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Activation cross-sections of ion beam induced nuclear reactions on iron

Kwangsoo Kim[1‡], M.U. Khandaker[1], Kyung-Sook Kim[1], Manwoo Lee[1], Y-S. Cho[2], Y-O. Lee[2], Guinyun Kim[1*]

[1]Department of Physics, Kyungpook National University, 1370 Sankyok-dong, Buk-gu, Daegu 702-701, Korea

[2]Nuclear Data Evaluation Laboratory, Korea Atomic Energy Research Institute, 150-1 Duckjin-dong, Yusung-gu, Daejeon 305-600, Korea

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1. Introduction

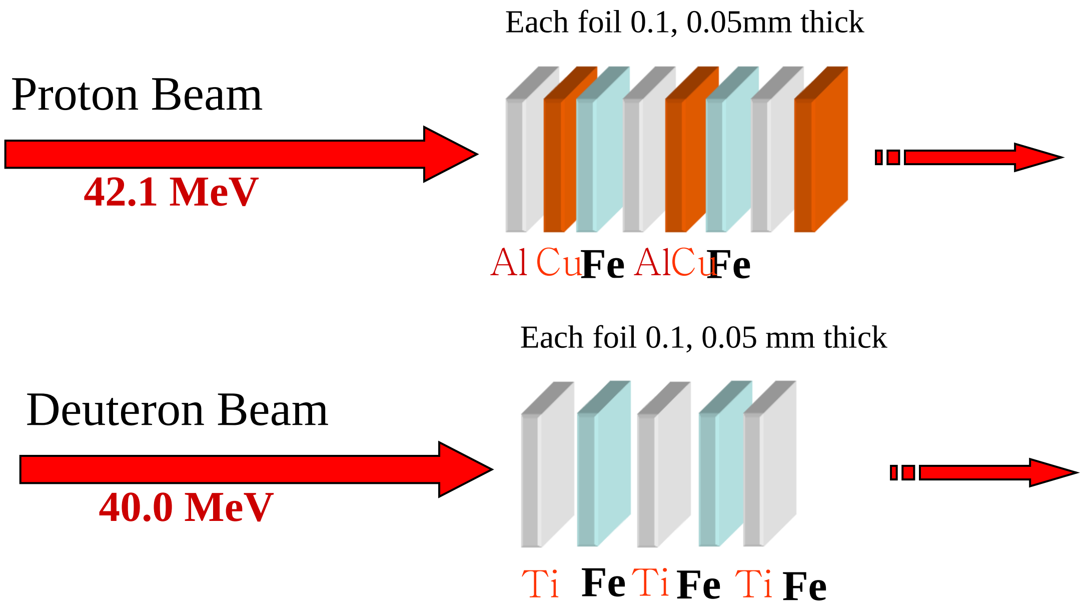
We measured the production cross-sections of $^{52,54,56}Mn$, $^{55,56,57,58}Co$, and ^{51}Cr radionuclides from 11-38 MeV deuteron-induced reactions on natural iron at the AVF Cyclotron of the Cyclotron and Radioisotope Center, Tohoku University.

In addition, We measured the production cross-sections of $^{52,54}Mn$, $^{55,56,57}Co$, and ^{51}Cr radionuclides from 8-40 MeV proton-induced reactions on natural iron and the production cross-sections of ^{56}Mn, $^{55,56,57,58,61}Co$, and $^{56,57}Ni$ radionuclides from 3-43 MeV alpha-induced reactions on natural iron at the MC50 cyclotron of the Korea Institute of Radiological and Medical Sciences.

The results are compared with the available literature values as well as the theoretical data calculated by the TALYS codes. The thick target integral yields were also deduced using the measured cross-sections of the produced radionuclides. In the investigated energy region, the present results are in generally good agreement with the earlier reported data and with the calculated data.

2. Experimental procedures

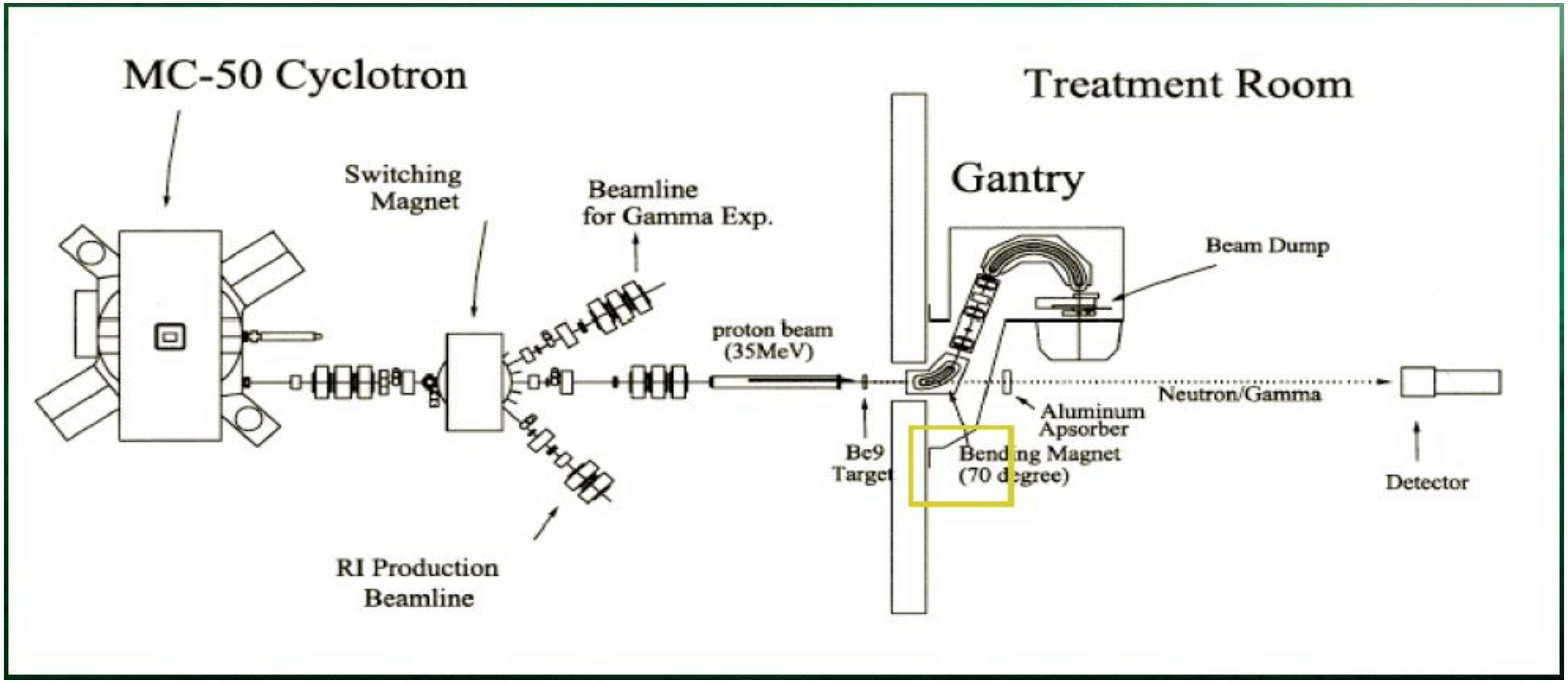
The Stacked-foil Activation Technique



The stacks were designed to meet the following requirements:

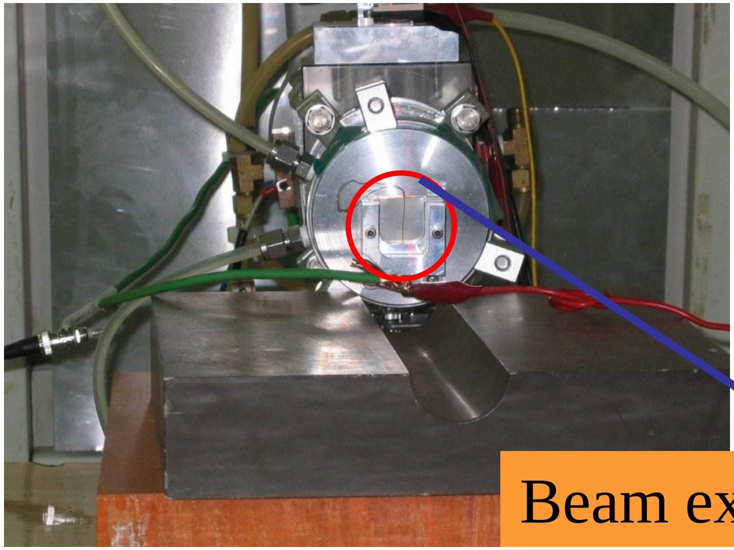
- to measure "**independent & cumulative cross-sections**" of Fe as a function of incident beam energy.
- to **provide overlapping energy regions** by arranging several stacks to complement each other.
- to **determine the proton flux inside the stack** via monitor reactions using Copper and Alumunum foils.
- to **avoid any recoil contamination** or recoil loss of produced nuclides by covering each measured foil with thin catcher-foils.

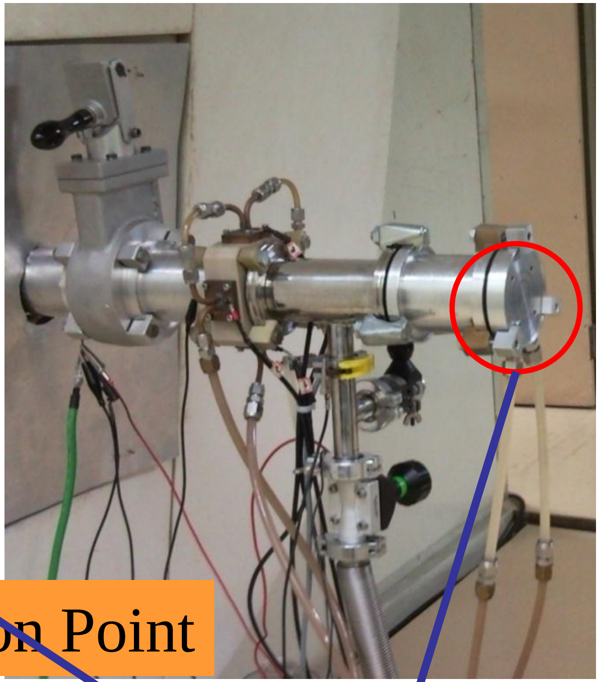
MC 50 Cyclotron



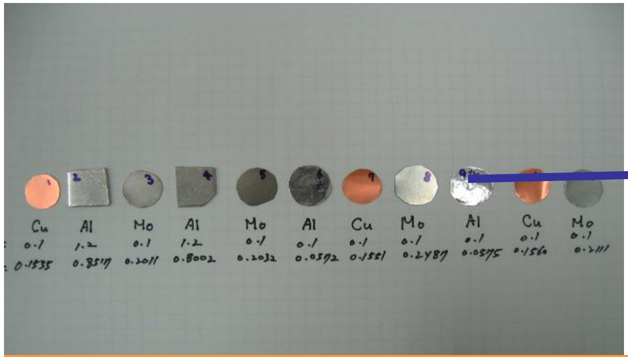
Proton Beam Energy	maximum	This work
	50 MeV	45 MeV
Current	60μA	100nA

Sample Holder and Samples

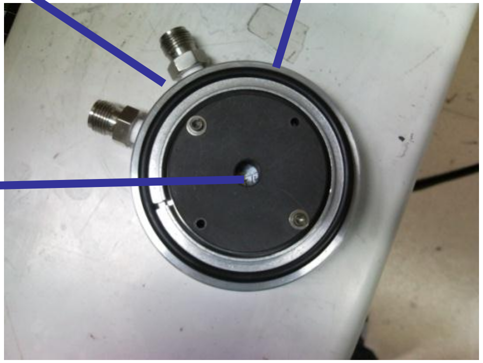




Beam extraction Point

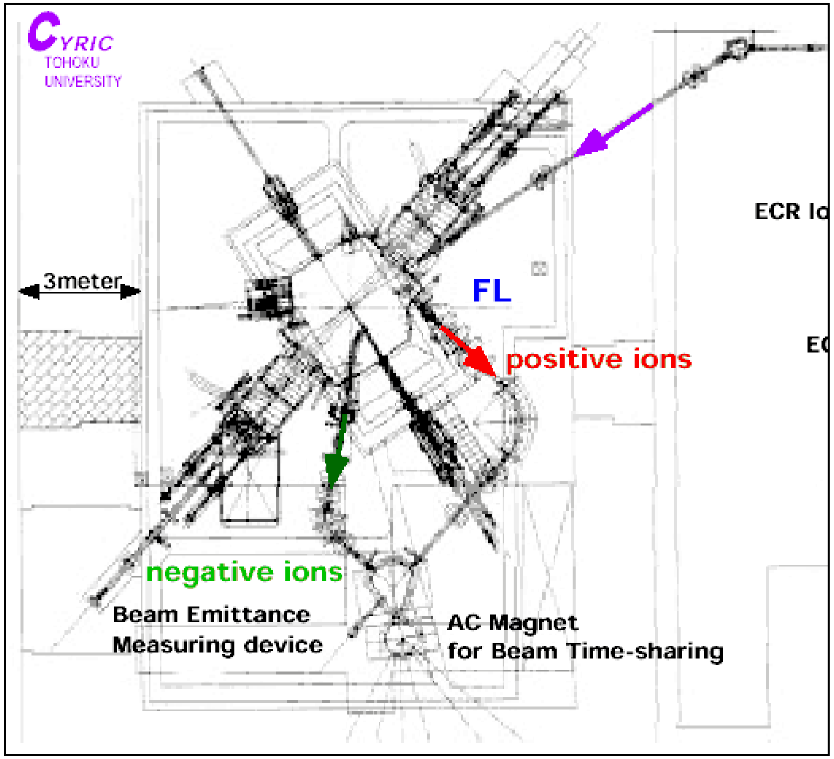


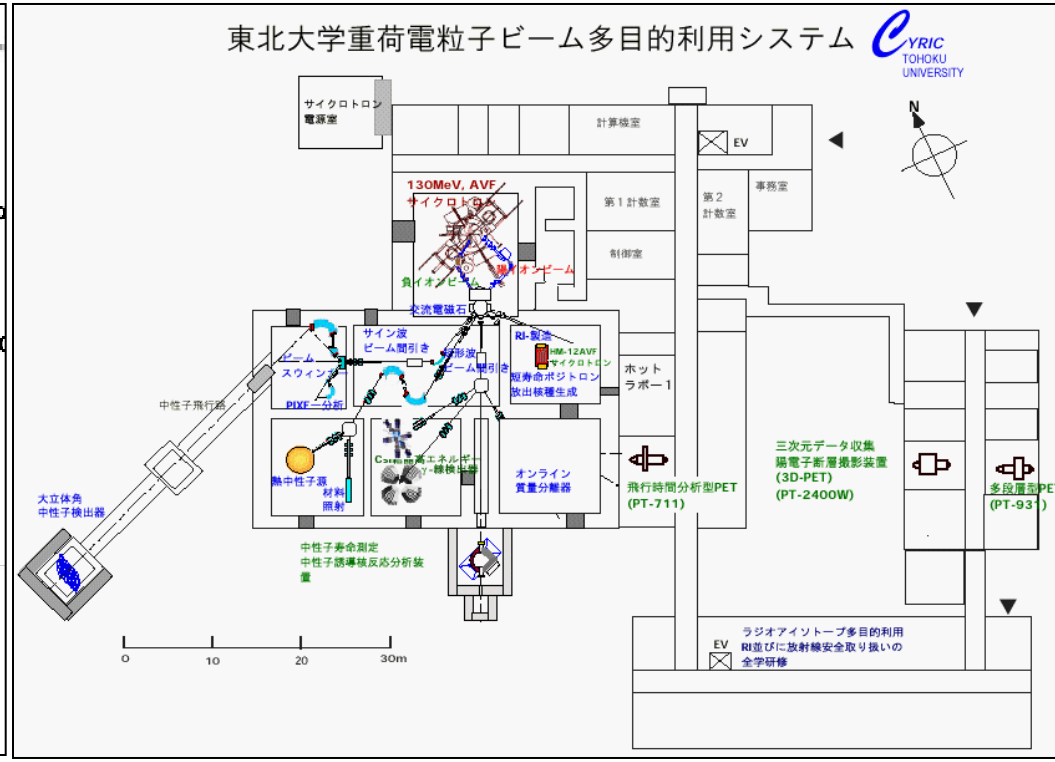
Targets & Monitor samples



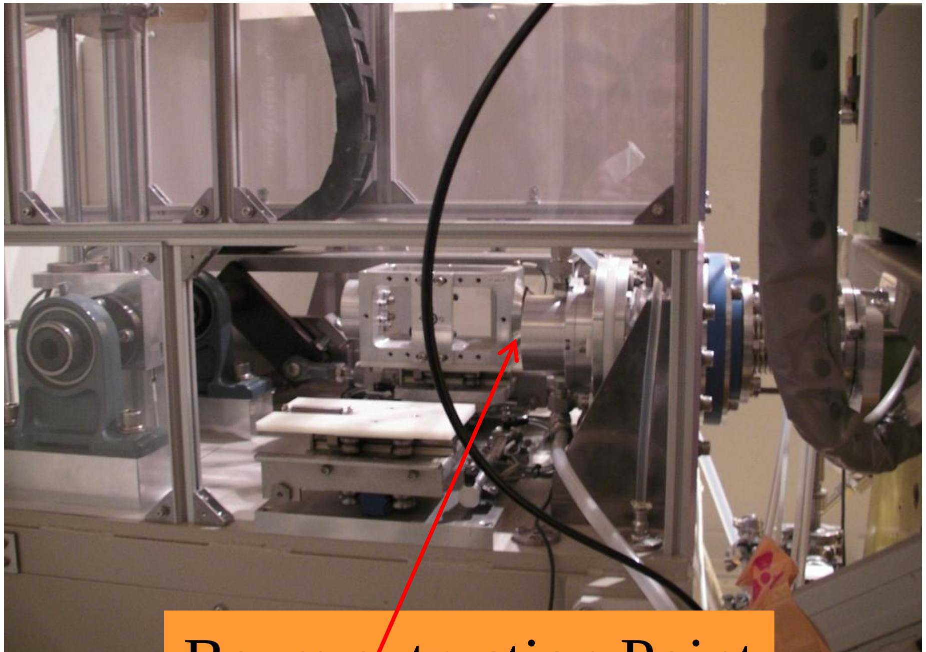
Collimator & Sample Holder

AVF Cyclotron in CYRIC





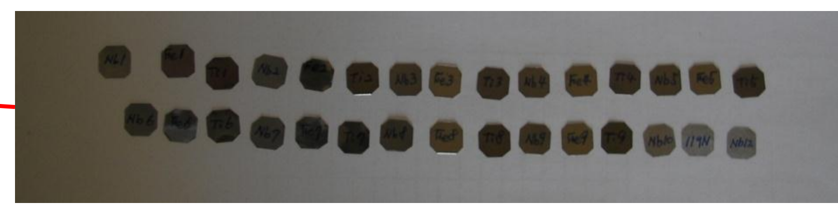
Deuteron Beam Energy	maximum	This work
	65 MeV	40 MeV
Current	50μA	100nA



Beam extraction Point

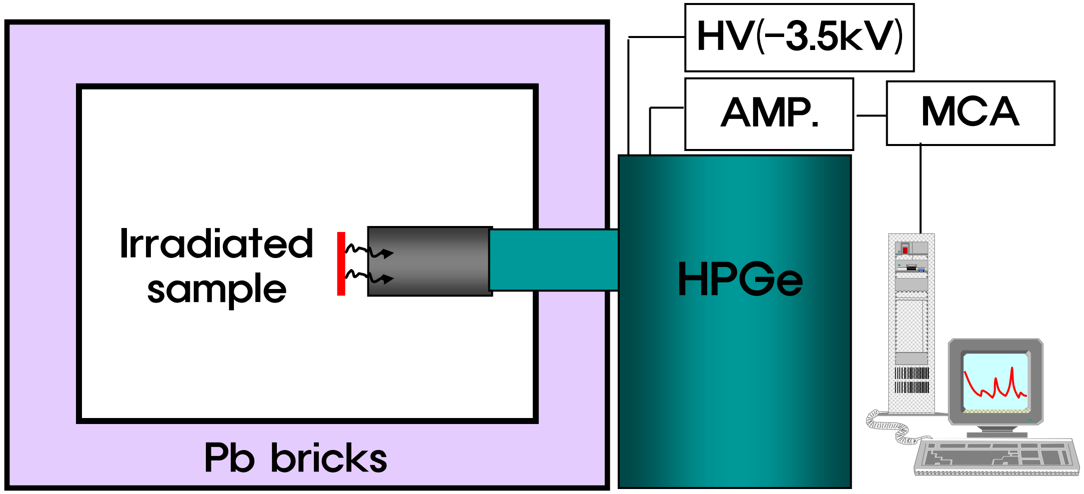
Control Room

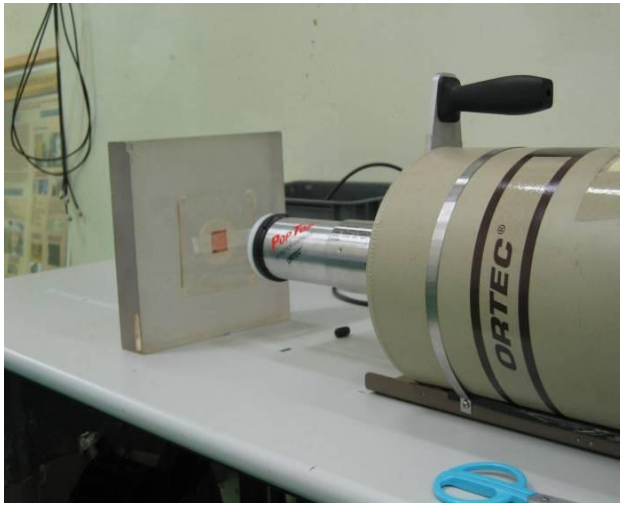
Sample Holder



Targets & Monitor samples

The 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

Calculations of Produced Activity

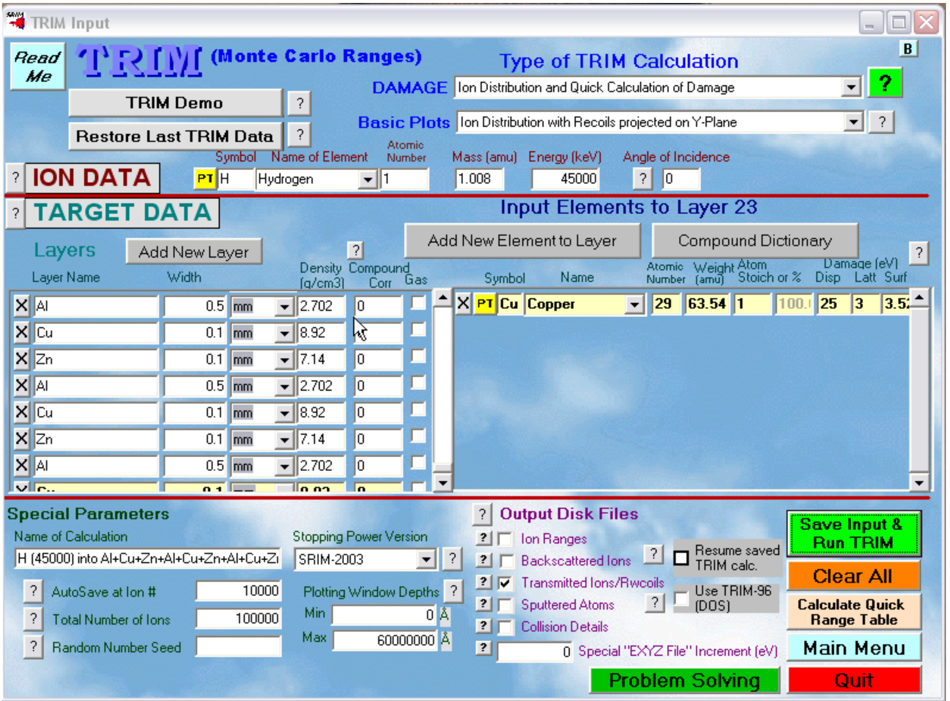
$$A = 6.24\times10^{18} \times I \times (t/z) \times N \times \sigma\,(1-e^{-\lambda t_{irr}})$$

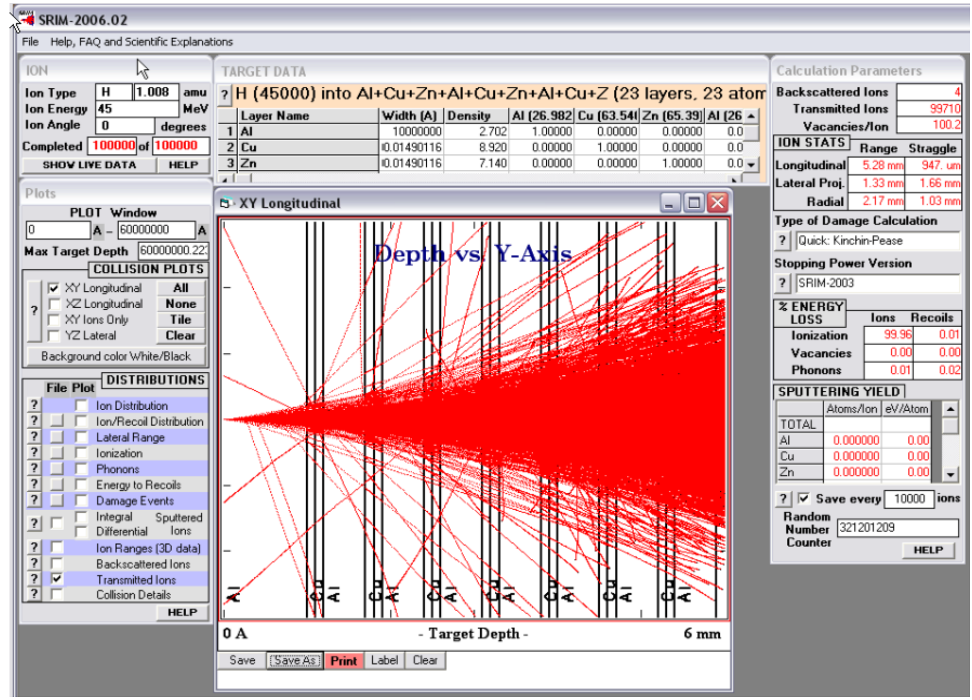
A = Absolute activity of isotope ^{A+1}Z in sample
N = Number of atoms of target isotope ^{A}Z in sample
σ = Capture cross section (cm^2) for target isotope ^{A}Z
λ = Radioactive decay constant (s^{-1}) for isotope ^{A+1}Z
t_{irr} = Irradiation time (s)
I = Beam current (Amp)
t = Thickness of the sample (cm)
z = Charge number of the bombarding particle

After a delay of time t_d ; $A = 6.24\times10^{18} \times I \times (t/z) \times N \times \sigma\,(1-e^{-\lambda t_{irr}})\,\exp(-\lambda t_d)$

For a counting time of t_c ; $A = 6.24\times10^{18} \times I \times (t/z) \times N \times \sigma\,(1-e^{-\lambda t_{irr}})\,\exp(-\lambda t_d)\,[1-\exp(-\lambda t_c)]$

Calculation of proton beam energy degradation



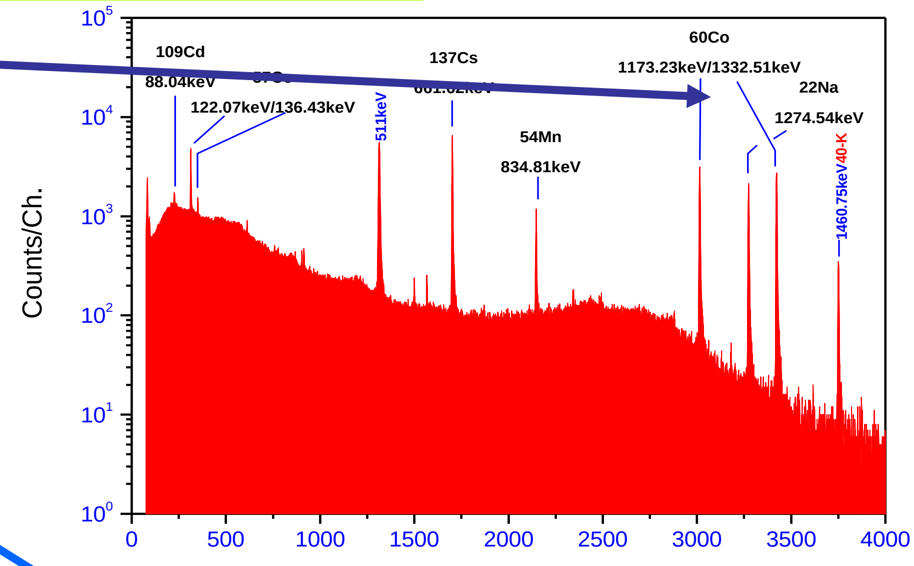


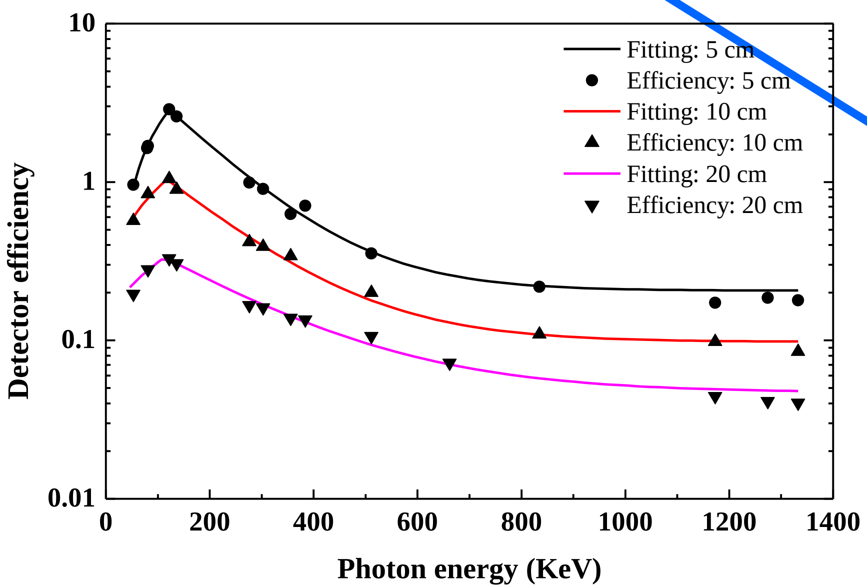
http://www.srim.org

- SRIM(The Stopping and Range of Ions in Matter) : Monte Carlo Transport Calculation
- Calculate the stopping and range of ions

Determination of efficiencies of HPGe detector

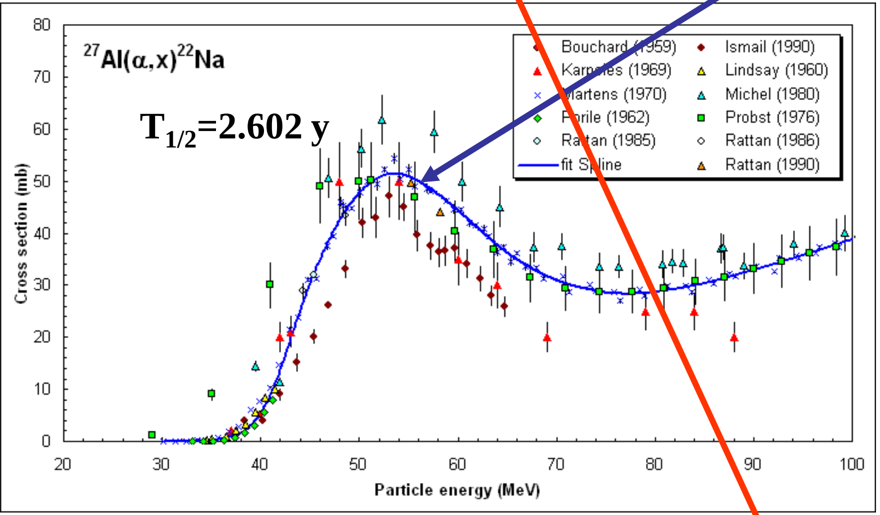
$$\varepsilon = \frac{CPS}{A_0 e^{-\lambda t} \times I_\gamma}$$



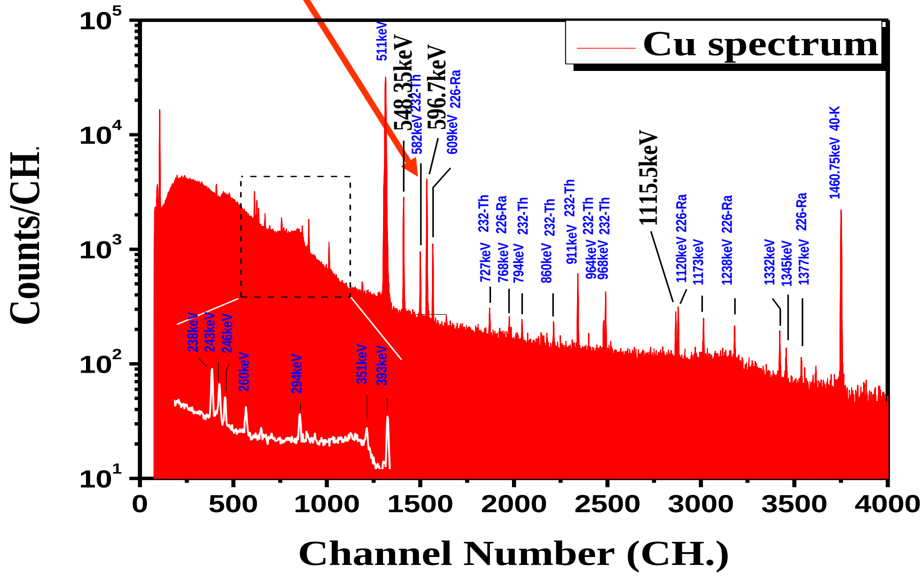


Determination of beam flux

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



http://www-nds.iaea.org/medical/monitor_reactions.html



Nuclide	Half-life	E_γ(keV)	I_γ(%)	Reaction	Q-value(MeV)	Threshold(MeV)
^{22}Na	2.6019 y	1274.53	99.944	^{27}Al(a,2an)	-22.510	25.849
^{24}Na	14.659 h	1368.598	100	^{27}Al(a,an2p)	-31.427	36.089

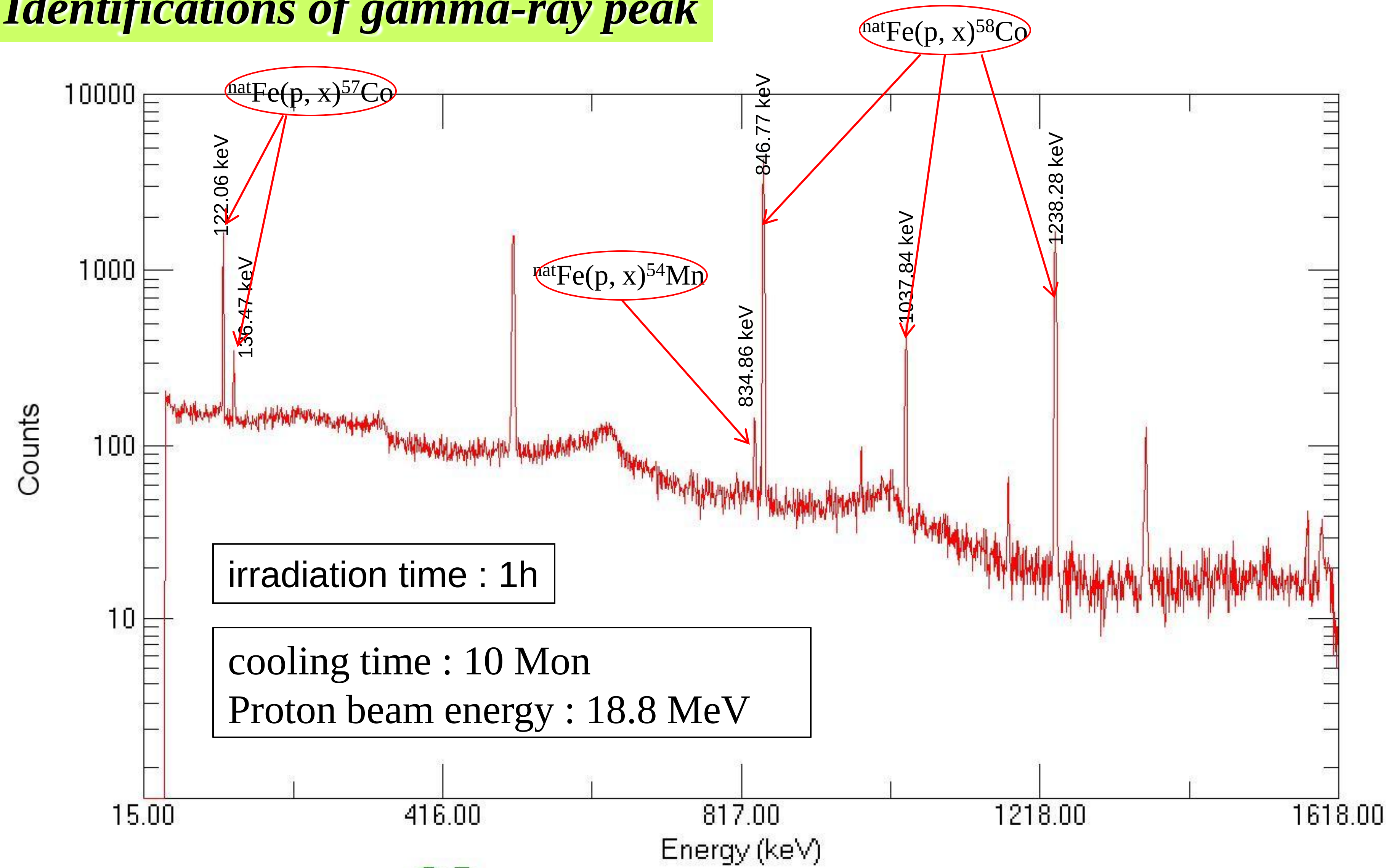
Decay data for the produced radionuclides

Nuclide	Half-life	Decay mode	E_γ(keV)	I_γ(%)	Contributing reaction	Q-value (MeV)	E_{th} (MeV)
^{51}Cr	27.7 d	EC	**320.1**	10.0	^{56}Fe(p, ^{6}Li)^{51}Cr	-15.59	16.24
				75	^{54}Fe(p, α2p)^{51}Cr	-27.45	28.00
^{55}Co	17.54 h	EC	**477**	20.0	^{54}Fe(p, γ)^{55}Co	5.06	0.00
			931.3	75	^{56}Fe(p, 2n) ^{55}Co	-15.43	15.71
			1408.4	16.88	^{57}Fe(p, 3n) ^{55}Co	-23.08	23.49
					^{58}Fe(p, 4n) ^{55}Co	-33.12	33.70
^{56}Co	77.3 d	EC	**846.7**	99.99	^{56}Fe(p, n)^{56}Co	-5.35	5.44
			1037.8	14.13	^{57}Fe(p, 2n) ^{56}Co	-12.99	13.22
			1238.3	66.1	^{58}Fe(p, 3n) ^{56}Co	-23.04	23.44
^{57}Co	271 d	EC	**122.13**	85.6	^{56}Fe(p, γ)^{57}Co	6.03	0.00
			136.4	10.68			
^{52}Mn	5.59 d	EC	**744.23**	90	^{54}Fe(p, 2pn)^{52}Mn	-20.91	21.30
			935.54	94.5	^{56}Fe(p, αn) ^{52}Mn	-13.11	13.34
			1434.09	100	^{57}Fe(p, α2n)) ^{52}Mn	-20.75	21.12
					^{58}Fe(p, α3n) ^{52}Mn	-30.80	31.33
^{54}Mn	312.3 d	EC	**834.85**	99.98	^{57}Fe(p, α)^{54}Mn	-1.1	1.1

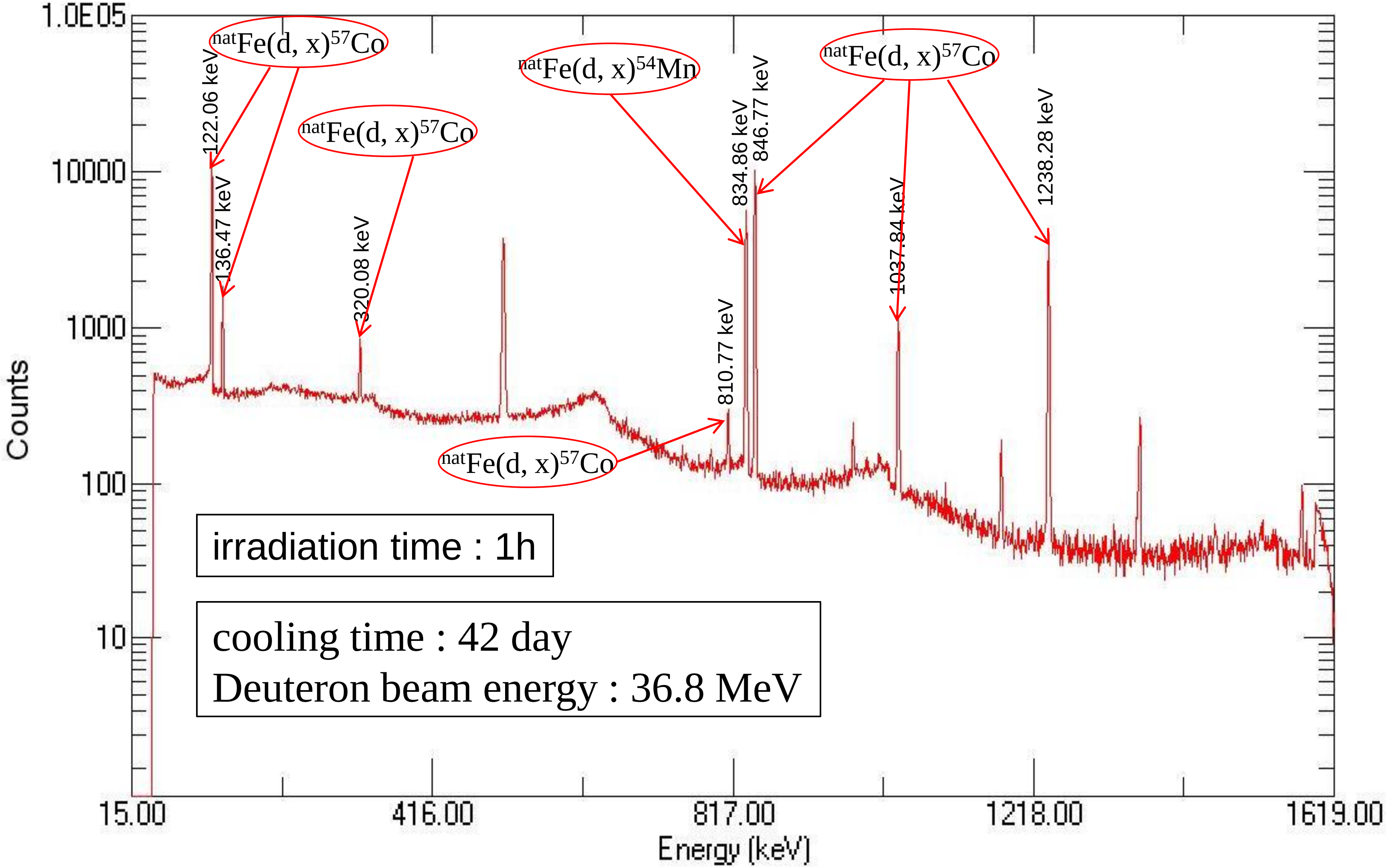
Nuclide	Half-life	E_γ(keV)	I_γ(%)	Contributing reaction	Q-value (MeV)	E_{th} (MeV)
^{51}Cr	27.70 d	**320.082**	10	^{56}Fe(d,αt)^{51}Cr	-13.395	13.877
				^{54}Fe(d,αp)^{51}Cr	-1.381	1.433
^{52}Mn	5.591 d	**744.233**	90.0	^{57}Fe(d,α3n)^{52}Mn	-22.977	23.790
		935.538	94.5	^{56}Fe(d,α2n)^{52}Mn	-15.331	15.883
				^{54}Fe(d,α)^{52}Mn	5.163	0.0
^{54}Mn	312.3 d	**834.848**	99.976	^{57}Fe(d,αn)^{54}Mn	-1.985	2.055
				^{56}Fe(d,α)^{54}Mn	5.660	0.0
				^{54}Fe(d,2p)^{54}Mn	-2.139	2.219
^{55}Co	17.53 h	**477.2**	20.2	^{56}Fe(d,3n)^{55}Co	-17.656	18.291
		931.3	75	^{54}Fe(d,n)^{55}Co	2.839	0.0
		1408.4				
^{56}Co	77.27 d	**846.771**	100	^{57}Fe(d,3n)^{56}Co	-15.219	15.757
		1037.840	13.99	^{56}Fe(d,2n)^{56}Co	-7.572	7.845
^{57}Co	271.79 d	**122.06**	85.60	^{57}Fe(d,2n)^{57}Co	-3.842	3.978
		136.47	10.68	^{56}Fe(d,n)^{57}Co	3.803	0.0
^{58}Co	70.86 d	**810.775**	99	^{57}Fe(d,n)^{58}Co	4.730	0.0
				^{56}Fe(d,γ)^{58}Co	12.376	0.0

Nuclide	Half-life	E_γ(keV)	I_γ(%)	Reaction	Q-value(MeV)	Threshold(MeV)
^{56}Mn	2.5785h	**846.771**	98.9	^{56}Fe(a,n3p)	-31.208	33.442
		1810.772	27.2	^{57}Fe(a,2n3p)	-38.855	41.586
^{55}Co	17.53h	477.2	20.2	^{54}Fe(a,2np)	-23.231	24.955
		931.3	75	^{56}Fe(a,4np)	-43.727	46.856
		1316.4	7.09	^{55}Ni decay		
		14.08.4	16.88			
^{56}Co	77.27d	**846.771**	100	^{54}Fe(a,np)	-13.148	14.124
		1037.84	13.9	^{56}Fe(a,3np)	-33.644	36.051
		1238.282	67.6	^{57}Fe(a,4np)	-41.290	44.192
		1771.351	15.69	^{56}Ni decay		
^{57}Co	271.79d	**122.0614**	85.60	^{54}Fe(a,p)	-1.772	1.903
		136.4743	10.68	^{56}Fe(a,2np)	-22.267	23.861
				^{57}Fe(a,3np)	-29.913	32.016
				58Fe(a,4np)	-39.958	42.719
				^{57}Ni decay		
^{58}Co	70.86d	**810.775**	99.03	^{56}Fe(a,np)	-13.694	14.674
				^{57}Fe(a,2np)	-21.340	22.841
				^{58}Fe(a,3np)	-31.385	33.553
^{61}Co	1.650h	**67.85**	85	^{58}Fe(a,p)	-4.119	4.403
		908.631	3.6			
^{56}Ni	6.077d	**158.38**	98.8	^{54}Fe(a,2n)	-16.066	17.258
		269.350	36.5	^{56}Fe(a,4n)	-36.562	39.178
		480.44	36.5	^{57}Fe(a,5n)	-44.208	47.315
		749.95	49.5			
		811.85	86.0			
		1561.80	14.0			
^{57}Ni	36.60h	127.164	16.7	^{54}Fe(a,n)	-5.816	6.248
		1377.63	81.7	^{56}Fe(a,3n)	-26.312	28.195
		1757.55	5.75	^{57}Fe(a,4n)	-33.958	36.345
				^{58}Fe(a,5n)	-44.003	47.043

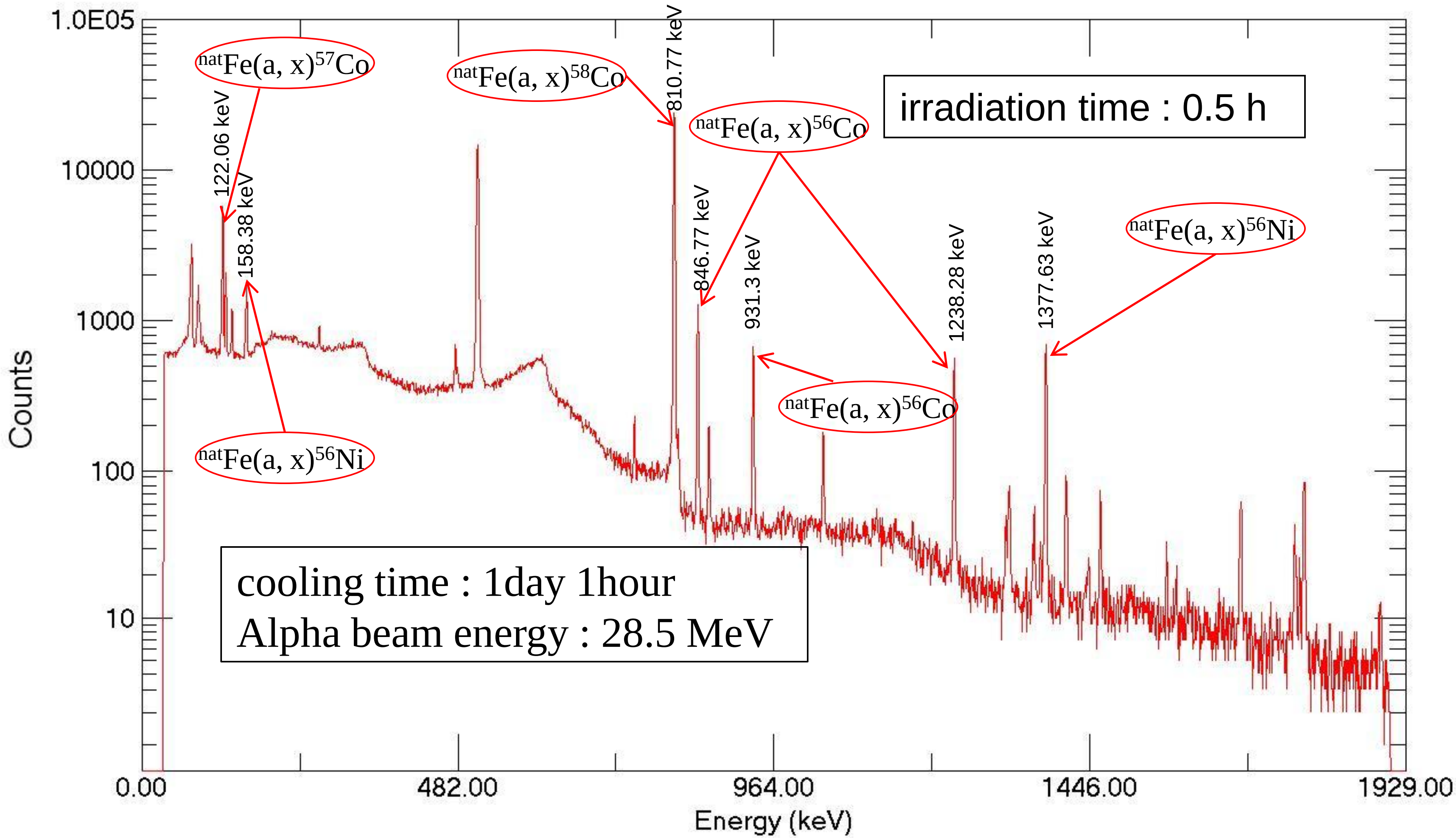
Identifications of gamma-ray peak



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, $p/cm^2/sec$

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

Deduction of Integral Yield

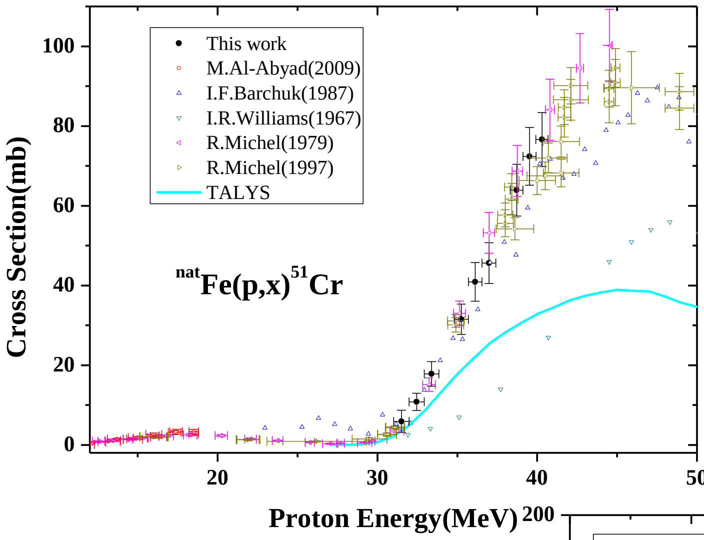
$$Y = I_p . N_d . \int_0^E \frac{\sigma(E)}{\left(dE/dx\right)_E} . dE \times \lambda$$

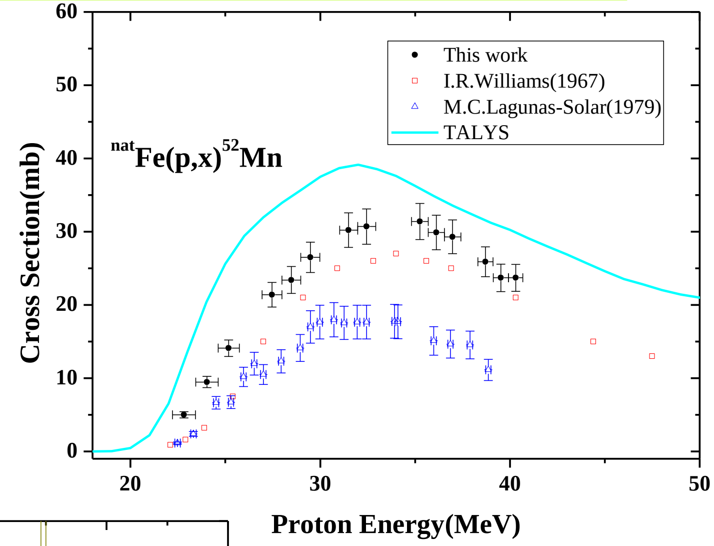
I_p = Proton flux (p/cm2-sec)
N_d = Number density (atoms/cm3)
$\sigma(E)$ = Cross-sections (cm2)
$(dE/dx)_E$ = Stopping power (MeV/cm)
$dE = E_{in} - E_{out}$: energy difference
λ = Decay constant

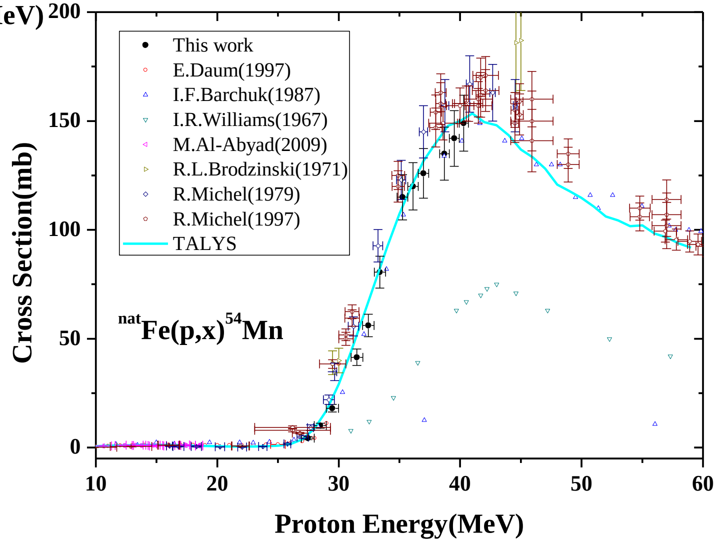
3. Results and discussion

http://www-nds.iaea.org/exfor/exfor.htm

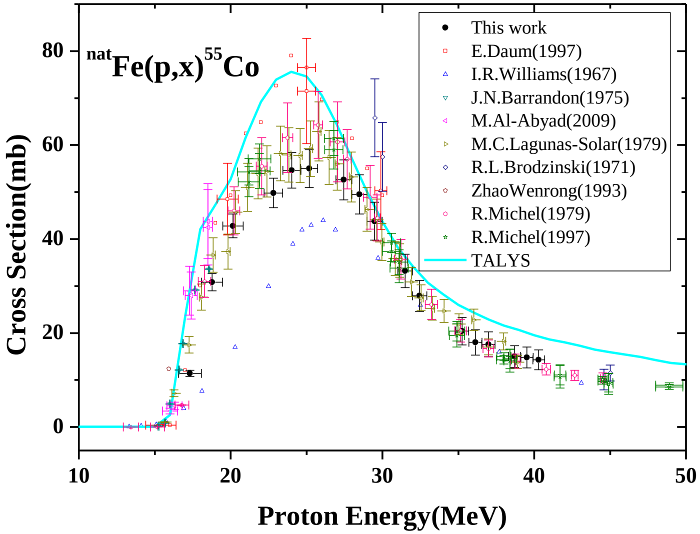
Excitation functions of the measured radionuclides(Proton)

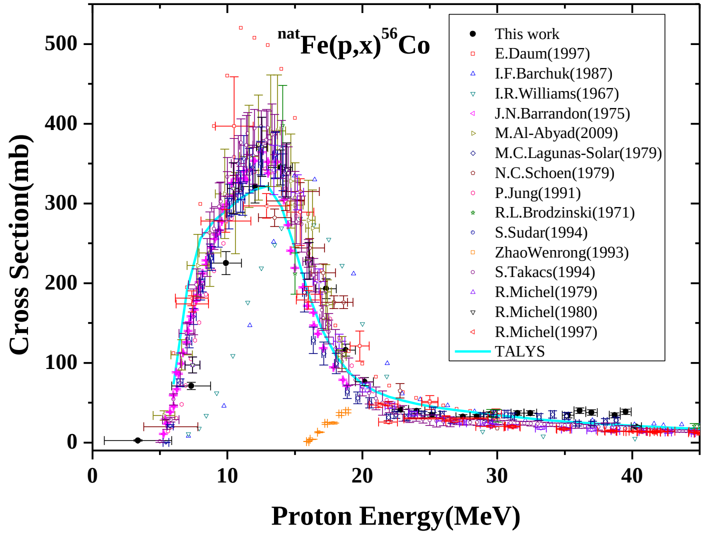


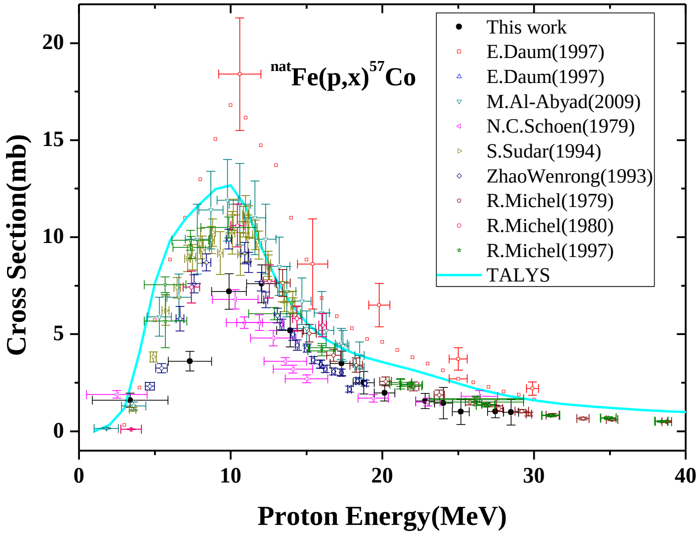




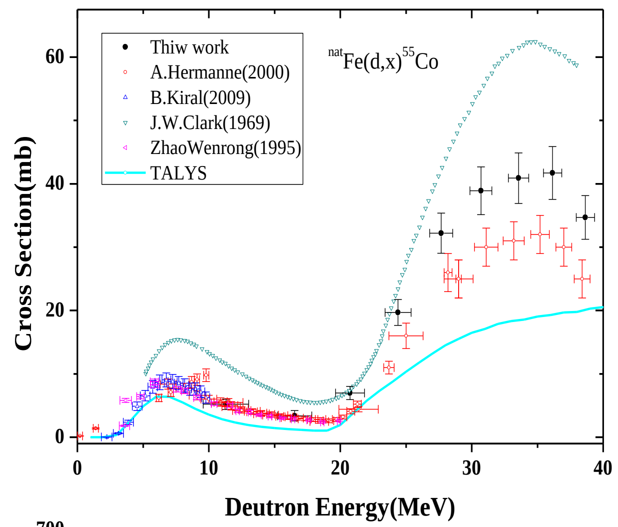
Excitation functions of the measured radionuclides(Proton)

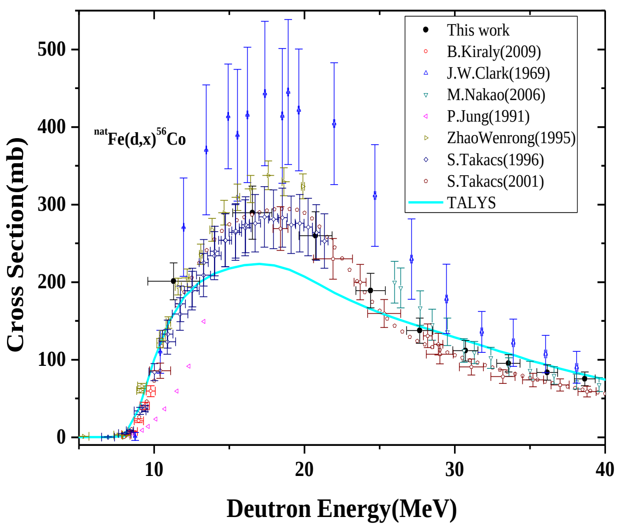


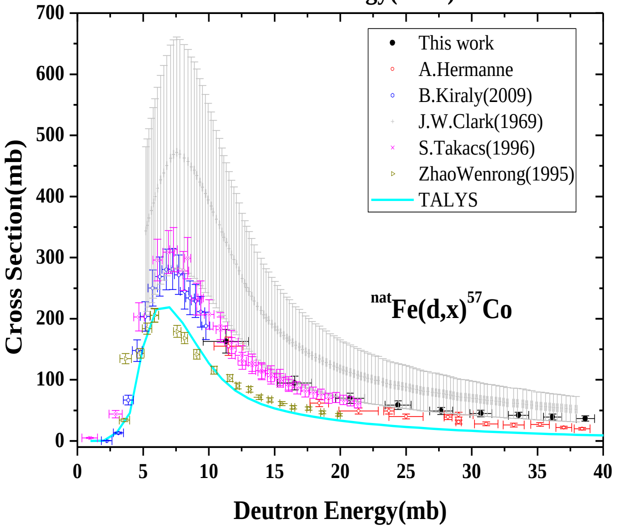


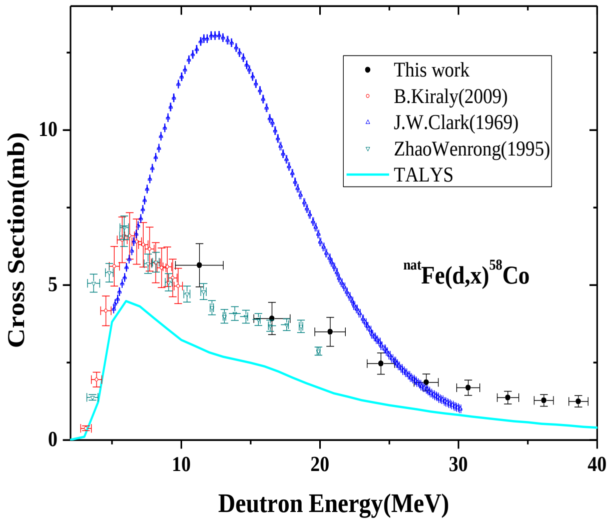


Excitation functions of the measured radionuclides(Deuteron)

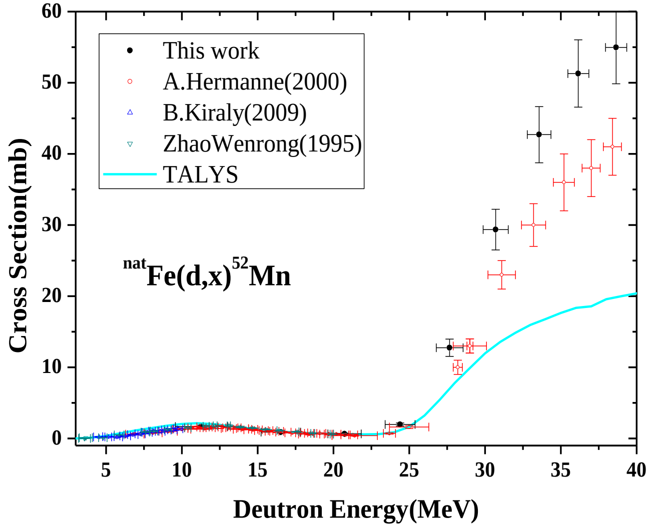


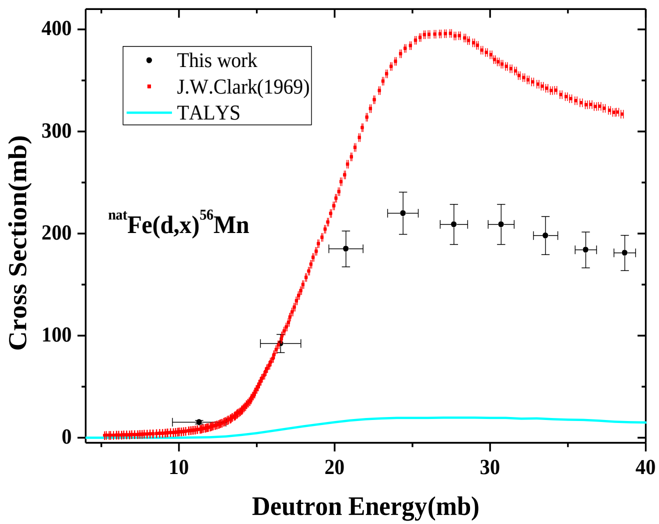


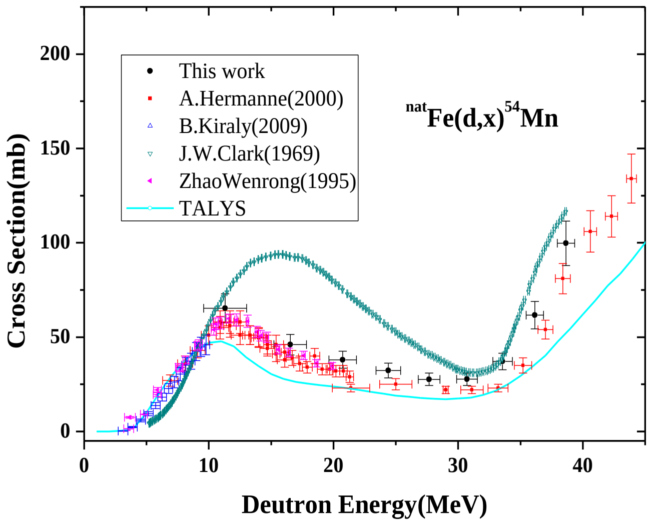


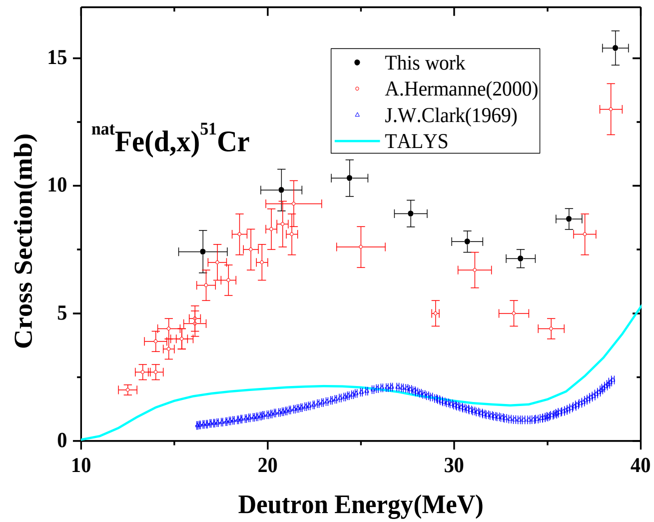


Excitation functions of the measured radionuclides(Deuteron)

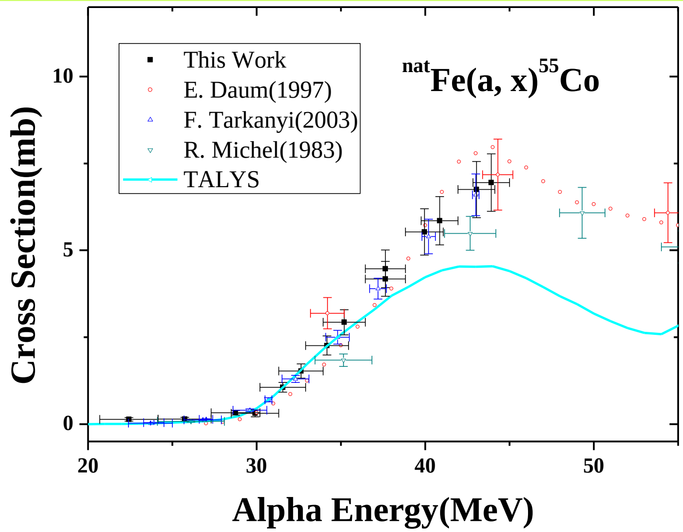


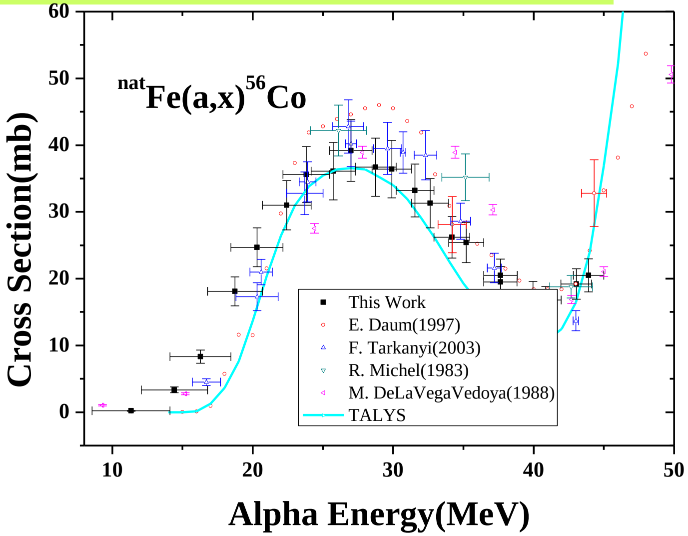


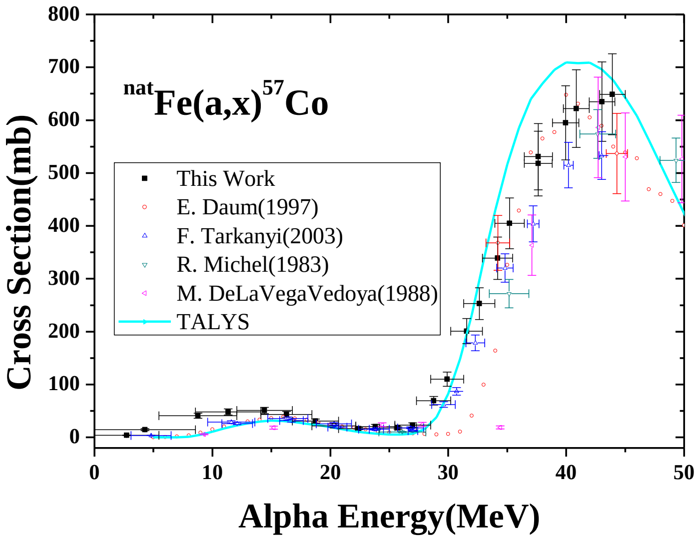


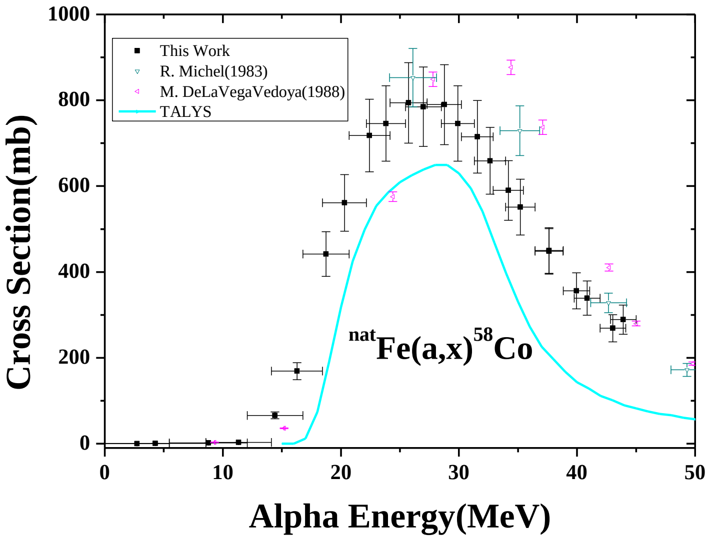


Excitation functions of the measured radionuclides(Alpha)

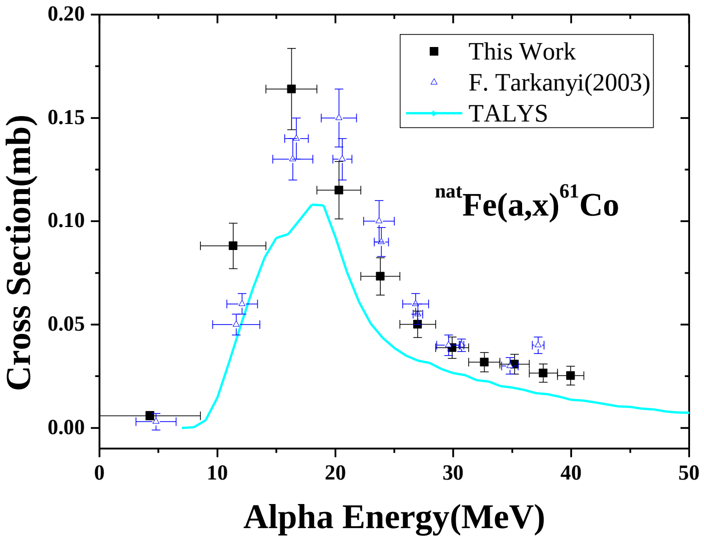


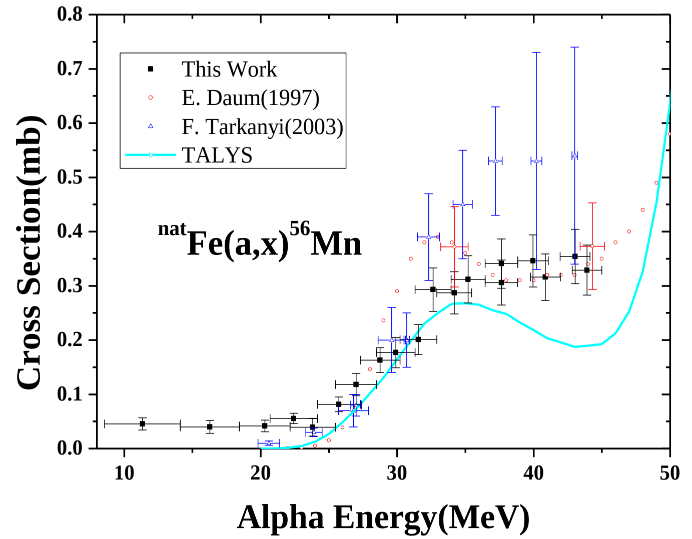


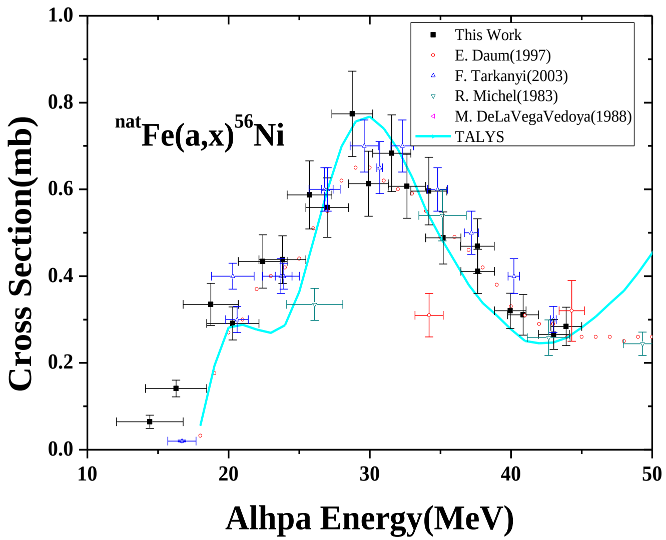


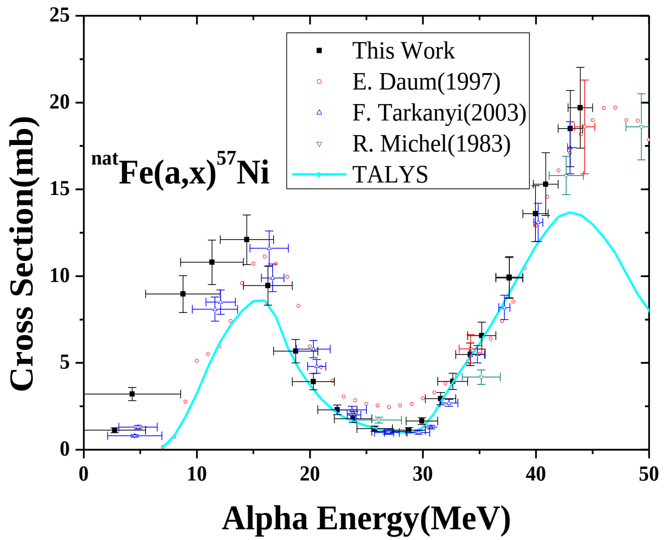


Excitation functions of the measured radionuclides(Alpha)

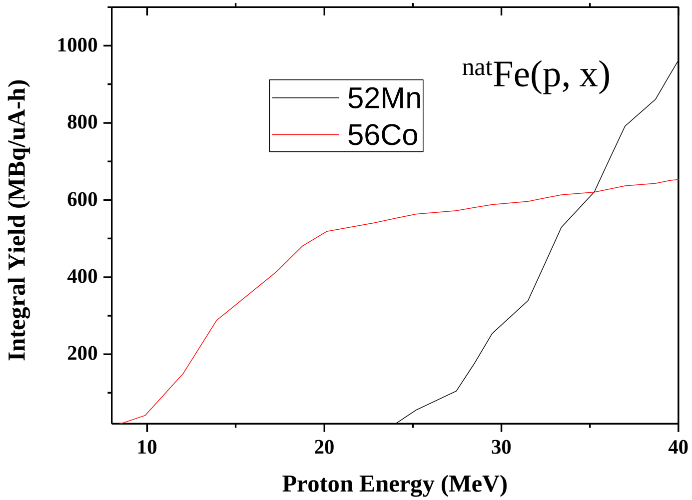


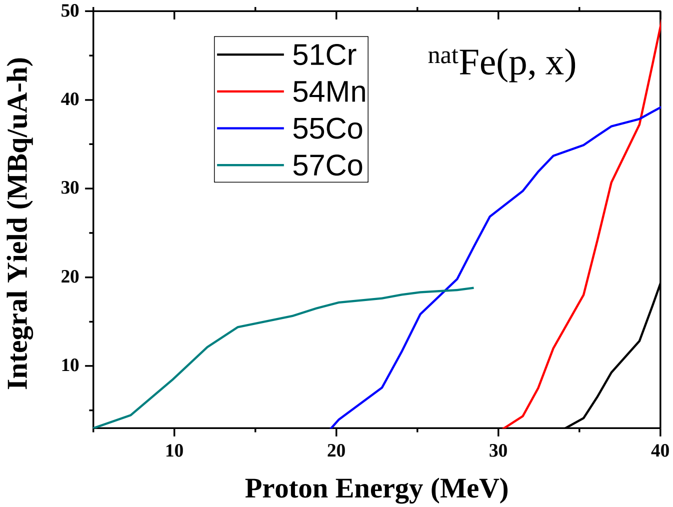






Deduction of Integral Yield





4. Conclusions

- We measured the production cross-sections of $^{52,54,56}Mn$, $^{55,56,57,58}Co$, and ^{51}Cr radionuclides from 11-38 MeV deuteron-induced reactions on natural iron at the AVF Cyclotron of the Cyclotron and Radioisotope Center, Tohoku University.

- In addition, We measured the production cross-sections of $^{52,54}Mn$, $^{55,56,57}Co$, and ^{51}Cr radionuclides from 8-40 MeV proton-induced reactions on natural iron and the production cross-sections of ^{56}Mn, $^{55,56,57,58,61}Co$, and $^{56,57}Ni$ radionuclides from 3-43 MeV alpha-induced reactions on natural iron at the MC50 cyclotron of the Korea Institute of Radiological and Medical Sciences.

- The results are compared with the available literature values as well as the theoretical data calculated by the TALYS codes.

- The thick target integral yields were also deduced using the measured cross-sections of the produced radionuclides.

The end

Thank you

감사합니다

ありがとうございます