Report on Brazilian nuclear data needs and activities
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Nuclear data needs

Data for new medical radioisotope production would be of great interest, to increase the range of products available in Brazil. At the moment, the available facilities restrict their interest to radioisotopes produced by proton-induced reactions in low-energy cyclotrons (up to at most 30 MeV). Higher energy proton-induced reactions could become of interest if the Institute for Energy and Nuclear Research (IPEN) in São Paulo succeeds in its bid to obtain a higher energy (70 MeV?) cyclotron. Interest in reactor production of radioisotopes will also resurge when the Brazilian multipurpose reactor begins operation.

There is a general consensus that short courses on nuclear data, such as those given at the ICTP in Trieste and at the IAEA headquartes in Vienna, are very important for attracting and preparing young researchers in the area.

More data on particle production in light-ion-induced reactions might seem to be of purely theoretical interest, but could be of eventual use in measurements using surrogate reactions, as well as for neutron production.

Nuclear data for particle production in proton-induced reactions in the range of the cosmic ray peak (from about 200 MeV to 600 MeV) as well as more consistent modeling of these reactions is of interest in the area of aerospace dosimetry.

In this context, implementation of the Generalized Nuclear Database Structure (GNDS) could provide the impetus for an improved description of multiple emission cross sections, appropriate for Monte Carlo calculations and calculations of correlated emissions. This would require further extensions to the allowed formats, however, which still seem to adhere closely to the ENDF philosophy.

Finally, we emphasize the importance of the EXFOR data base and its continued expansion to include charged-particle-induced reaction data as well as new neutron-induced reaction data. The database is known and used by most researchers in nuclear physics and nuclear data in Brazil. Brazilian experimental nuclear physicists at the Open Nuclear Physics Laboratory of the University of São Paulo have also shown great interest in contributing to the database.

Nuclear Data Activities

Nuclear data activities in Brazil cover almost the entire range of pertinent subjects and applications. The scope and number of activities undertaken by the researchers associated with CNEN can to a large degree be discerned from the Program of the International Nuclear Atlantic Conference (INAC), a biennial nuclear engineering/nuclear applications conference organized by the Brazilian Nuclear Energy Association. Although researchers from universities and other institutes interested in nuclear applications do attend this conference, it is dominated by participants from the CNEN institutes. In the most recent event, INAC 2019, attendees presented over 160 talks and posters on nuclear reactor physics and about 350 talks and posters on nuclear applications. The 2019 program can be found at http://www.inac2019.org.br/livro/livro.pdf.

The Institute for Energy and Nuclear Research (IPEN) in São Paulo, the principal CNEN research center, furnishes a record of its research activities through a compilation available online of published papers authored by its researchers. This database reveals a production of about 320 papers in each of 2018, 2019 and 2020, of which an average of about 85 appeared annually in *Radiation Physics and Chemistry*, about 15 appeared annually in *Annals of Nuclear Energy* and about 7 appeared each year in *Applied Radiation and Isotopes*.

Experimental activities at the Open Nuclear Physics Laboratory of the University of São Paulo continue unabated. Most of the experimental data sets of scattering and reactions induced by light heavy-ions measured at the laboratory during the last few years have been compiled in EXFOR, as well as having been published. An incomplete but fairly inclusive list of these experiments is given at the end of this report.

A long-term project at the Aeronautical Technology Institute in collaboration with the Advanced Studies Institute of the Aerospace Technology Center and with researchers from the University of Seville has lead to the development of simulations of cosmic-ray produced particle spectra and angular distributions as a function of altitude, taking into account the magnetic field minimum close to the Brazilian coast. The project continues with flights of detectors and a phantom aboard Brazilian Air Force aircraft, as well as ground measurements, to further refine the modelling. The results obtained so far are being used in dosimetry studies in aircraft. A database containing particle fluxes and fluences for dosimetry calculations as a function of altitude and flight path is being prepared.

General information

Nuclear data activities in Brazil can, for the most be part, be divided into applied research performed at the research centers of the National Nuclear Energy Commission (CNEN) and at the Nuclear Engineering Department of the Federal University of Rio de Janeiro (COPPE-UFRJ) and basic and applied research performed at the University of São Paulo and the University Federal Fluminense in Niteroi, with some basic and applied research conducted at several other public universities. There are also strong university-based experimental groups associated with several of the high-energy experiments at Jefferson Lab and at CERN, as well as a strong Brazilian participation in the Pierre Auger cosmic-ray observatory in Argentina. The nuclear data needs and activities of these groups have not been discussed here.

The National Nuclear Energy Comission (CNEN) oversees six centers that perform research and development in nuclear science and engineering. The centers belong to the Directorate of Research and Development (DPD) of the CNEN. They are (information taken, in part, from the 2019 IAEA CNPP on Brazil):

1. IPEN (São Paulo/SP) - Institute for Energy and Nuclear Research;
with two research reactors, of 5MW and 100W, and two cyclotrons for radioisotope production (123I, 18F, 67Ga, 201Tl, 111In); Research on fuel cycles and materials, reactor technology, safety fundamentals, radiation and radioisotope applications, biotechnology, environmental and waste technologies.

2. IEN (Rio de Janeiro/RJ) - Institute for Nuclear Engineering;
with a 100 kW research reactor and two cyclotrons for radioisotope production (123I, 18F); Research on instrumentation, control and man-machine interfaces, chemistry and materials, safety, reactor technology.

3. CDTN (Belo Horizonte/MG) - Centre for Nuclear Technology Development Research;
with a 250 kW research reactor and a cyclotron for radioisotope production (18F); Research on mining, reactor technology, materials, safety, chemistry, environmental and waste technologies, radoisotope applications.

4. IRD (Rio de Janeiro/RJ) - Institute for Radiation Protection and Dosimetry;
Research on radiation protection and safety, environmental technology, metrology, medical physics.

5. CRCN-NE (Recife/PE) - Nuclear Sciences Regional Center;
with a cyclotron for radioisotope production (18F); Research and development in radiation protection, dosimetry, metrology and reactor technology.

6. CRCN-CO (Goiânia/GO) – Nuclear Sciences Regional Centre of the Center-west;
Research and development on underground water and environmental technologies.

The Federal University of Rio de Janeiro, COPPE-UFRJ, has a strong nuclear engineering program, conducting research in reactor physics and engineering as well as nuclear applications.

The government-sponsored cyclotrons are obviously too few and far between to meet the demand for short-lived radioisotopes such as 18F and 123I. Production was thus opened to the private sector, under CNEN regulation, in 2006, and there are now 7 (?) privately run cylcotrons producing 18F in Brazil. Together with the 5 government-sponsored cyclotrons, they attempt to satisfy the demand of the approximately 150 PET/CT scanners now installed in the country.

The 5MW reactor at IPEN in São Paulo is the only Brazilian reactor producing medical radioisotopes - 100% of the 153Sm and 60% of 131I in demand. All other reactor-derived radioisotopes, 99Mo, in particular, are imported.

Brazil has an ongoing project to build a multipurpose research reactor (RMB), with a maximum power of 30 MW, powered by uranium silicate enriched up to 20%. The project comprises the reactor as well as several associated facilities and laboratories to perform: radioisotope production - 99Mo, in particular; irradiation tests of nuclear fuels and materials; and scientific research using neutron beams. The reactor site has been chosen and environmental impact assessments have already been conducted. Basic engineering design has been concluded and detailed engineering design was to be contracted in early 2016, in cooperation with Argentina. However, this is now a thirteen-year-old project eagerly awaited by most Brazilian researchers in nuclear energy and nuclear physics but whose conclusion is still uncertain.

Turning to the contribution of universities to basic research, one finds the University of São Paulo (USP) and the University Federal Fluminense (UFF) to be the only ones with significant experimental installations. However, the installation at UFF is a dedicated AMS facility, important for many applications, but of lesser interest for nuclear data.

The Physics Institute at USP (IFUSP) operates an Open Nuclear Physics Laboratory with an 8UD Tandem Pelletron used to produce light heavy ion beams of 3-5 MeV/nucleon. The installation is used for time-of-flight decay studies, gamma-gamma and gamma-particle coincidence studies and, with the installation of a fragmenter and a double solenoid, the production and study of light exotic nuclei, such as 6He, 7Be, 8Li, 8B and 10Be. The facility is quite active, having furnished experimental data for about 60 dissertations and theses and on the order of a hundred publications in the last ten years.

The Ion Beam Material Analysis Laboratory at IFUSP also uses the Pelletron accelerator for studies of elastic scattering and gamma and X-ray spectroscopy. The faclility has a beam line dedicated to PIXE analysis, another to Rutherford backscattering spectrometry and a third for more general material analyses.

Other universities and research institutes develop smaller research programs in reactor physics and applied nuclear physics, such as dose determination, instrumentation development, data processing and studies of cosmic-ray and weather-induced particle spectra in the atmosphere.

Recent measurements realized by Brazilian nuclear physicists at the Open Nuclear Physics Laboratory (LAFN) at the University of São Paulo, with data deposited in the EXFOR library at the IAEA:

1) 10B+197Au: L. R. Gasques et al., Phys Rev C **101**, 044604 (2020).

2) 10B+120Sn: L. R. Gasques et al., Phys. Rev. C **97**, 034629 (2018).

3) 10B+120Sn: M. A. G. Alvarez et al., Phys. Rev. C **98**, 024621 (2018).

4) 8Li+p: E. Leistenschneider et al., Phys Rev.C **98**, 064601 (2018).

5) 8Li+p: D. R. Mendes Jr et al., Phys. Rev. C **98**, 069901 (2018). Erratum

6) 6He+120Sn: S. Appanababu et al., Phys. Rev. C **99**, 014601 (2019).

7) 7Be+9Be: U. Umbelino et al, Phys. Rev. C **99**, 064617 (2019).

8) 12B+58Ni: E. O. N. Zevallos et al., PRC C **99**, 064613 (2019).

9) 13C+28Si: R. Linares, et al, Phys. Rev. C **101**, 014611 (2020).

Measurements by Brazilian researchers in collaborations at other laboratories:

11) 10B+197Au: M. Aversa et al., Phys. Rev. C **101**, 044601 (2020). (measurements realized at TANDAR (CNEA,Argentina) by Brazilian-Argentinian collaboration)

12) 10C+58Ni : V. Guimarães, et al. Phys. Rev. C **100**, 034603 (2019). (measurements realized at Twinsol-U.Notre Dame, USA by Brazilian-American collaboration)

13) 16O+27Al, 28Si: L. M. Fonseca et al., Phys. Rev. C **100**, 014604 (2019). (measurements realized at INFN-LNS, Italy by the NUMEN collaboration)

14) (18O, 17O) on 16O, 28Si, 64Ni: R. Linares et al., Phys. Rev. C **98**, 054615 (2018).
(measurements realized at INFN-LNS, Italy by the NUMEN collaboration)

15) 18O+28Si: E. N. Cardozo et al., Phys. Rev. C **97**, 064611 (2018).
(measurements realized at INFN-LNS, Italy by the NUMEN collaboration)