{24}Si was disentangled, finally resolving conflicting results from two previous measurements. Moreover, it was possible to extract spectroscopic factors using GRETINA and LENDA simultaneously. This new technique may be used to constrain other important reaction rates for various astrophysical scenarios.

Phys. Rev. Lett. 122, 232701 6 (2019)

19. Approaching the Gamow Window with Stored Ions: Direct Measurement of ^{124}Xe(p,γ) in the ESR Storage Ring

J. Glorius, C. Langer, Z. Slavkovská, L. Bott, C. Brandau, B. Brückner, K. Blaum, X. Chen, S. Dababneh, T. Davinson, P. Erbacher, S. Fiebiger, T. Gaßner, K. Göbel, M. Groothuis, A. Gumberidze, G. Gyürky, M. Heil, R. Hess, R. Hensch, P. Hillmann, P.-M. Hillenbrand, O. Hinrichs, B. Jurado, T. Kausch, A. Khodaparast, T. Kisselbach, N. Klapper, C. Kozhuharov, D. Kurtulgil, G. Lane, C. Lederer-Woods, M. Lestinsky, S. Litvinov, Yu. A. Litvinov, B. Löher, F. Nolden, N. Petridis, U. Popp, T. Rauscher, M. Reed, R. Reifarth, M. S. Sanjari, D. Savran, H. Simon, U. Spillmann, M. Steck, T. Stöhlker, J. Stumm, A. Surzhykov, T. Szücs, T. T. Nguyen, A. Taremi Zadeh, B. Thomas, S. Yu. Torilov, H. Törnqvist, M. Träger, C. Trageser, S. Trotsenko, L. Varga, M. Volknandt, H. Weick, M. Weigand, C. Wolf, P. J. Woods, Y. M. Xing

We report the first measurement of low-energy proton-capture cross sections of ^{124}Xe in a heavy-ion storage ring. $^{124}Xe^{54+}$ ions of five different beam energies between 5.5 and 8 AMeV were stored to collide with a windowless hydrogen target. The ^{125}Cs reaction products were directly detected. The interaction energies are located on the high energy tail of the Gamow window for hot, explosive scenarios such as supernovae and x-ray binaries. The results serve as an important test of predicted astrophysical reaction rates in this mass range. Good agreement in the prediction of the astrophysically important proton width at low energy is found, with only a 30% difference between measurement and theory. Larger deviations are found above the neutron emission threshold, where also neutron and γ widths significantly impact the cross sections. The newly established experimental method is a very powerful tool to investigate nuclear reactions on rare ion beams at low center-of-mass energies.

Phys. Rev. Lett. 122, 92701-92706 (2019)

20. Study of the reaction mechanisms of ^{136}Xe + p and ^{136}Xe + ^{12}C at 1 A GeV with inverse kinematics and large-acceptance detectors

T. Gorbinet, O. Yordanov, J.-E. Ducret, T. Aumann, Y. Ayyad, S. Bianchin, O. Borodina, A. Boudard, C. Caesar, E. Casarejos, B. Czech, S. Hlavac, J. Klimo, N. Kurz, C. Langer, T. Le Bleis, S. Leray, J. Lukasik, D. Mancusi, P. Pawlowski, S. Pietri, C. Rappold, M.-D. Salsac, H. Simon, M. Veselsky

The reactions ^{136}Xe + p and ^{136}Xe + ^{12}C have been studied in inverse kinematics at 1 A GeV with the SPALADiN setup at GSI. The detection in coincidence of the final-state charged particles (projectile residues, nuclei of charge $Z \geq 2$ and neutrons was performed with a big-aperture dipole magnet and large-acceptance detectors. This provided an extended coverage of the phase space of decay products of the prefragment formed at the end of the intranuclear cascade. This coincidence

measurement, performed on an event-by-event basis permits both an estimate of the excitation energy of the prefragments and a determination of their deexcitation channels. The element production cross sections are compared with existing data and theoretical models. The evolution of observables such as the total multiplicity or the fragment production with the prefragment's excitation energy is studied for both reactions and compared with models.

European Physical Journal A 55, 11 (2019)

21. Cross section measurements of ^{155,157}Gd(n,γ) induced by thermal and epithermal neutrons

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Neutron capture cross section measurements on ^{155}Gd and ^{157}Gd were performed using the time-of-flight technique at the n_TOF facility at CERN on isotopically enriched samples. The measurements were carried out in the n_TOF experimental area EAR1, at 185 m from the neutron source, with an array of 4 C_6D_6 liquid scintillation detectors. At a neutron kinetic energy of 0.0253 eV, capture cross sections of 62.2(2.2) and 239.8(8.4) kilobarn have been derived for ^{155}Gd and ^{157}Gd, respectively, with up to 6% deviation relative to values presently reported in nuclear data libraries, but consistent with those values within 1.6 standard deviations. A resonance shape analysis has been performed in the resolved resonance region up to 181 eV and 307 eV, respectively for ^{155}Gd and ^{157}Gd, where on average, resonance parameters have been found in good agreement with evaluations. Above these energies and up to 1 keV, the observed resonance-like structure of the cross section has been analysed and characterised. From a statistical analysis of the observed neutron resonances we deduced: neutron strength function of $2.01(28)\times10^{-4}$ and $2.17(41)\times10^{-4}$; average total radiative width of 106.8(14) meV and 101.1(20) meV and *s*-wave resonance spacing 1.6(2) eV and 4.8(5) eV for n + ^{155}Gd and n + ^{157}Gd systems, respectively.

European Physical Journal A 55, 9 (2019)

22. Measurement of ^{73}Ge(n,γ) cross sections and implications for stellar nucleosynthesis

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^{73}Ge(n,γ) cross sections were measured at the neutron time-of-flight facility n_TOF at CERN up to neutron energies of 300 keV, providing for the first time experimental data above 8 keV. Results indicate that the stellar cross section at keV is 1.5 to 1.7 times higher than most theoretical predictions. The new cross sections result in a substantial decrease of ^{73}Ge produced in stars, which would explain the low isotopic abundance of ^{73}Ge in the solar system.

Physics Letters B 790, 458-465 (2019)

23. Remnants and ejecta of thermonuclear electron-capture supernovae. Constraining oxygen-neon deflagrations in high-density white dwarfs

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The explosion mechanism of electron-capture supernovae (ECSNe) remains equivocal: it is not completely clear whether these events are implosions in which neutron stars are formed, or incomplete thermonuclear explosions that leave behind bound ONeFe white dwarf remnants. Furthermore, the frequency of occurrence of ECSNe is not known, though it has been estimated to be of the order of a few per cent of all core-collapse supernovae. We attempt to constrain the explosion mechanism (neutron-star-forming implosion or thermonuclear explosion) and the frequency of occurrence of ECSNe using nucleosynthesis simulations of the latter scenario, population synthesis, the solar abundance distribution, pre-solar meteoritic oxide grain isotopic ratio measurements and the white dwarf mass–radius relation. Tracer particles from the 3d hydrodynamic simulations were post-processed with a large nuclear reaction network in order to determine the complete compositional state of the bound ONeFe remnant and the ejecta, and population synthesis simulations were performed in order to estimate the ECSN rate with respect to the CCSN rate. The 3d deflagration simulations drastically overproduce the neutron-rich isotopes ^{48}Ca, ^{50}Ti, ^{54}Cr , ^{60}Fe and several of the Zn isotopes relative to their solar abundances. Using the solar abundance distribution as our constraint, we place an upper limit on the frequency of thermonuclear ECSNe as 1−3% the frequency at which core-collapse supernovae (FeCCSNe) occur. This is on par with or 1 dex lower than the estimates for ECSNe from single stars. The upper limit from the yields is also in relatively good agreement with the predictions from our population synthesis simulations. The ^{54}Cr/^{52}Cr and ^{50}Ti/^{48}Ti isotopic ratios in the ejecta are a near-perfect match with recent measurements of extreme pre-solar meteoritc oxide grains, and ^{53}Cr/^{52}Cr can also be matched if the ejecta condenses before mixing with the interstellar medium. The composition of the ejecta of our simulations implies that ECSNe, including accretion-induced collapse of oxygen-neon white dwarfs, could actually be partial thermonuclear explosions and not implosions that form neutron stars. There is still much work to do to improve the hydrodynamic simulations of such phenomena, but it is encouraging that our results are consistent with the predictions from stellar evolution modelling and population synthesis simulations, and can explain several key isotopic ratios in a sub-set of pre-solar oxide meteoritic grains. Theoretical mass–radius relations for the bound ONeFe WD remnants of these explosions are apparently consistent with several observational WD candidates. The composition of the remnants in our simulations can reproduce several, but not all, of the spectroscopically-determined elemental abundances from one such candidate WD.

A&A 622, 74 (2019)

24. Accelerator mass spectrometry measurement of the reaction ^{35}Cl(n,γ)^{36}Cl at keV energies

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The nuclide ^{35}Cl can act as a minor “neutron poison” in the stellar slow neutron capture process. Neutron activation combined with accelerator mass spectrometry (AMS) was applied to measure the (n,γ) cross section of ^{35}Cl for neutron spectra simulating Maxwell-Boltzmann distributions of kT≈30 and 40 keV. The neutron activations were performed at the Karlsruhe Van de Graaff accelerator and at the superconducting linear accelerator of the Soreq Applied Research Accelerator Facility utilizing the ^{7}Li(p,n)^{7}Be reaction. AMS measurements of the irradiated samples were performed at the 3 MV Vienna Environmental Research Accelerator, the 6 MV tandem accelerator at the Dresden AMS facility, and the 14 UD tandem accelerator of the Australian National University in Canberra. Our method is independent of previous measurements. For an energy of kT=30keV, we report a Maxwellian averaged cross section of 8.33(32) mb. Using this new value in stellar isotopic abundance calculations, minor changes for the abundances of ^{35}Cl, ^{36}Cl, and ^{36}S are derived.

Phys. Rev. C 99, 015801 11 (2019)

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1. Thermal (n ,γ) cross section and resonance integral of ^{171}Tm

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Background: About 50% of the heavy elements are produced in stars during the slow neutron capture process. The analysis of branching points allows us to set constraints on the temperature and the neutron density in the interior of stars.
Purpose: The temperature dependence of the branch point ^{171}Tm is weak. Hence, the ^{171}Tm neutron capture cross section can be used to constrain the neutron density during the main component of the s process in thermally pulsing asymptotic giant branch (TP-AGB) stars.
Methods: A ^{171}Tm sample produced at the ILL was activated with thermal and epithermal neutrons at the TRIGA research reactor at the Johannes Gutenberg-Universität Mainz.
Results: The thermal neutron capture cross section and the resonance integral have been measured for the first time to be σ_{th}=9.9±0.9 b and σ_{RI}=193±14 b.
Conclusions: Based on our results, new estimations of the direct capture components' impact on the Maxwellian-nAveraged cross sections (MACS) are possible.

Phys. Rev. C 99, 65810 (2019)

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT

PTB contribution to the measurement of the ^{235}U(n,f) cross section relative to n-p scattering up to 1 GeV

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The neutron-induced fission cross section of ^{235}U is the most important secondary reference cross section for neutron measurements. Therefore, measurements of the cross section ratio for ^{235}U(n,f) relative to the primary standard ^{1}H(n,n)p are still very important, in particular in the energy range above 20 MeV where only few experimental data are available.
A consortium of IPN Orsay, INFN Bari and Catania, University of Bologna, and PTB, performed a measurement of this cross-section ratio at n_TOF, the spallation neutron source at CERN, aiming at covering energies up to 1 GeV. Samples of uranium and polyethylene were irradiated simultaneously at the Experimental Area 1 (EAR1), which is well suited for measurements at high energies because of the long flight path of 183 m.
The PTB contribution to the experiment were a parallel-plate fission ionization chamber (PPFC) and a recoil proton telescope (RPT). Two other recoil proton telescopes of different design were provided by the Italian collaborators, while IPN Orsay made available a parallel-plate avalanche counter (PPAC) which had already been used earlier at n_TOF for measurements of fission cross section ratios.

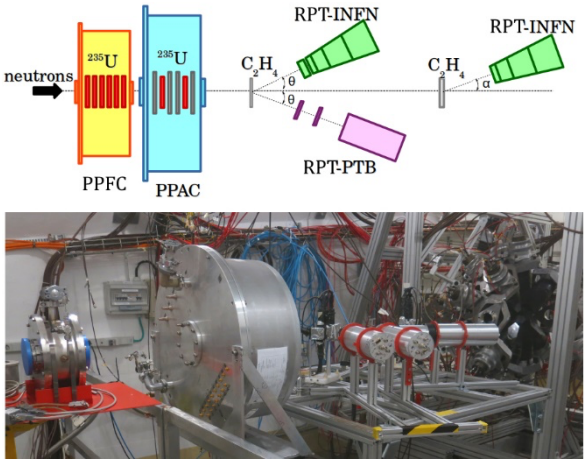

Figure 1. Layout and picture of the setup installed in EAR1 at n_TOF.

The measurement was carried out in September 2018 and lasted six weeks. The cross-section ratio is determined from the number of fission fragments and recoil protons from n-p elastic scattering in the polyethylene, and by careful characterizing the efficiency of the detectors. The analysis is ongoing, the critical point being the modelling of the telescopes. The preliminary results for the fission cross section below 150 MeV are in agreement with the most recent evaluation of the IAEA [A.D. Carlson *et al.*, Nuclear Data Sheets 148 (2018) 143-188].

Abstract of the proceedings submitted to ND2019:

Measurement of the angular distribution of neutrons scattered from deuterium below 3 MeV

E. Pirovano, R. Nolte, M. Nyman, and A. Plompen

The differential cross section of neutron scattering on deuterium was investigated in the energy range from 400 keV to 2.5 MeV using the recoil detection method, irradiating with monoenergetic neutrons a proportional counter filled with deuterated gases. Comparing simulations of the transport of neutrons and recoil nuclei in the detector to the experimental pulse-height distribution, it was possible to establish a procedure for the determination of the coefficients of the Legendre expansion of the n-d angular distribution.

EPJ Web of Conferences 239, 01016 (2020)

Setup for the measurement of the ^{235}U(n,f) cross section relative to n-p scattering up to 1 GeV

A. Manna, M. Barbagallo, N. Colonna, L. Cosentino, Q. Ducasse, P. Finocchiaro, C. Massimi, A. Mengoni, R. Nolte, E. Pirovano, L. Tassan-Got, and the nTOF collaboration.

The neutron induced fission of ^{235}U is extensively used as a reference for neutron fluence measurements in various applications, ranging from the investigation of the biological effectiveness of high energy neutrons, to the measurement of high energy neutron cross sections of relevance for accelerator driven nuclear systems. Despite its widespread use, no data exist on neutron induced fission of ^{235}U above 200 MeV. The neutron facility n_TOF offers the possibility to improve the situation. The measurement of ^{235}U(n,f) relative to the differential n-p scattering cross-section, was carried out in September 2018 with the aim of providing accurate and precise cross section data in the energy range from 10 MeV up to 1 GeV. In such measurements, Recoil Proton Telescopes (RPTs) are used to measure the neutron flux while the fission events are detected and counted with dedicated detectors. In this paper the measurement campaign and the experimental set-up are illustrated.

EPJ Web of Conferences 239, 01008 (2020)

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1. Self-absorption with quasi-monochromatic photon beams

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We present a new experimental technique to perform self-absorption experiments in combination with nuclear resonance fluorescence using a quasi-monochromatic photon beam for the determination of absolute level widths of excited low-spin states. By measuring simultaneously at two target positions the amount of absorbed photon intensity is directly measured in a single experiment, which strongly reduces systematic uncertainties and reduces the amount of needed beam time by a factor of two. In addition the method does not rely on a given shape of the energy profile of the photon beam and, thus, can also be applied with quasi-monochromatic beams produced via Laser-Compton-Backscattering (LCB). Due to the strongly reduced background with these kind of photon beams this new method in combination with LCB promises a highly improved sensitivity for self-absorption experiments compared to experiments using bremsstrahlung.

Nuclear Inst. and Methods in Physics Research, A 899 (2018) 28–31
https://doi.org/10.1016/j.nima.2018.05.018

2. Multi-messenger investigation of the Pygmy Dipole Resonance in ^{140}Ce

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We report on the first (p,p′γ) experiments at Ep=80 MeV to investigate the Pygmy Dipole Resonance (PDR) in the semi-magic nucleus 140Ce. This experiment is the latest in a series of experiments to investigate the PDR with different complementary probes to provide a multi-messenger data set on the properties of the PDR in 140Ce. In addition, calculations within the Quasi-particle Phonon Model (QPM) have been performed. Cross sections have been calculated for proton- as well as α-scattering reactions based on the transition densities obtained from the QPM, not only at the RPA level, but including the full model space of up to 3p–3h configurations. This allows for the first time to compare the calculations to the experimental results on an absolute scale for single excitations. Agreement between QPM and experiment is observed, which proves the high accuracy of the calculated transition densities for individual PDR states.

PhysicsLettersB786(2018)16–20
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3. **Valence-shell dependence of the pygmy dipole resonance: E1 strength difference in ^{50,54}Cr**

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Background: The low-lying electric dipole strength provides insights into the parameters of the nuclear equation of state via its connection with the pygmy dipole resonance and nuclear neutron skin thickness. Purpose: The aim was to complement the systematic of the pygmy dipole resonance and first study its behavior across the N=28 neutron shell closure. Methods: Photon-scattering cross sections of states of Cr50,54 were measured up to an excitation energy of 9.7 MeV via the nuclear resonance fluorescence method using γ-ray beams from bremsstrahlung and Compton backscattering. Results: Transitions strengths, spin and parity quantum number, and average branching ratios for 55 excited states, 44 of which were observed for the first time, were determined. The comparison between the total observed strengths of the isotopes Cr50,52,54 shows a significant increase above the shell closure. Conclusions: The evolution of the pygmy dipole resonance is heavily influenced by the shell structure.

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4. The concept of nuclear photon strength functions: A model-independent approach via (γ, γ‘γ‘‘) reactions

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Most theoretical approaches used in nuclear astrophysics to model the nucleosynthesis of heavy elements incorporate the so-called statistical model in order to describe the excitation and decay properties of atomic nuclei. One of the basic assumptions of this model is the validity of the Brink–Axel hypothesis and the related concept of so-called photon strength functions to describe γ-ray transition probabilities. We present a novel experimental approach that allows for the first time to experimentally determine the photon strength function simultaneously in two independent ways by a unique combination of quasi-monochromatic photon beams and a newly implemented γ–γcoincidence setup. This technique does not assume a priori the validity of the Brink–Axel hypothesis and sets a benchmark in terms of the detection sensitivity for measuring decay properties of photo-excited states below the neutron separation energy. The data for the spherical off-shell nucleus 128Te were obtained for γ-ray beam-energy settings between 3MeV and 9MeV in steps of 130keV for the lower

beam energies and in steps of up to 280keV for the highest beam settings. We present a quantitative analysis on the consistency of the derived photon strength function with the Brink–Axel hypothesis. The data clearly demonstrate a discrepancy of up to a factor of two between the photon strength functions extracted from the photoabsorption and photon emission process, respectively. In addition, we observe that the photon strength functions are not independent of the excitation energy, as usually assumed. Thus, we conclude, that the Brink–Axel hypothesis is not strictly fulfilled in the excitation-energy region below the neutron separation threshold (Sn=8.78MeV) for the studied case of 128Te.

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5. Low-lying dipole strength in the well-deformed nucleus ^{156}Gd

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The low-lying dipole strength of the deformed nucleus 156 Gd was investigated in the energy region from 3.1 MeV to 6.2 MeV using the method of nuclear resonance fluorescence (NRF). The NRF experiments were performed at the Darmstadt High Intensity Photon Setup (DHIPS)at Technische Universität Darmstadt using unpolarized continuous-energy bremsstrahlung and at the High-Intensity γ-ray Source (HIγS)at Duke University using quasi-monoenergetic and linearly-polarized photon beams. The combination of both experiments allows to separate electric and magnetic contributions and to determine absolute transition strengths for individual excited states as well as averaged quantities over narrow excitation energy regions. The investigated energy regions cover the region of the scissors mode as well as the low-energy part of the Pygmy Dipole Resonance. This is the first experiment where both of these excitation modes as well as the region in between has been successfully studied in a deformed heavy nucleus using the NRF method.

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6. Experimental M1 response of ^{40}Ar as a benchmark for neutrino-nucleus scattering calculations

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The excitation of atomic nuclei via magnetic dipole transitions is closely related to the inelastic neutral-current neutrino-nucleus (NC-νA) scattering process due to the similarity of the transition operators. NC-νA-scattering serves for the detection of supernova neutrinos and poses a significant source of background in modernliquid-argon based high-energy neutrino detection experiments. To enable tests of the reliability of predictionsfor neutrino-nucleus scattering, the magnetic dipole response of ^{40}Ar below 7.7 MeV was characterized in anuclear resonance fluorescence experiment using quasimonoenergeticγ-ray beams. The linear polarization of thebeams allowed for assignments of electric or magnetic character to previously known dipole excitations. A totalmagnetic dipole strength of $0.36+0.04-0.05\ \mu^2_N$ was identified in the energy range of the present experiment. Combinedwith data from previous measurements, the full magnetic dipole strength of ^{40}Ar below the neutron separationthreshold was investigated. Due to the low background in the energy range within the bandwidth of theγ-raybeams, the previous sensitivity limit was improved. A large-scale nuclear shell model calculation in the sd-fpspace satisfactorily agrees with the data in terms of excitation energies and strengths of the observed 1^+ states.

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7. The (^{6}Li,^{6}Li* [3.56 MeV]) reaction at 100 MeV/u as a probe of Gamow-Teller transition strengths in the inelastic scattering channel

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Background: Inelastic neutrino-nucleus scattering is important for understanding core-collapse supernovae and the detection of emitted neutrinos from such events in earth-based detectors. Direct measurement of the cross sections is difficult and has only been performed on a few nuclei. It is, therefore, important to develop indirect techniques from which the inelastic neutrino-nucleus scattering cross sections can be determined. Purpose: This paper presents a development of the (^{6}Li,^{6}Li*[T=1,Tz=0,0^+,3.56 MeV]) reaction at 100 MeV/u as a probe for isolating the isovector spin-transfer response in the inelastic channel ($\Delta S=1,\Delta T=1,\Delta T_z=0$) from which the Gamow-Teller transition strengths from nuclei of relevance for inelastic neutrino-nucleus scattering cross sections can be extracted. Method: By measuring the ^{6}Li ejectile in a magnetic spectrometer and selecting events in which the 3.56 MeV γ ray from the decay of the ^{6}Li*[3.56bMeV] state is detected, the

isovector spin-transfer selectivity is obtained. High-purity germanium clover detectors served to detect the γ rays. Doppler reconstruction was used to determine the γ energy in the rest frame of ^{6}Li. From the ^{6}Li and 3.56 MeV γ-momentum vectors the excitation energy of the residual nucleus was determined. Results: In the study of the ^{12}C(^{6}Li,^{6}Li*[3.56 MeV]) reaction, the isovector spin-transfer excitation-energy spectrum in the inelastic channel was successfully measured. The strong Gamow-Teller state in ^{12}C at 15.1 MeV was observed. Comparisons with the analog ^{12}C(^{6}Li,^{6}He) reaction validate the method of extracting the Gamow-Teller strength. In measurements of the ^{24}Mg,^{93}Nb(^{6}Li,^{6}Li*[3.56 MeV]) reactions, the 3.56 MeV γ peak could not be isolated from the strong background in the γ spectrum from the decay of the isoscalar excitations. It is argued that by using a γ-ray tracking array instead of a clover array, it is feasible to extend the mass range over which the (^{6}Li,^{6}Li*) reaction can be used for extracting the isovector spin-transfer response up to mass numbers of ∼25 and perhaps higher. Conclusions: It is demonstrated that the (^{6}Li,^{6}Li*[3.56 MeV]) reaction probe can be used to isolate the inelastic isovector spin-transfer response in nuclei. Application to nuclei with mass numbers of about 25 or more, however, will require a more efficient γ-ray array with a better tracking capability.

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8. Nuclear isovector valence-shell excitation of ^{202}Hg

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Excited states of ^{202}Hg have been studied via the ^{12}C(^{202}Hg,^{202}Hg∗) Coulomb excitation reaction at a beam energy of 890 MeV. The γ-ray transitions from the excited states of ^{202}Hg were detected by the Gammasphere array. The intensities of the observed γ-rays determined the relative populations of the excited states which were used to extract the absolute M1 and E2 transition strength distributions for excited 2^{+} states of ^{202}Hg up to
2 MeV. The measured absolute B(M1; $2^{+}_{7} \rightarrow 2^{+}_{1}$) strength of 0.18(8) μ^{2}_{N} indicates that the 2^{+}_{7} level of ^{202}Hg is the main fragment of the proton-neutron mixed-symmetry $2^{+}_{1,ms}$ state. Upper limits for the F-spin mixing matrix elements of ^{202,204}Hg are determined as well.

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9. Sub-shell closure and shape coexistence in the transitional nucleus ^{98}Zr

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In the rapid shape change from spherical to deformed nuclei in the Z=40 Zr isotopic chain, recent work has identified shape coexistence in Zr96. Between Zr96 and the strongly deformed Zr100, Zr98 is expected to also exhibit coexistence of nuclear shapes. The degree of mixing between different configurations is mainly determined by the nucleon-nucleon interactions. For nuclear model predictions, experimental constraints are needed, but they are barely available for Zr98. To study low-lying transitions in Zr98, a Coulomb excitation experiment was conducted at the Argonne Tandem-Linac Accelerator System (ATLAS) facility using a Zr98 beam extracted from the Californium Rare Ion Breeder Upgrade (CARIBU) ion source and Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA) for γ-ray spectroscopy coupled to the compact heavy ion counter (CHICO2) for ion detection. This paper reports on the first decisive deduction of the B(E2;21+→01+) transition strength in Zr98 and on its interpretation.

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10. Evolution of E2 strength in the rare-earth isotopes ^{174,176,178,180}Hf

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Mean lifetimes of yrast states of the isotopes ^{174,176,178,180}Hf have been measured using fast-electronic scintillation timing. Excited states of ^{174,176,178}Hf were populated via β decay, while ^{180}Hf was populated via Coulomb excitation. The lifetimes of the 2^+_1 and 4^+_1 states of all isotopes and the lifetimes of the 6^+_1 states of ^{174,178}Hf were measured, using the slope and the centroid shift methods. The mean lifetime, $\tau(4^+_1) = 85(13)$ ps, of ^{178}Hf has been determined for the first time. In addition, the mean lifetimes of the 2^-_1 and the 3^-_1 states of ^{176}Hf have been determined. Systematic uncertainties on the evolution of data as a function of neutron number were reduced by using the same setup for all the isotopes of interest. The data are in agreement with other recent life time measurements where available and shows a shift of the maximum of collectivity for the Hf isotopic chain from neutron midshell at N=104 to N=100.

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11. Data on the structural coexistence in the ^{96}Zr nucleus

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On the brink of the phase transition from spherical to deformed Zr isotopes, ^{96}Zr shows a co-existence of low-lying level structures with different degrees of quadrupole collectivity. Experimental data are available, but a coherent description of the measured properties is yet missing. This paper analyses available data and critically compiles the information relevant for the interpretation of the quadrupole-collective structure of ^{96}Zr.

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12. Photonuclear reactions: Achievements and perspectives

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Probing the structure of an atomic nucleus by the electromagnetic interaction can be the cleanest and most direct way to obtain information on how the constituting nucleons are organizing themselves within the nucleus. Precise characterization of photonuclear reactions has contributed significantly to the establishment of modern nuclear physics. A brief overview on the Nuclear Resonance Fluorescence method, its applications and potential future opportunities will be given. In particular, we address recent studies of the dipole strength distributions of ^{76}Se and ^{40}Ar, of the determination of the Photon Strength Function of ^{128}Te, and dare an outlook to even more sensitive measurements in the future.

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13. Low-lying octupole isovector excitation in ^{144}Nd

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The nature of low-lying 3^- levels in ^{144}Nd was investigated in the ^{143}Nd(n,γγ) cold neutron-capture reaction. The combination of the high neutron flux from the research reactor at the Institut Laue-Langevin and the high γ-ray detection efficiency of the EXILL setup allowed the recording of γγ coincidences. From the coincidence data precise branching ratios were extracted. Furthermore, the octagonal symmetry of the setup allowed angular-distribution measurements to determine multipole-mixing ratios. Additionally, in a second measurement the ultra-high resolution spectrometer GAMS6 was employed to conduct lifetime measurements using the gamma-ray induced Doppler-shift technique (GRID). The confirmed strong M1 component in the $3^-_3 \rightarrow 3^-_1$ decay strongly supports the assignment of the 3^-_3 level at 2779 keV as low-lying isovector octupole excitation. Microscopic calculations within the quasiparticle phonon model confirm an isovector component in the wave function of the 3^-_3 level, firmly establishing this fundamental mode of nuclear excitation in near-spherical nuclei.

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14. Chaos and regularity in the spectra of the low-lying dipole excitations of ^{50,52,54}Cr

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Recent high-resolution nuclear resonance fluorescence experiments performed on the even-even Chromium isotopes ^{50,52,54}Cr have lead to the identification (energy, spin, parity, and transition strength) of altogether 108 nuclear levels of spin J=1 (70 levels with $J^\pi=1^-$ and 38 with $J^\pi=1^+$) at excitation energies E_x ranging roughly from 4.5 to 9.7 MeV. In this region just above the orbital magnetic-dipole scissors mode, sizable spin-flip magnetic-dipole strength as well as electric-dipole strength belonging to the pygmy dipole resonance (PDR) is expected. Using statistical measures for short- and long-range correlations, we perform an analysis of the fluctuation properties in the subspectra of the energy levels and also of the distributions of their respective dipole transition strengths. We compare the results with those of a random matrix ensemble interpolating between Poisson statistics generally describing the fluctuation properties in the energy spectra of many-body systems with collective, i.e., regular motion of the particles and the Gaussian orthogonal ensemble (GOE) for complex (i.e., chaotic) behavior. This comparison reveals that the spectral properties of the 1^+ states are close to the GOE results while those of the 1^- states are closer to Poisson. This is confirmed by an analysis of the spectral fluctuations based on the method of Bayesian inference and corroborated by large-scale shell-model and quasiparticle-phonon model calculations, respectively. The nearly Poissonian behavior of the 1^- levels suggests a sizable collectivity of the PDR indeed.

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15. First spectroscopy of ^{61}Ti and the transition to the Island of Inversion at $N = 40$

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Isomeric states in ^{59,61}Ti have been populated in the projectile fragmentation of a 345 AMeV ^{238}U beam at the Radioactive Isotope Beam Factory. The decay lifetimes and delayed γ-ray transitions were measured with the EURICA array. Besides the known isomeric state in ^{59}Ti, two isomeric states in ^{61}Ti are observed for the first time. Based on the measured lifetimes, transition multipolarities as well as tentative spins and parities are assigned. Large-scale shell model calculations based on the modified LNPS interaction show that both ^{59}Ti and ^{61}Ti belong to the Island of Inversion at N=40 with ground state configurations dominated by particle-hole excitations to the $g_{9/2}$ and $d_{5/2}$ orbits.

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16. Toward the limit of nuclear binding on the N=Z line: Spectroscopy of ^{96}Cd

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A γ-decaying isomeric state ($\tau_{1/2} = 197^{+19}_{-17}$ ns) has been identified in ^{96}Cd, which is one α particle away fromthe last known bound N=Z nucleus, ^{100}Sn. Comparison of the results with shell-model calculations has allowed a tentative experimental level scheme to be deduced and the isomer to be interpreted as a medium-spin negative-parity spin trap based on the coupling of isoscalar (T=0) and isovector (T=1) neutron-proton pairs. The data also suggest evidence for the population of a 9+T=1 state, which is predicted by shell-model calculations tobe yrast. Such a low-lying T=1 state, which is unknown in lighter mass even-even self-conjugate nuclei, can also be interpreted in terms of the coupling of T=0 and T=1 neutron-proton pairs.

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17. Lifetimes of the 4_1^+ states of ^{206}Po and ^{204}Po: A study of the transition from non collective seniority-like mode to collectivity

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Low-lying yrast states of ^{204}Po and ^{206}Po were investigated by the γ-γ fast timing technique with LaBr3(Ce) detectors. Excited states of these nuclei were populated in the ^{197}Au(^{11}B,4n)^{204}Po and the ^{198}Pt(^{12}C,4n)^{206}Po fusion-evaporation reactions, respectively. The beams were delivered by the FN-Tandem accelerator at theUniversity of Cologne. The lifetimes of the 4_1^+ states of both nuclei were measured, along with an upper lifetime limit for the 2_1^+ state of ^{204}Po. A comparison between the derived B(E2; $4_1^+ \rightarrow 2_1^+$) values and results from simplified empirical two-state mixing calculations suggests that for the 4_1^+ states of even-even polonium isotopes the transition from single-particle mode at N=126 to collective mode, when reducing the number of neutrons, occurs above N=122.

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18. Half-lives of ^{73}Sr and ^{76}Y and the consequences for the proton dripline

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The half-lives of seven nuclei have been determined in the neutron-deficient mass-70 region following their production via fragmentation of a 345 MeV/nucleon ^{124}Xe primary beam on a 740 mg/cm ^{29}Be target at the RI Beam Factory, RIKEN. The results include two new (^{73}Sr and ^{76}Y) half-lives and a more precise measurement for the ground-state half-life of ^{74}Sr. The new results are discussed with reference to previously published calculations that predict the location of the proton dripline in the light Sr and Y region of the nuclear chart. In addition, differences in the ground-state structure of ^{72}Rb and ^{76}Y are discussed with the aid of density functional theory calculations. These provide a

possible explanation for why ^{72}Rb undergoes proton decay while the α-conjugate nucleus ^{76}Y predominantly undergoes β^+ decay.

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19. Lifetimes and shape-coexisting states of ^{99}Zr

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Lifetimes of intermediate-spin states in two rotational bands of ^{99}Zr have been measured. These states were populated following the neutron-induced fission of ^{235}U at the PF1B beamline of the Institut Laue-Langevin,Grenoble, during the EXILL-FATIMA campaign. The nucleus $^{99}Zr_{59}$ exhibits shape coexistence and lies precisely on the border of an abrupt change in ground-state deformation when going from N=58 to N=60, making its study interesting for understanding the mechanisms involved in the rapid onset of deformation here. The B(E2) values extracted for decays in the $\nu_{3/2}$[541] band allow quadrupole deformations of β_2=0.34(1) and 0.26(3) to be determined for the 821.6- and 1236.6-keV members, whereas β_2=0.32(3) was found for the 850.5-keV member of the $\nu_{3/2}$[411] band. Some of the excited states known in ^{99}Zr have been reasonably described with interacting boson-fermion model (IBFM) calculations. Type-II shell evolution is proposed to play a major role in modifying single-particle energies in ^{99}Zr.

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20. Nuclear structure of ^{76}Ni from the (p,2p) reaction

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The nuclear structure of the ^{76}Ni nucleus was investigated by (p,2p) reaction using a NaI(Tl) array to detect the deexciting prompt γ rays. A new transition with an energy of 2227 keV was identified by γγ and γγγ coincidences. According to these coincidence spectra the observed transition connects a new state at 4147 keV and the previously known 4_{+1} state at 1920 keV. Two weaker transitions were also obtained at 2441 and 2838 keV, which could be tentatively placed to feed the known 2_{+1} state at 990 keV. Our shell-model calculations using the Lenzi, Nowacki, Poves, and Sieja interaction produced good candidates for the experimental proton hole states in the observed energy region, and the theoretical cross sections showed good agreement with the experimental values. Although we could not assign all the experimental states to the theoretical ones unambiguously, the results are consistent with a reasonably large Z=28 shell gap for nickel isotopes in accordance with previous studies.

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21. Decay properties of the 3_1^- level in ^{96}Mo

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The first excited 3^-_1 level of ^{96}Mo was investigated in a high-statistics experiment using the ^{95}Mo(n, γγ) cold neutron capture reaction. The measurements used the high cold neutron flux from the research reactor at Institut Laue-Langevin and employed the highly-efficient EXILL array to detect γ-ray coincidences. The recorded statistics allow identification of decay branches with only a small relative intensity including the $3^-_1 \rightarrow 0^+_{gs}$ E3 decay. With the knowledge of the newly measured branching ratio and the known B(E3, $3^-_1 \rightarrow 0^+_{gs}$) transition probability, the lifetime of the 3^-_1 level was determined and, subsequently, the B(E1) strength of the other decay branches of the 3^-_1 octupole phonon were calculated. The extracted electromagnetic decay strengths are compared to the systematics of the stable even–even molybdenum isotopes and values calculated in a Skyrme-force based quasiparticle random phase approximation and in a cluster approach. Additionally, the $3^-_1 \rightarrow 2^+_{iv}$ decay branch to the low-lying 2^+_{iv} quadrupole isovector level was observed.

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22. Inelastic scattering of neutron-rich Ni and Zn isotopes off a proton target

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Proton inelastic scattering of ^{72,74}Ni and ^{76,80}Zn ions at energies around 235 MeV/nucleon was performed at the Radioactive Isotope Beam Factory and studied using γ-ray spectroscopy. Angular integrated cross sections for direct inelastic scattering to the 2^+_1 and 4^+_1 states were measured. The Jeukenne-Lejeune-Mahaux folding model, extended beyond 200 MeV, was used together with neutron and proton densities stemming from quasiparticle random-phase approximation (QRPA) calculations to interpret the experimental cross sections and to infer neutronto proton matrix element ratios. In addition, coupled-channels calculations with a phenomenological potential were used to determine deformation lengths. For the Ni isotopes, correlations favor neutron excitations, thus conserving the Z=28 gap. A dominance of proton excitation, on the other hand, is observed in the Zn isotopes, pointing to the conservation of the N=50 gap approaching ^{78}Ni. These results are in agreement with QRPA andlarge-scale shell-model calculations.

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23. Proton-neutron structure of first and second quadrupole excitations of ^{90}Sr

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Starting from the Skyrme interaction f_ together with the density-dependent pairing interaction, we study the g factors for the $2^+_{1,2}$ excitations of $^{88, 90}$Sr and $^{90, 92}$Zr. The coupling between one- and two-phonon terms in the wave functions of excited states is taken into account within the finite-rank separable approximation. Using the same set of parameters we describe available experimental data and give the prediction for ^{90}Sr g(2^+_2) = +0.03, in comparison to +0.31 in the case of ^{92}Zr.

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24. One-neutron stripping processes to excited states of 90Y* in the ^{89}Y(^{6}Li,^{5}Li)^{90}Y* reaction

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The measurement of one-neutron stripping cross sections for the ^{89}Y(^{6}Li,^{5}Li)^{90}Y*reaction at 22 MeV and 34 MeV is reported, using both in-beam and off-beamγ-ray spectroscopy methods. Characteristicγlines of ^{90}Y are clearly identified by both the γ-γ and proton-γ coincidence methods. The obtained cross section of one-neutron stripping at 34 MeV is found to be much smaller than that at 22 MeV. The one-neutron stripping cross sections measured for this system have the same order of magnitude as the one measured for the same reaction for the ^{6}Li+^{96}Zr system at energies around the Coulomb barrier. Parameter-free coupled reaction channel calculations agree quite well with the experimental data. Theoretical study of the effect of the one-neutron transfer on the elastic total fusion cross section is performed.

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25. Millisecond 23/2^{+} isomers in the N= 79 isotones ^{133}Xe and ^{135}Ba

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Detailed information on isomeric states inA≈135nuclei is exploited to benchmark shell-model calculations in the region northwest of doubly-magic nucleus ^{132}Sn. The N= 79 isotones ^{133}Xe and ^{135}Ba are studied after multinucleon transfer (MNT) in the ^{136}Xe +^{208}Pb reaction employing the

high-resolution Advanced GAmma Tracking Array (AGATA) coupled to the magnetic spectrometer PRISMA at the Laboratori Nazionali di Legnaro, Italy and in a pulsed-beam experiment at the FNtandem accelerator of the University of Cologne, Germany utilizing a ^{9}Be +^{130}Te fusion-evaporation reaction at a beam energy of 40 MeV. Isomeric states are identified via delayed γ-ray spectroscopy. Hitherto tentative excitation energy, spin, and parity assignments of the 2107-keVJ^{π}= $23/2^{+}$isomer in ^{133}Xe are confirmed and a half-life of$T_{1/2}$= 8.64(13) ms is measured. The 2388-keV-state in ^{135}Ba is identified as a J^{π}= $23/2^{+}$isomer with a half-life of1.06(4) ms. The new results show a smooth onset of isomeric J^{π}= $23/2^{+}$states along the N= 79 isotones and close a gap in the high-spin systematics towards the recently investigated J^{π}= 23/2+isomer in^{139}Nd. The resulting systematics ofM2 reduced transition probabilities is discussed within the framework of the nuclear shell model. Latest large-scale shell-model calculations employing the SN100PN, GCN50:82,SN100-KTH, and a realistic effective interaction reproduce the experimental findings generally well and give insight into the structure of the isomers.

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26. High-spin structure in the transitional nucleus ^{131}Xe: Competitive neutron and proton alignment in the vicinity of the N=82 shell closure

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The transitional nucleus ^{131}Xe is investigated after multinucleon transfer in the ^{136}Xe+^{208}Pb and ^{136}Xe+^{238}U reactions employing the high-resolution Advancedγ-Tracking Array (AGATA) coupled to the magnetic spectrometer PRISMA at the Laboratori Nazionali di Legnaro, Italy, and as an elusive reaction product in the fusion-evaporation reaction ^{124}Sn(^{11}B,p3n)^{131}Xe employing the High-

efficiency Observatory for γ-Ray Unique Spectroscopy (HORUS) γ-ray array coupled to a double-sided silicon strip detector at the University of Cologne, Germany. The level scheme of ^{131}Xe is extended to 5 MeV. A pronounced back bending is observed at ħω≈0.4 MeV along the negative-parity one-quasiparticle νh11/2(α=−1/2) band. The results are compared to the high-spin systematics of the Z=54 isotopes and theN=77 isotones. Large-scale shell-model calculations employing the PQM130, SN100PN, GCN50:82, SN100-KTH, and a realistic effective interaction reproduce the experimental findings and provide guidance to elucidate the structure of the high-spin states. Further calculations in $^{129-132}$Xe provide insight into the changing nuclear structure along the Xe chain towards the N=82 shell closure. Proton occupancy in the π0h11/2orbital is found to be decisive for the description of the observed back bending phenomenon.

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27. Towards the lowest-energy limit for light ions identification with silicon pixel-type detectors

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An in-beam test of two pixel-type silicon detectors of the TRACE detector project has been performed at Laboratori Nazionali di Legnaro (Italy). The aim was to investigate the lowest kinetic energy values at which isotopic identification of heavy-ion reactions products with mass A∼10 is possible, by using a single-layer silicon detector. Two separate read-out chains, analog and digital, were used, and the Pulse Shape Analysis technique was employed to obtain the particle identification matrices for the digitally processed data. The results confirmed the high capability of the Pulse Shape Analysis method which can be used for light ion identification, with performances similar to the analog approach. Separation in both charge and mass was obtained for Li and Be isotopes, however, the presence of a significant background from alpha particles severely limited the data analysis in the lower energy region. Due to this effect, the identification of the light products (^{7,6}Li isotopes) could be possible down to∼24.5 MeV only, while the ^{9,7}Be isotopes were separable down to∼29 MeV. This gives the value of<4 MeV/nucleon as the lowest kinetic energy for light products identification by using the pixel-type detectors of the TRACE project, in the present experimental conditions.

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28. Identification of high-spin proton configurations in ^{136}Ba and ^{137}Ba

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The high-spin structures of ^{136}Ba and ^{137}Ba are investigated after multinucleon-transfer (MNT) and fusion-evaporation reactions.136Ba is populated in a ^{136}Xe+^{238}U MNT reaction employing the high-resolution Advanced GAmma Tracking Array (AGATA) coupled to the magnetic spectrometer PRISMA at the Laboratori Nazionali di Legnaro, Italy, and in two ^{9}Be+^{130}Te fusion-evaporation reactions using the High-efficiency Observatory forγ-Ray Unique Spectroscopy (HORUS) at the FN tandem accelerator of the University of Cologne, Germany. Furthermore, both isotopes are populated in an elusive reaction channel in the ^{11}B+^{130}Te fusion-evaporation reaction utilizing the HORUSγ-ray array. The level scheme above the Jπ=10+isomer in ^{136}Ba is revised and extended up to an excitation energy of approximately 5.5 MeV. From the results of angular-correlation measurements, the Ex=3707- and Ex=4920-keV states are identified as the band heads of positive- and negative-parity cascades. While the high-spin regimes of both132Te and ^{134}Xe are characterized by high-energy 12+→10+transitions, the ^{136}Ba E2 ground-state band is interrupted by negative-parity states only a few hundred keV above the $J\pi=10^{+}$ isomer. Furthermore, spins are established for several hitherto unassigned high-spin states in ^{137}Ba. The new results close a gap along the high-spin structure of N<82 Ba isotopes. Experimental results are compared to large-scale shell-model calculations employing the GCN50:82 Realistic SM, PQM130, and SN100PN interactions. The calculations suggest that the band heads of the positive-parity bands in both isotopes are predominantly of proton character.

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29. The 4π highly-efficient light-charged–particle detector EUCLIDES, installed at the GALILEO array for in-beam γ-ray spectroscopy

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In a fusion-evaporation reaction, nuclei are produced by evaporating light-charged particles and neutrons from the compound nucleus. Typically, a nucleus of interest is produced as a result of a part of the total cross-section and, in order to guarantee a good channel discrimination, a particle detector, like the EUCLIDES 4π Si-ball array, is necessary. EUCLIDES has been quoted in more than a hundred publications resulting from many experiments performed in combination with the EUROBALL and GASPγ-ray spectrometers. The present paper reports on the upgraded version of EUCLIDES, that is presently coupled to the new GALILEOγ-ray spectrometer, installed at the Laboratori Nazionali di Legnaro, INFN.The design, characteristics and performance of the EUCLIDES array are presented and discussed.

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30. A powerful combination measurement for exploring the fusion reaction mechanisms induced by weakly bound nuclei

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The GALILEO array is a high-efficiency γ-ray spectrometer, resident at the Legnaro National Laboratory (LNL) in Italy, and it is currently used in combination with the Si-ball EUCLIDES for the detection of charged-particles. The combined setup was used in the ^{6}Li+ ^{89}Y experiment with incident energies of 22 MeV and 34 MeV to investigate the influence of breakup and transfer of weakly bound projectile on the fusion process. Using the coincidence by the charged particles and γ-rays, the different reaction channels can be clearly identified and the different reaction mechanisms can be clearly studied. It is shown that this facility can be used well to explore the fusion reaction mechanisms induced by weakly bound nuclei.

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31. Isomer spectroscopy in ^{133}Ba and high-spin structure of ^{134}Ba

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The transitional nuclei ^{134}Ba and ^{133}Ba are investigated after multinucleon transfer employing the high-resolution Advanced GAmma Tracking Array coupled to the magnetic spectrometer PRISMA at the Laboratori Nazionali di Legnaro, Italy, and after fusion-evaporation reaction at the FN tandem accelerator of the University of Cologne, Germany. TheJπ=19/2+state at 1942 keV in ^{133}Ba is identified as an isomer with a half-life of 66.6(20) ns corresponding to a B(E1) value of 7.7(4)×10−6e2fm2 for the J π=19/2+toJπ=19/2−transition. The level scheme of ^{134}Ba above the Jπ=10^{+}isomer is extended to approximately 6 MeV. A pronounced back bending is observed at ħω=0.38 MeV along the positive-parity yrast band. The results are compared to the high-spin systematics of theZ=56 isotopes. Large-scale shell-model calculations employing the GCN50:82, SN100PN, SNV, PQM130, Realistic SM, and EPQQM interactions reproduce the experimental-findings and elucidate the structure of the high-spin states. The shell-model calculations employing theGCN50:82 and PQM130 interactions reproduce alignment properties and provide detailed insight into the microscopic origin of this phenomenon in transitional ^{134}Ba.

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32. Coulomb excitation studies at LNL with the SPIDER-GALILEO set-up

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Low-energy Coulomb excitation is one of the simplest and most known tools to study the nuclear shape; for this reason it is nowadays widely used at radioactive beam facilities. The Selective Production of Exotic Species (SPES) facility, for the acceleration of radioactive beams will soon provide the first exotic beams at the Laboratori Nazionali di Legnaro (LNL) in Italy. To this end a new particle detector (Silicon PIe DEtectoR) to be used for Coulomb excitation studies has been installed at LNL. SPIDER has been coupled to the GALILEO array of germanium detectors, and a number of experiments have been already successfully performed. This paves the way for future experiments with the radioactive beams provided by the SPES facility.

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