Measurement of Excitation Functions of charged particle (proton, alpha) induced reactions on ^{nat}Fe, ^{nat}Nb, ^{nat}Y, and ^{nat}Hf from MC50 Cyclotron

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RESEARCH OBJECTIVES:

The objectives are to measure the production cross-sections

- **for $^{nat}Fe(p,x)$, $^{nat}Nb(p,x)$,and $^{nat}Hf(p,x)$ reactions and**
- **for $^{nat}Fe(\alpha,x)$, $^{nat}Y(\alpha,x)$, and $^{nat}W(\alpha,x)$ reactions by using a stacked-foil activation technique at the MC-50 cyclotron of the Korea Institute of Radiological and Medical Science.**

ANTICIPATED OUTCOMES:

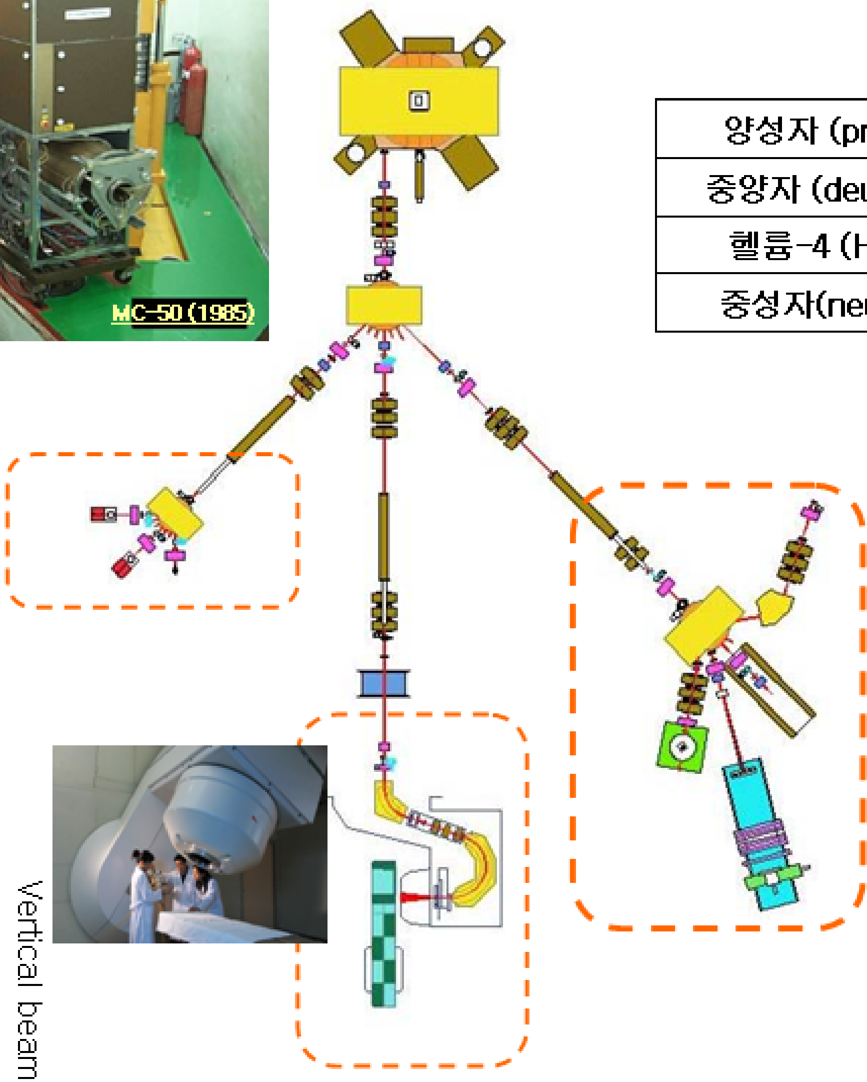
The anticipated outcomes are the production cross-sections of the following nuclear processes from the threshold energy to about 40 MeV:

- $^{nat}Fe(p,x)^{55,56,57}Co$, ^{51}Cr, and $^{52,54}Mn$ nuclear processes
- $^{nat}Nb(p,x)^{90,93m}Mo$, $^{90,91m,92m,92g}Nb$, ^{88}Zr, and ^{88}Y nuclear processes
- $^{nat}Hf(p,x)^{173,174,175,176,177,178m,180g}Ta$, $^{173,175,179m,180m}Hf$, and $^{172m+g,173,177g}Lu$ nuclear processes
- $^{nat}Fe(\alpha,x)^{55,56,57,58}Co$, ^{61}Co, ^{56}Mn, $^{56,57}Ni$ nuclear processes
- $^{nat}Y(\alpha,x)^{90,92m}Nb$, $^{88,89}Zr$, $^{87m,87g,88,90m,91m}Y$ nuclear processes
- $^{nat}W(\alpha,x)^{182,182m,183,184,184m,186,188}Re$, ^{187}W, and $^{182,183,184}Ta$ nuclear processes

MC-50 Cyclotron:

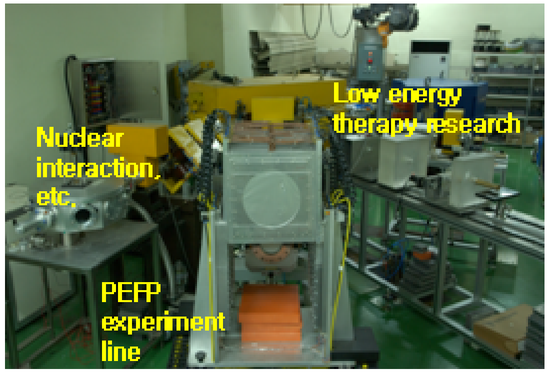
MC-50 cyclotron

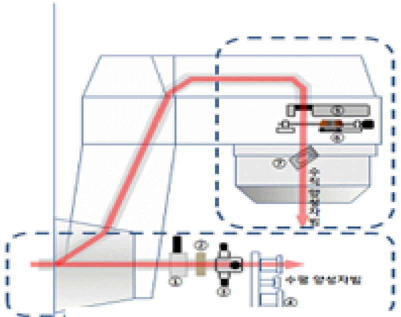
양성자 (proton)	20~51 MeV / 40 uA
중양자 (deuteron)	10~25 MeV / 30 uA
헬륨-4 (He-4)	20~50 MeV / 1 uA
중성자(neutron)	$E_{n,max} < E_{proton} - 2MeV$



RI target irradiation

Low intensity irradiation

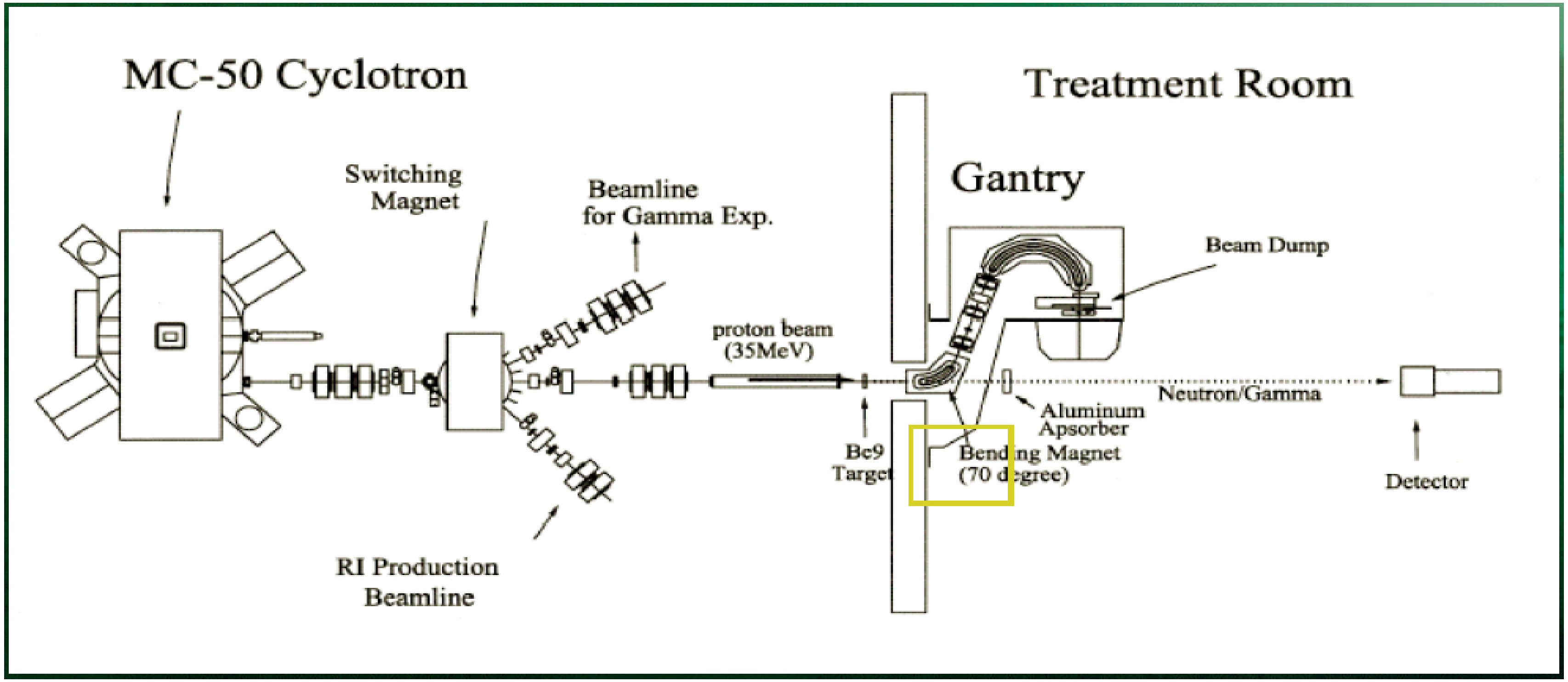


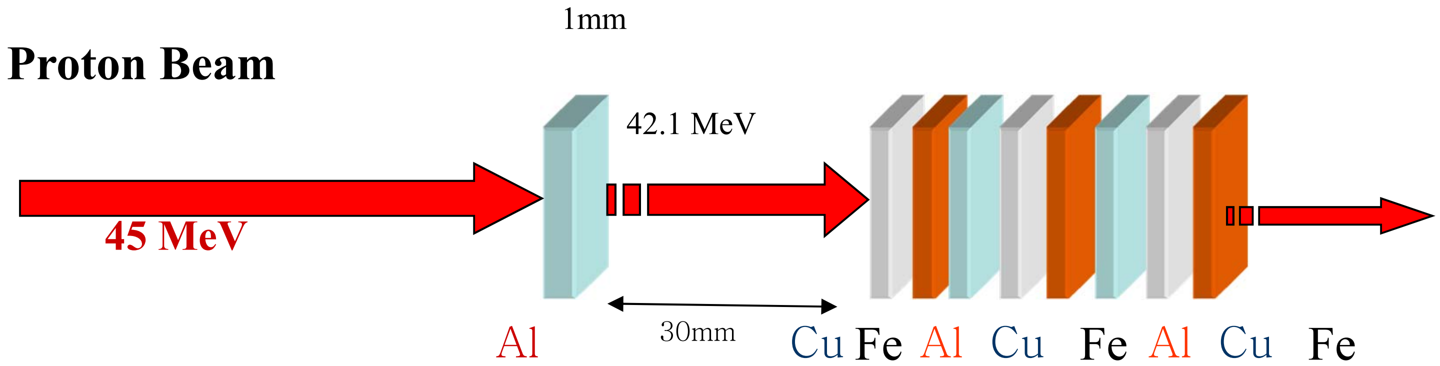


Vertical beam

Horizontal beam

Neutron and High Intensity Irradiation


MC-50 Cyclotron
Treatment Room
Switching Magnet
Beamline for Gamma Exp.
Gantry
Beam Dump
proton beam (35MeV)
Neutron/Gamma
Aluminum Apsorber
Be9 Target
Bending Magnet (70 degree)
Detector
RI Production Beamline


1mm
Proton Beam
42.1 MeV
45 MeV
30mm
Al
Cu Fe Al Cu Fe Al Cu Fe

Work Plan:

1. From December 1 , 2012 to November 31, 2013

We will deliver the production cross sections of the ${}^{nat}Fe(p,x)^{55,56,57}Co$, ${}^{51}Cr$, and ${}^{52,54}Mn$ nuclear processes and ${}^{nat}Fe(\alpha,x)^{55,56,57,58}Co$, ${}^{61}Co$, ${}^{56}Mn$, ${}^{56,57}Ni$ nuclear processes from threshold energy to about 40 MeV by using a stacked-foil activation technique at the MC-50 cyclotron.

2. From December 1 , 2013 to November 31, 2014

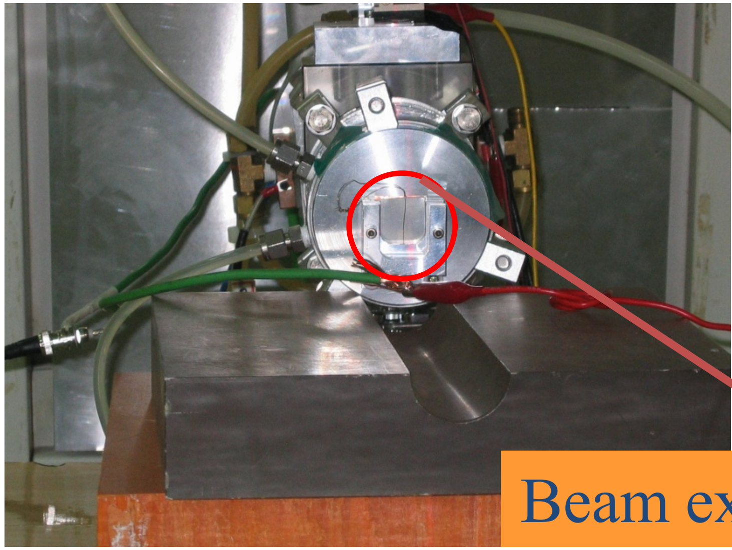
We will deliver the production cross sections of the ${}^{nat}Nb(p,x)$ ${}^{90,93m}Mo$, ${}^{90,91m,92m,92g}Nb$, ${}^{88}Zr$, and ${}^{88}Y$ nuclear processes and ${}^{nat}Y(\alpha,x)^{90,92m}Nb$, ${}^{88,89}Zr$, ${}^{87m,87g,88,90m,91m}Y$ nuclear processes from threshold energy to about 40 MeV by using a stacked-foil activation technique at the MC-50 cyclotron.

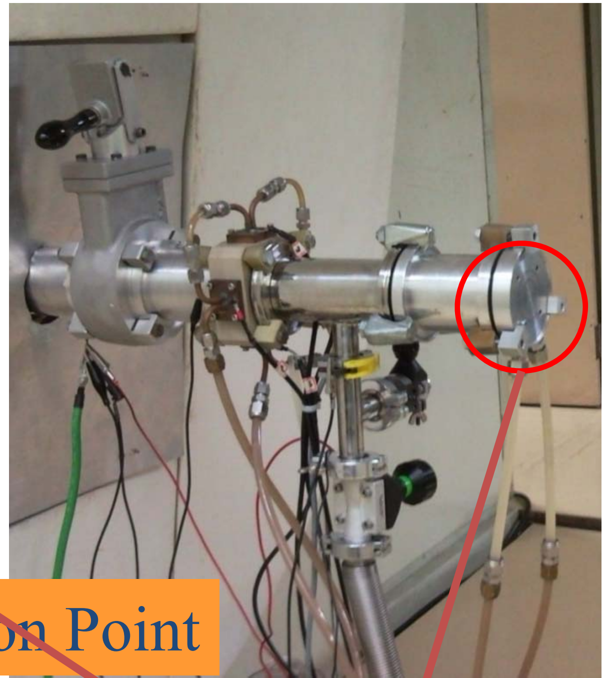
3. From December 1 , 2013 to November 31, 2014

We will deliver the production cross sections of the ${}^{nat}Hf(p,x)^{173,174,175,176,177,178m,180g}Ta$, ${}^{173,175,179m,180m}Hf$, and ${}^{172m+g,173,177g}Lu$ nuclear processes and ${}^{nat}W(\alpha,x)^{182,182m,183,184,184m,186,188}Re$, ${}^{187}W$, and ${}^{182,183,184}Ta$ nuclear processes from threshold energy to about 40 MeV by using a stacked-foil activation technique at the MC-50 cyclotron.

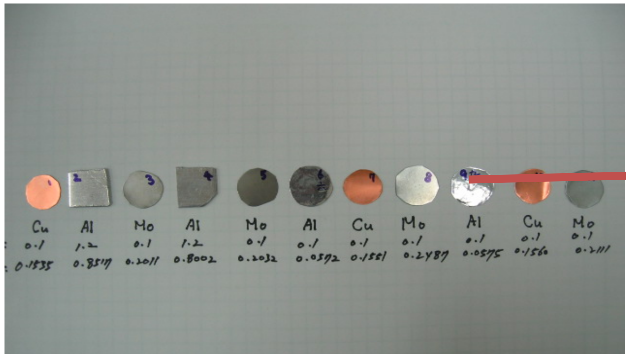
Experimental Set-up:

Sample Holder and Samples

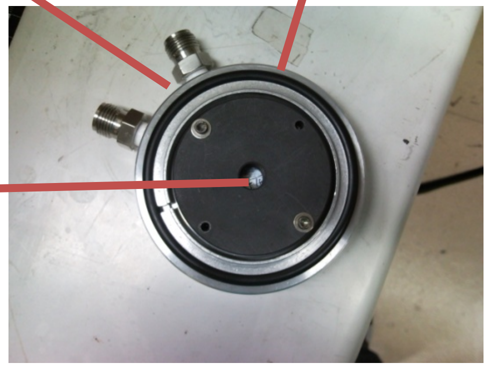




Beam extraction Point

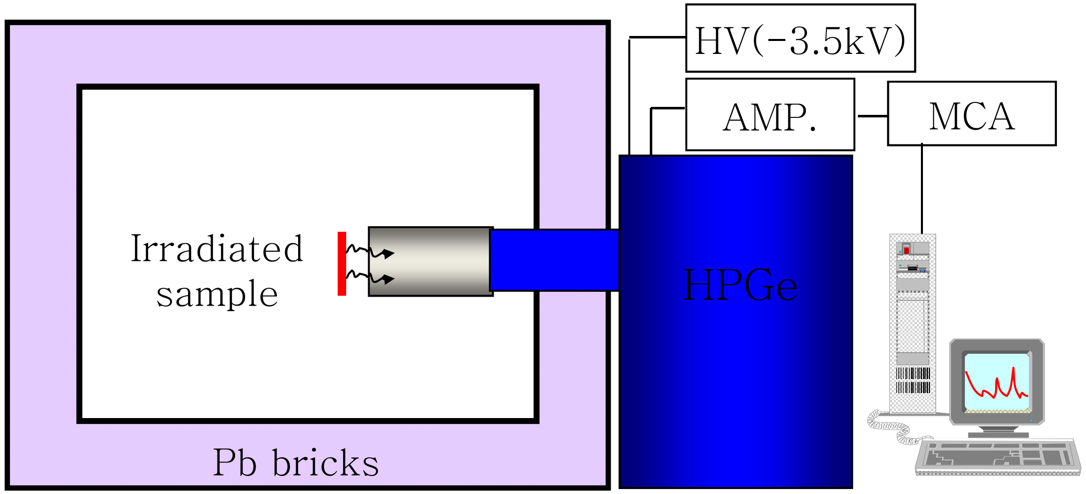


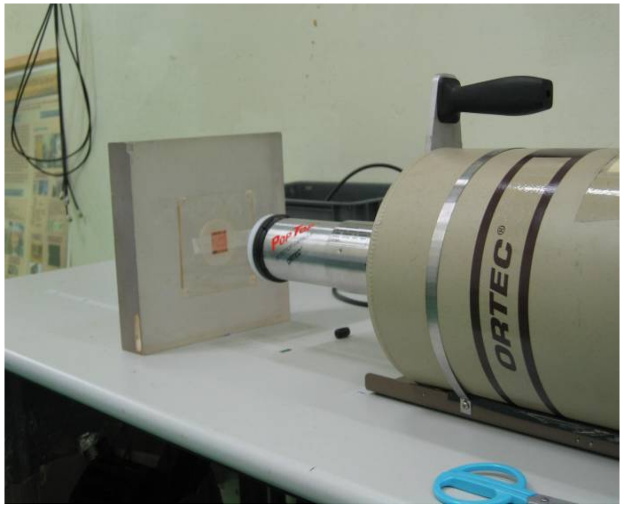
Targets & Monitor samples



Collimator & Sample Holder

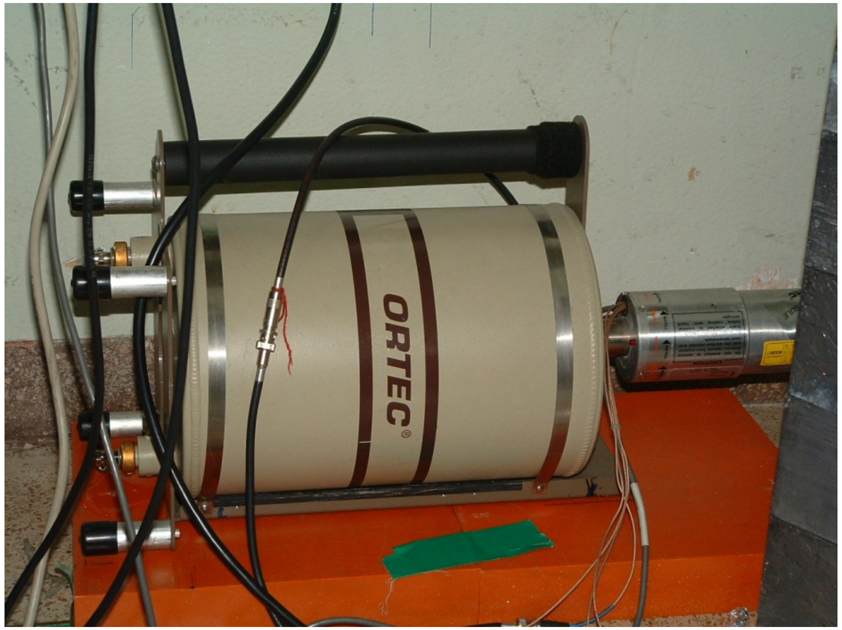
Gamma-ray Spectrometry:





Gamma-ray Spectrometry:

Gamma-ray spectrometry and Standard Sources



Nuclide	Half-life	Energy	Activity
^{109}Cd	462.6d	88.0336 keV	123.7 kBq
^{57}Co	271.79d	122.06065 / 136.47350 keV	53.2 kBq
^{137}Cs	30.07y	661.657 keV	370.2 kBq
^{54}Mn	312.1 d	834.841 keV	6.9 kBq
^{60}Co	5.27 y	1173.228 / 1332.490 keV	266.3 kBq
^{22}Na	2.6019 y	1274.537 keV	219.1 kBq

Measurement of Production Cross sections for $^{nat}Fe(p,x)^{55,56,57}Co$, ^{51}Cr, and $^{52,54}Mn$:

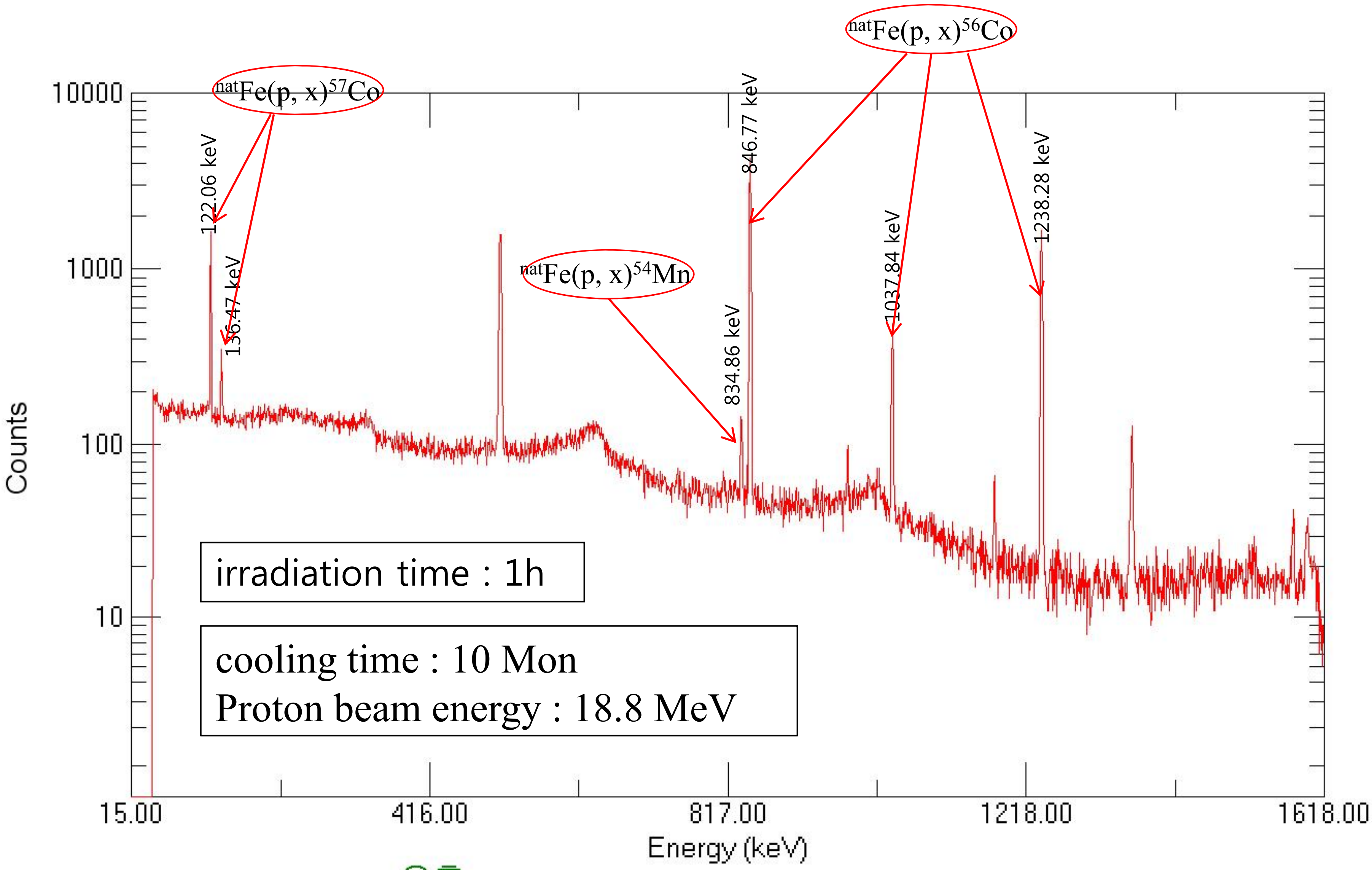
^{nat}Fe : ^{54}Fe(5.845%), ^{56}Fe(91.754%), ^{57}Fe(2.119%), ^{58}Fe(0.282%)

Decay data for the produced radionuclides

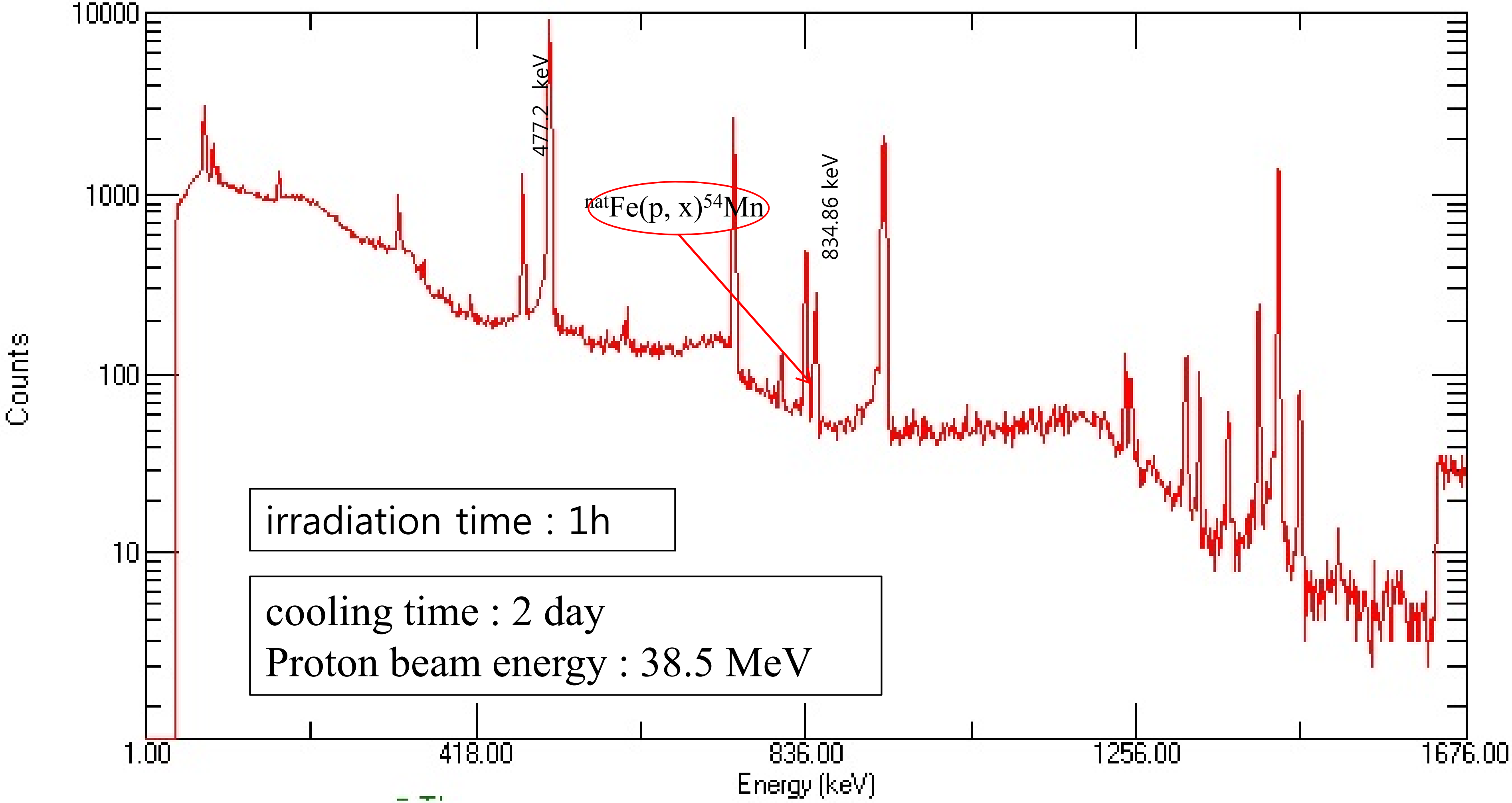
www.nndc.bnl.gov/chart/

Nuclide	Half-life	Decay mode (%)	E_γ (keV)	I_γ (%)	Contributing reactions	Q-value (MeV)	Threshold (MeV)
^{51}Cr	27.7010 d(11)	EC (100)	320.0824 (4)	9.9910(10)	$^{56}Fe(p, ^6Li)$ $^{54}Fe(p, \alpha 2p)$	-15.954 -27.452	16.241 27.965
^{55}Co	17.53 h(3)	EC (100)	477.2 (2) 931.1 (3) 1316.6 (3) 1408.5 (3)	20.2 (17) 75 7.1 (3) 16.9 (8)	$^{54}Fe(p, \gamma)$ $^{56}Fe(p, 2n)$ $^{57}Fe(p, 3n)$ $^{58}Fe(p, 4n)$	5.06 -15.43 -23.08 -33.12	0.0 15.71 23.49 33.7
^{56}Co	77.226 d(26)	EC (100)	846.770 (2) 1037.843 (3) 1238.288 (3)	99.9399 14.05 (4) 66.46 (12)	$^{56}Fe(p, n)$ $^{57}Fe(p, 2n)$ $^{58}Fe(p, 3n)$	-5.35 -12.99 -23.04	5.44 13.22 23.44
^{57}Co	271.74 d(6)	EC (100)	14.4129 (6) 122.06065(12) 136.47356(29)	9.16 (15) 85.60 (17) 10.68 (8)	$^{56}Fe(p, \gamma)$	6.0	0
^{52}Mn	5.591 d(3)	EC (100)	744.233 (13) 935.544 (12) 1434.092 (17)	90.0 (8) 94.5 (9) 100.0 (6)	$^{54}Fe(p, \alpha p)$ $^{56}Fe(p, \alpha n)$ $^{57}Fe(p, \alpha 2n)$ $^{58}Fe(p, \alpha 3n)$	-18.682 -13.11 -20.75 -30.80	19.031 13.34 21.12 31.33
^{54}Mn	312.05 d(4)	IT+EC (100)	834.848 (3)	99.9760(10)	$^{57}Fe(p, \alpha)$	-1.1	1.1

Identifications of gamma-ray peak



Identifications of gamma-ray peak



Formula of Cross sections calculations

Reaction Rate

$$R = \frac{\lambda C}{\varepsilon I_\gamma NQ\,(1 - e^{-\lambda t_m})e^{-\lambda t_c}(1 - e^{-\lambda t_i})}$$

R = Reaction rate
λ = decay constant, s^{-1}
C = total counts of gamma-ray peak area
N = number of target atoms, atom
ε = peak efficiency
I_γ = branching ratio of gamma-ray
t_c, t_m, t_{irr} = cooling time, measuring time, irradiation time (s)
Q = proton beam current, coulomb.

Cross-Sections

$$\sigma = \frac{RQN}{\phi N_d l}$$

σ = cross section, cm^{-2}
N_d = atomic density, atom/cm^3
l = foil thickness, cm
ϕ = beam intensity, p/cm^2/sec

$$\sigma = \frac{\lambda C}{\varepsilon \times I_\gamma \times N_d \times t \times \phi\,(1-e^{-\lambda t_m})e^{-\lambda t_c}(1-e^{-\lambda t_i})}$$

Results for production cross sections

Proton energy [MeV]	^{51}Cr[mb]	^{52}Mn[mb[	^{54}Mn[mb]	^{55}Co[mb]	^{56}Co[mb]	^{57}Co[mb]
40.30 ± 0.38	90.10 ± 4.05	22.10 ± 1.89	200.00 ± 17.00	13.60 ± 1.21	23.30 ±2.09	0.68 ± 0.08
39.52 ± 0.40	79.40 ± 3.61	23.00 ± 1.97	194.00 ± 16.50	14.00 ± 1.24	23.20 ± 2.09	0.64 ± 0.08
38.71 ± 0.40	75.80 ± 3.47	23.80 ± 2.04	184.00 ± 15.70	14.70 ± 1.30	23.80 ± 2.14	0.73 ± 0.08
36.98 ± 0.43	54.50 ± 2.69	26.80 ± 2.29	169.00 ± 14.40	17.00 ± 1.50	25.20 ± 2.27	0.76 ± 0.08
36.12 ± 0.43	42.00 ± 2.23	27.40 ± 2.35	152.00 ± 13.00	17.80 ± 1.57	25.50 ± 2.29	0.83 ± 0.09
35.25 ± 0.44	31.80 ± 1.84	28.30 ± 2.42	134.00 ± 11.50	19.50 ± 1.71	25.70 ± 2.31	0.80 ± 0.08
33.39 ± 0.46	16.40 ± 1.39	29.40 ± 2.52	104.00 ± 9.04	24.20 ± 2.12	27.30 ± 2.47	1.00 ± 0.10
32.46 ± 0.47	12.40 ± 1.61	29.00 ± 2.48	80.40 ± 7.15	27.10 ± 2.37	28.30 ± 2.53	1.06 ± 0.10
31.50 ± 0.48		27.80 ± 2.38	62.90 ± 5.72	30.30 ± 2.64	29.50 ± 2.64	1.21 ± 0.11
29.48 ± 0.50		23.10 ± 1.99	25.40 ± 2.92	38.10 ± 3.34	31.40 ± 2.79	1.37 ± 0.12
28.48 ± 0.50		21.10 ± 1.82	13.50 ± 2.11	41.40 ± 3.60	32.90 ± 2.92	1.57 ± 0.14
27.46 ± 0.52		18.80 ±1.63	6.62 ± 0.58	43.90 ± 3.81	34.90 ± 3.08	1.71 ± 0.15
25.18 ± 0.56		12.30 ± 1.08	1.54 ± 0.16	45.50 ± 3.95	40.50 ± 3.53	2.20 ± 0.19
24.03 ± 0.60		8.62 ± 0.77	1.15 ± 0.14	44.90 ± 3.90	45.80 3.97	2.44 ± 0.21
22.82 ± 0.61		4.43 ± 0.42	0.96 ± 0.13	43.10 ± 3.74	53.30 ± 4.59	2.61 ± 0.23
20.15 ± 0.67			1.11 ± 0.16	36.10 ± 3.14	97.20 ± 8.26	3.43 ± 0.30
18.77 ± 0.70			1.41 ± 0.19	26.70 ± 2.33	138.00 ± 11.70	3.98 ± 0.34
17.31 ± 0.76			1.50 ± 0.21	10.80 ± 0.97	214.00 ± 18.10	4.96 ± 0.43
13.92 ± 0.89			1.22 ± 0.25		365.00 ± 30.80	9.10 ± 0.77
12.04 ± 0.99			0.85 ± 0.24		352.00 ± 29.70	12.00 ± 1.02
9.89 ± 1.15					263.00 ± 22.20	12.30 ± 1.04
7.31 ± 1.43					93.90 ± 7.98	7.71 ± 0.66
3.37 ± 2.50					5.80 ± 0.63	1.51 ± 0.13
0.43 ± 0.43						0.06 ± 0.01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