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KAERI Charged Particle Cross Section Library for Radioisotope Production

한 국 원 자 력 연 구 소

제 출 문

한국원자력연구소장 귀하

본 보고서를 2001 년도 “원자력연구개발용 핵자료 구축평가” 과제의 기술 보고서로 제출합니다.

2001 년 11 월 일

핵 자 료 평 가 랩

연 구 자 : 이 영 욱
김 두 환
Yinlu HAN
You Xiang ZHUANG

요 약 문

본 보고서는 한국원자력연구소 핵자료평가랩에서 생산한 "의료용 동위원소 생산을 위한 하전입자 핵단면적 자료집" (KAERI Charged Particle Cross Section Library for Radioisotope production)을 기술한다. 본 자료집에는 양성자, 중양자, He-3, 및 알파입자의 모니터 핵반응과, 감마선원과 양전자선원을 생산하는 핵반응에 대한 평가핵자료를 수록하고 있다. 평가에 사용된 실험자료와 평가방법을 기술하였고 IAEA 등 타 기관에서 생산한 평가핵자료들과 비교하였다. 평가핵단면적은 동위원소 생산시설의 입자수송해석에 적합한 수송단면적의 형태인 ENDF-6형식으로 생산하였으며 인테넷 웹 상의 http://atom.kaeri.re.kr/ 에서 얻을 수 있다.

Summary

This report summarizes information and figures describing the "KAERI Charged Particle Cross Section Library for Radioisotope production". The library contains proton-, deutron-, He-3-, and alpha particle-induced monitor cross sections, and gamma- and positron-emitter production cross sections. Experimental data and evaluation methods are described, and the evaluated cross sections are compared with those of the IAEA, MENDL, and LA150. The library has cross sections and emission spectra suitable for the transport analysis in the design of radioisotope production system, and it is available at http://atom.kaeri.re.kr/ in ENDF-6 format.

CONTENTS

KAERI Charged Particle Cross Section Library for Radioisotope Production

Young-Ouk LEE[1] and Doohwan KIM
Nuclear Data Evaluation Lab., KAERI, P.O Box 105 Yusung, Taejon, Korea

Yinlu HAN and You Xiang ZHUANG
Chinese Institute of Atomic Energy, 275(41), 102413, Beijing, P.R. China

1 Introduction

Medical radioisotopes are used for diagnostic and therapeutic purposes, as well as for metabolism and physiological function research in modern medicine. The excitation functions in charged particle nuclear reactions governing the medical radioisotope production are measured with the aid of either residual nucleus activity method or outgoing particle measurement method.

Recently, the IAEA(International Atomic Energy Agency) has published a report "Charged particle cross-section database for medical radioisotope production: diagnostic radioisotopes and monitor reactions" [1] which contains gamma- and positron-emitter poduction cross sections as well as proton, deutron, He-3, and alpha particle monitor reaction cross sections. The evaluation of the IAEA cross sections was performed mainly based on the analysis, selection, and fitting of experimental data, where the theoretical model calcuation was used as a guide rather than for full evaluation, using global input parameters.

In 1998, Nuclear Data evaluation Lab(NDEL) of Korea Atomic Energy Research Institute(KAERI) has started evaluation of charged particle nuclear reaction data for various applications such as radioisotope production, monitoring of light charged particle beams at cyclotron and accelerators, and surface analysis in industrial application. In the KAERI evaluation, theoretical model calculation is performed [2–13], along with the selection and fitting of the experimental data [14–20]. While the theoretical model calculation for the charged particle reaction has its weakness especially in the light target material, it has two distinct advantages over the data analysis: consistent estimation of minor reaction channels, and generation of transport cross sections (i.e. full energy-angle spectrum of

[1] E-mail : yolee@kaeri.re.kr

emitting particles). In the nuclear reaction for medical radioisotope production, the unwanted isotopes are parasitically produced by the accompanying reaction channels. The cross sections for these parasitic-productions should be evaluated for the exact estimates of the wanted productions. It is also worth noting that full information of transport cross sections of important reaction channels helps in the accurate design of target systems capable of giving ptimum yields.

This report summarizes evaluation results, via data analysis and model calculations, of charged particle cross-sections for medical radioisotope production at NDEL of KAERI. Chapter 2 describes data fitting and theoretical models applied in the evaluations. Chapters 3 - 8 present evaluated cross-sections and comparisons against those of IAEA, MENDL, and LA150, for proton, deuteron, He-3, alpha particle monitor reactions, and gamma and positron emitter production reactions.

2 Evaluation Methods

A typical procedure to produce the evaluated cross sections, as shown in Fig. 1 is as follows:

- Survey, analyses, and selection of reference measurements
- Applying appropriate fitting or theoretical models according to the reaction characteristics
- Selection or adjustment of the recommended model parameters to better produce the reference measurements
- Generation of the cross sections in the ENDF-6 format

The role of experimental data for the nuclear data evaluation is important; it guides modeling of nuclear reactions, but also validate the models and parameters. From this view point, it is desirable that the reference experimental data span over a certain number of nuclei, reactions and incident energies. For the reference data for the charged particle nuclear reactions, Primary journals and the EXFOR [21] database were surveyed and analyzed.

2.1 Method of Fitting

The spline fit method, adopted for data fitting in the evaluation in this work, uses the technque of piece wise approximation of experimental data by specifying important points

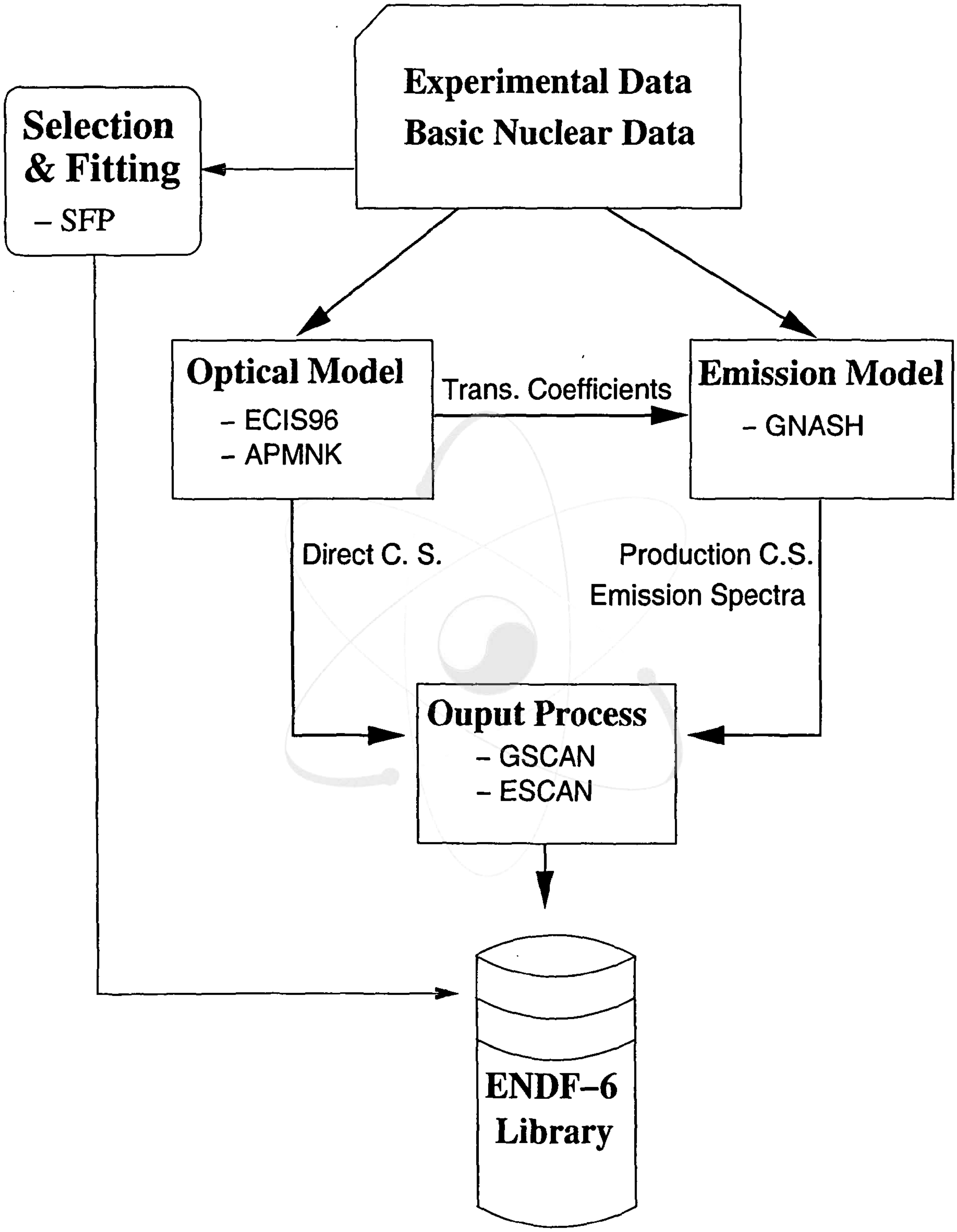


그림 1: Schematic Diagram of Evaluation of Charged Particle Nuclear Data

(termed knots of the spline), applying individual interpolation in each interval between two knots, and matching these interpolations so that the first and second derivatives are continuous at the knots. Interpolation functions are polynomials, usually of the 3rd order (cubic). By meaning the condition of continuous derivatives, one gets a continuous and smooth fit with minimum twisting (oscillating behavior) of the fitting curve. A particular feature of the spline method is that the fit in an interval is remarkably independent of data in other intervals. Evaluation of cross-sections by the spline fit was first descibed some 30 years ago. Since then, the description of the method become a part of many textbooks, and it was applied widely in nuclear data evalautions. The present descriptions is limited to basic ideas, followed by specific improvements worked out by the Chinese Nuclear Data Center (CNDC) and used in their SPF code [1, 20].

Consider a set of experimentl data

$$x_i, F_i, \sigma_i, \quad \text{with} \quad \mathrm{i} = 1, \ldots, \mathrm{N}, \tag{1}$$

Where F_i is the measured cross section with the uncertainty σ_i at the energy x_j. Knots, in general not identical with the experimental pints, are placed along the x-axis as judged to be needed,

$$x = \xi_1, \ldots, \xi_n, \tag{2}$$

the splice s(x) is constructed piece wise, for each interval as a polynomial

$$s(x) = \sum_{k=0}^{4} a_{jk} x^k \quad \text{where} \quad \xi_\mathrm{j} \leq \mathrm{x} \leq \xi_{\mathrm{j}+1} \tag{3}$$

with continuous derivatives at knots

$$s'(\xi_j), \quad s''(\xi_j) \quad \text{where} \quad \mathrm{j} = 1, \ldots, \mathrm{n} - 1, \tag{4}$$

and minimized using the least squares functional

$$\chi^2 = \sum_{i=1}^{N} (s(x_i) - F_i)^2 / \sigma_i^2 \tag{5}$$

Several methods have been previously adopted for the spline fitting, but some optimization problems remained to be solved:

- Knots have to be selected by a user, making the fit a time consumig procedure with somewhat arbitrary result.
- Cubic splines are not always adequate for complex shapes of curves.

- Calculated uncertainties of the fit value are not always representative.

The CNDC improved the spline fit method and developed the associated computer code SPF. Its basic advantage is generalization and statistically correct calculation of fit uncertainties. In particular, the code can handle discrepant sets of data, assuming that each set can be characterized by its overall weight. Input to the code, in addition to the experimental data (1), is a set of initial knots (2), along with the weight for each set of data. The code uses the iterative procedure, by first fitting the experimental data with the initial knots, then the knots are optimized and the data are fitted again, The reduced χ^2 value, differences between experimental data and fit values, and fit values, and add new knots are given as output at each iteration.

The code runs in an interactive mode.Selection of the base spline order, the number of iterations and fit results are controlled during the interactive process. In order to fit the curves with various shapes , splines with different order can be selected and used in the code. The SPF code is a part of the Nuclear Cross Section Evaluaion System of the CNDC Beijing, and one of the authors (Zhuang, Y.X.) used it during his stay in the NDEL of KAERI for the evaluation task.

2.2 Optical Model

The optical model provides the basis for theoretical evaluations of nuclear cross sections that are used in providing nuclear data for applications. In addition to offering a convenient means for calculations of reaction, shape elastic, and reaction cross sections, optical model potentials are widely used in quantum-mechanical preequilibrium and direct-reaction theory calculation. But the most important role of optical model analysis is to supply particle transmission coefficients for Hauser-Feshbach statistical theory analyses used in nuclear data evaluations.

The potential form factor was chosen to be of Woods-Saxon form for V_r and W_v, derivative Woods-Saxon for W_d and Thomas-Fermi form for spin-orbit parts as

$$\begin{aligned} U(r) &= -V_r f_v(r) - iW_v\ f_w(r) + 4i\ a_{wd}\ W_d\ \frac{df_{wd}(r)}{dr} \\ &\quad -\frac{1}{r}\left(\frac{\hbar}{m_\pi c}\right)^2 \left(V_{so}\frac{d}{dr}f_{vso}(r) + iW_{so}\frac{d}{dr}f_{wso}(r)\right)\ \boldsymbol{l}\cdot\boldsymbol{s}\ + V_{Coul}. \end{aligned} \tag{6}$$

where m_π is the mass of the pion and the form factors f_i are of the standard Woods-Saxon shape :

$$f_i(r) \equiv \frac{1}{1 + exp((r - r_i A^{1/3})/a_i)}, \quad i = v, w, wd, vso, wso \tag{7}$$

Usually, the potentials and form factors are functions of energy, and The best sets of optical model potentials are determined by adjusting coefficients defined in the functional forms. In this work, ECISPLOT [22, 23] and APMNK [13, 24] were applied to automatically search for the optimal optical potential parameters for protons and neutrons. Besides proton and neutron potentials, the following global potentials were employed in the evaluations for composite particles:

- Deuterons: Perey and Perey [25]

- Tritons: Becchetti and Greenlees [26]

- Alphas: Arthur and Young [27]

2.3 Equilibrium and Preequilibrium Emission

After the above steps have been completed, all model parameters are available for the decay processes including n, p, d, t and α particle emission. The latest version of the GNASH code [28] has been used to calculate nuclear reaction cross sections using the Hauser-Feshbach theory for equilibrium decay and the exciton model for preequilibrium decay. The Hauser-Feshbach theory with full angular momentum and parity conservation calculated the equilibrium emission [29]. The The exciton model was used to describe the processes of preequilibrium emission, and damping to equilibrium, during the evolution of the reaction. The file of discrete level information and ground-state masses, spin and parities were provided, the mass values were based upon an interim set from Wapstra obtained prior to the 1988 publication, and supplemented in the case of unmeasured masses with values from the Moller and Nix calculations.

The Ignatyuk [30] nuclear level densities are used, which include the washing-out of shell effects with increasing excitation energy, and are matched continuously onto low-lying experimental discrete levels. The Ignatyuk model for describing the statistical level density properties of excited nuclei is particularly appropriate for the relatively high energies studied in this work.

2.4 Compilation of Cross Sections

Evaluated cross sections are then compiled utilizing MF3-MT5 and MF6-MT5 combinations in the ENDF6 format which is suitable for a complete representation of the high energy reaction data. The total nonelastic cross section is tabulated in MF3-MT5, whereas the inclusive production cross sections (emission multiplicities) and emission spectra for neutron, proton, deuteron, triton, alpha particles, and all residual nuclides are tabulated by use of MF6-MT5. Descriptions of ENDF6 formats for the incident charged particle are summarized as follows:

ENDFB-6 format of the Charged Particle(z) Reaction Library

MF=3	MT= 2	integral of nuclear plus interference components of the elastic scattering cross section
	MT= 5	sum of binary (z,z') and (z,x) reactions
MF=6	MT= 2	elastic angular distributions given as ratios of the differential nuclear-plus-interference to the integrated value.
	MT= 5	production cross sections and energy-angle distributions for emission neutrons, protons, deuterons, and alphas; and angle-integrated spectra for gamma rays and residual nuclei that are stable against particle emission

3 Proton Beam Monitor Reactions

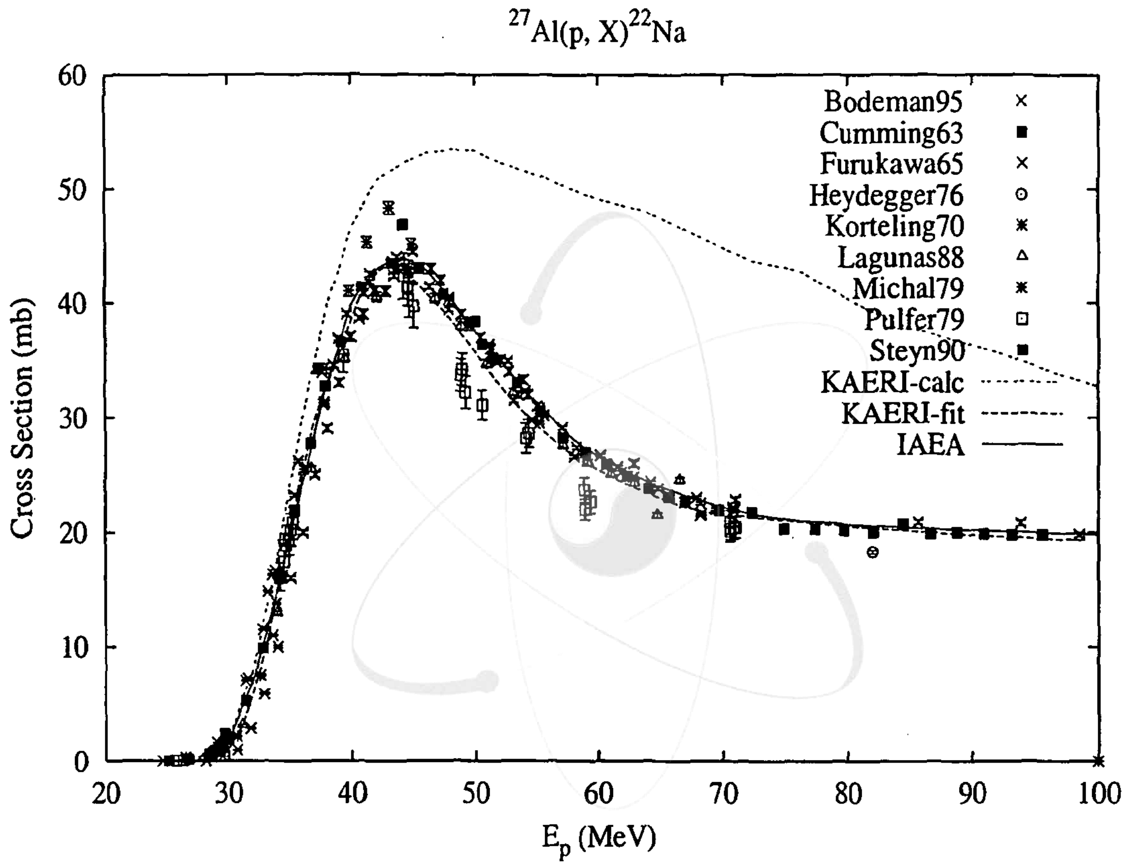
Table 1 lists 8 proton beam reactions evaluated, including the basic decay characteristics of roduct nuclei (half-lives, main γ-lines along with the intensities), and energy range of protons for which evaluations were performed.

表 1: Proton Beam Monitor Reactions

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{27}Al(p,X)^{22}Na$	2.60 a	1274.5	99.94	30-100
$^{27}Al(p,X)^{24}Na$	14.96 h	1368.6	100.0	30-100
		2754.0	99.94	
$^{nat}Ti(p,X)^{48}V$	15.98 d	983.5	99.99	5-30
		1312.0	97.49	
$^{nat}Ni(p,X)^{57}Ni$	1.50 d	1377.6	77.9	15-50
$^{nat}Cu(p,X)^{56}Co$	77.70 d	846.8	99.9	50-100
		1238.3	67.0	30-100
$^{nat}Cu(p,X)^{62}Zn$	9.26 h	596.7	25.7	14-60
$^{nat}Cu(p,X)^{63}Zn$	38.1 min	669.8	8.4	4.5-50
		962.2	6.6	
$^{nat}Cu(p,X)^{65}Zn$	244.10 d	1115.5	50.75	2.5-100

3.1 $^{27}Al(p,X)^{22}Na$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{27}Al(p,X)^{22}Na$	2.60 a	1274.5	99.94	30-100



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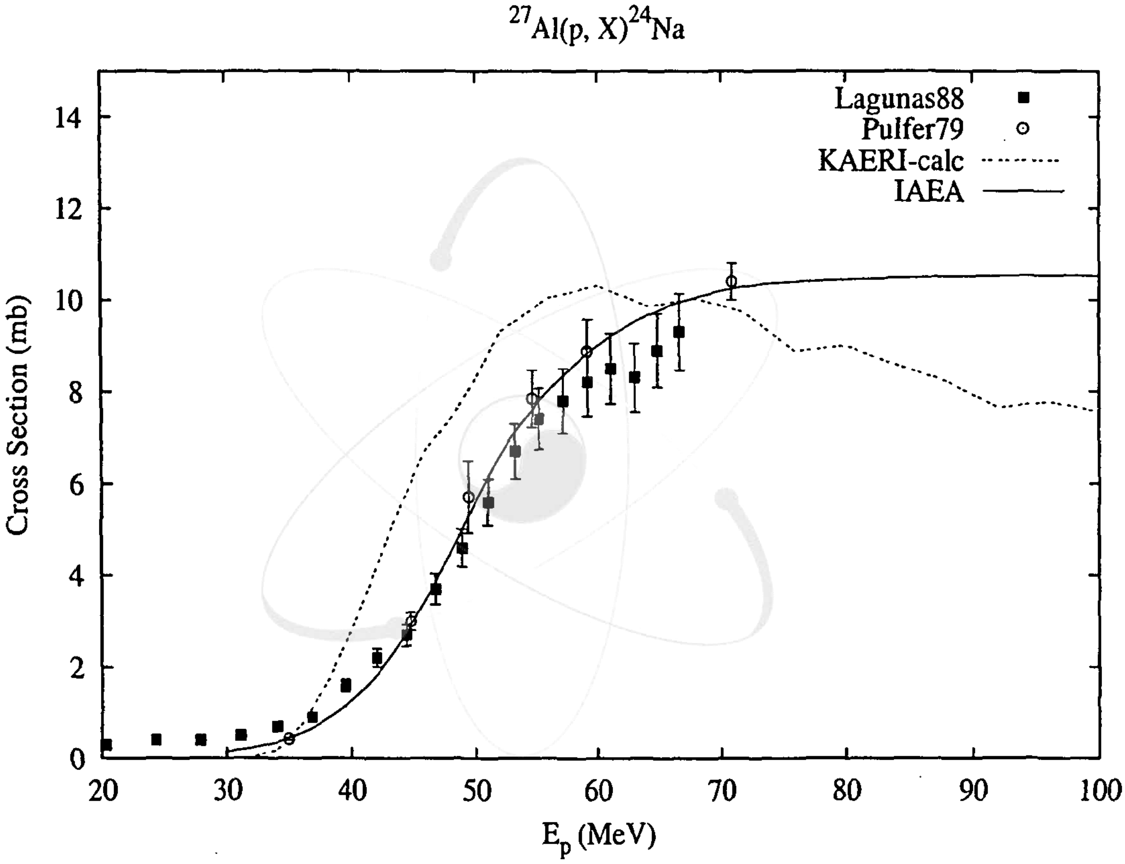
3.2 $^{27}Al(p,X)^{24}Na$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{27}Al(p,X)^{24}Na$	14.96 h	1368.6	100.0	30-100
		2754.0	99.94	



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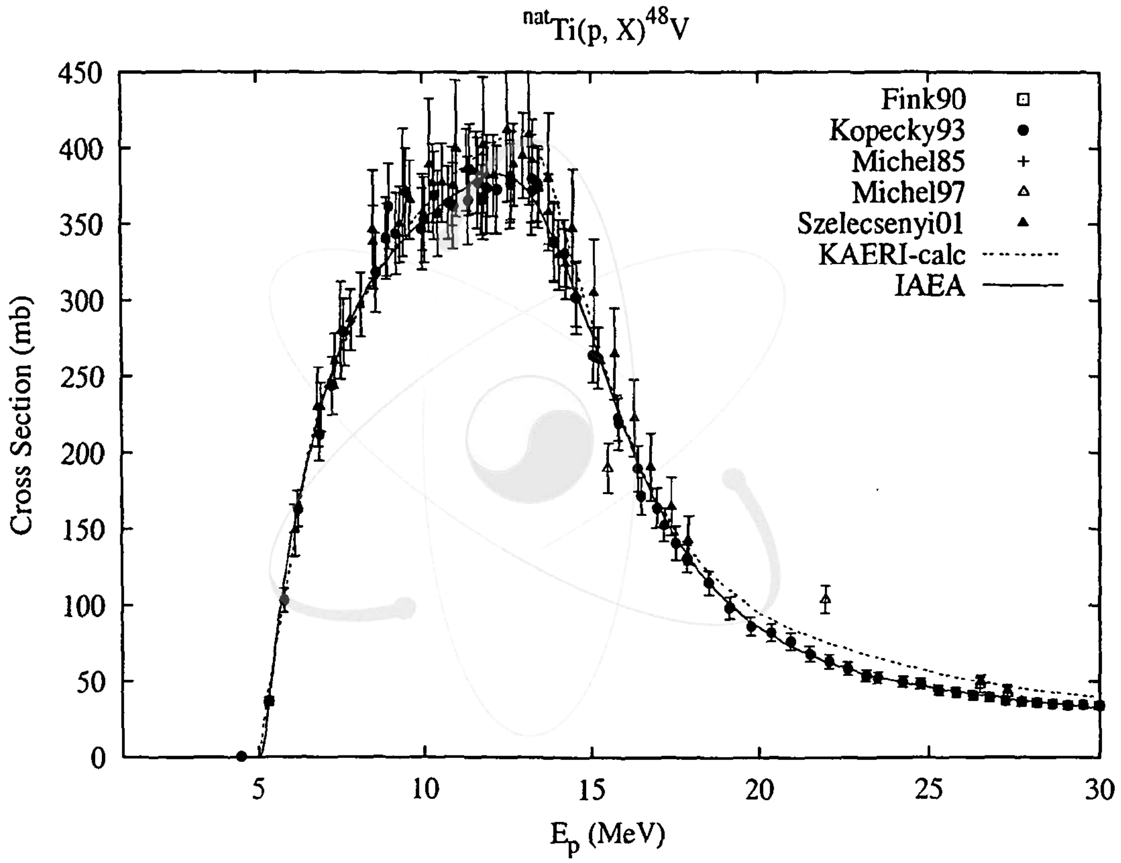
3.3 ^{nat}Ti(p,X)^{48}V

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{nat}Ti(p,X)^{48}V	15.98 d	983.5	99.99	5-30
		1312.0	97.49	



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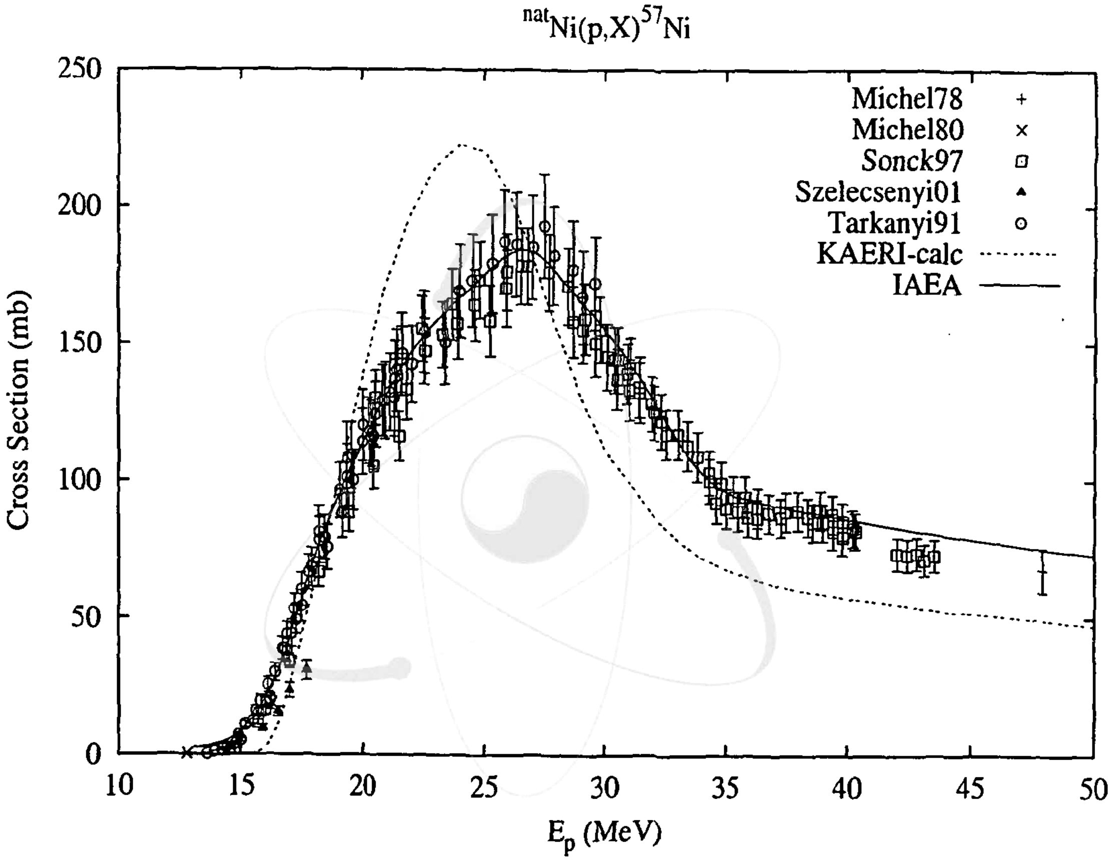
3.4 ^{nat}Ni(p,X)^{57}Ni

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{nat}Ni(p,X)^{57}Ni	1.50 d	1377.6	77.9	15-50



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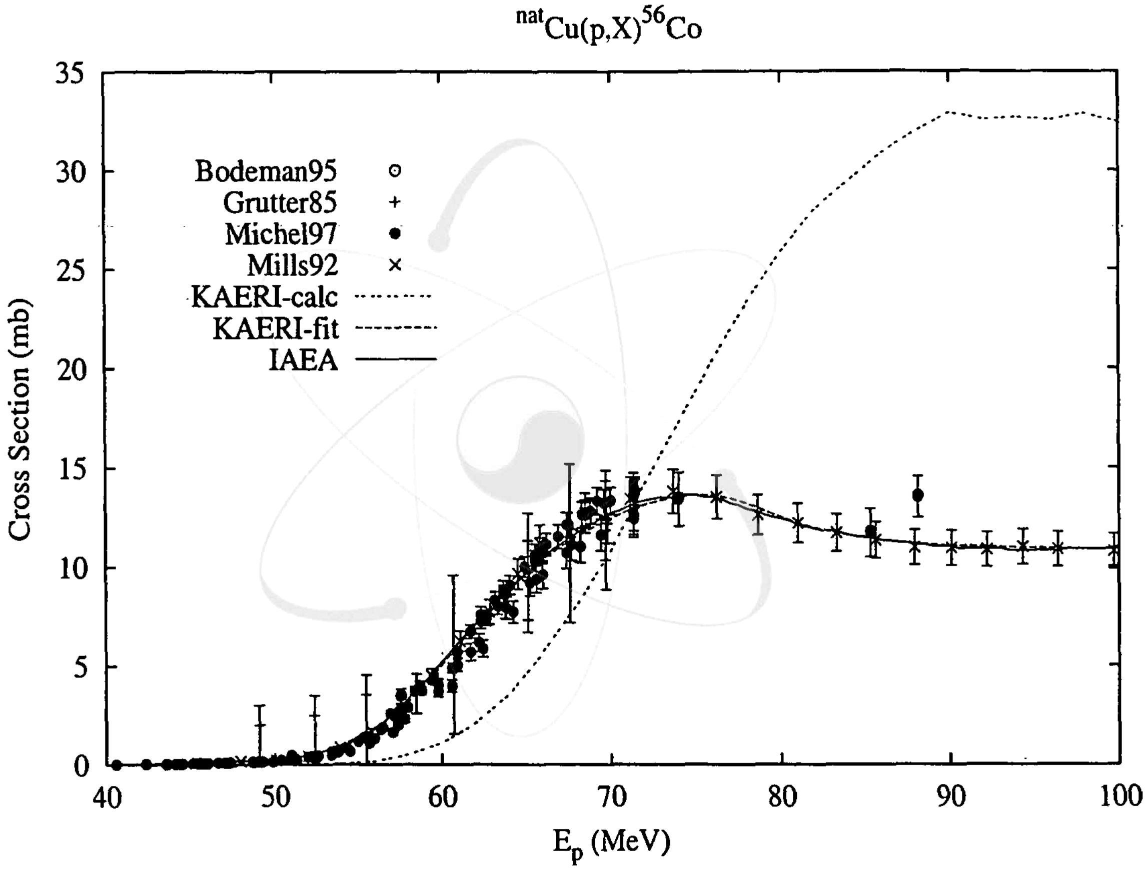
3.5 ^{nat}Cu(p,X)^{56}Co

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{nat}Cu(p,X)^{56}Co	77.70 d	846.8	99.9	50-100
		1238.3	67.0	30-100



Related documents:

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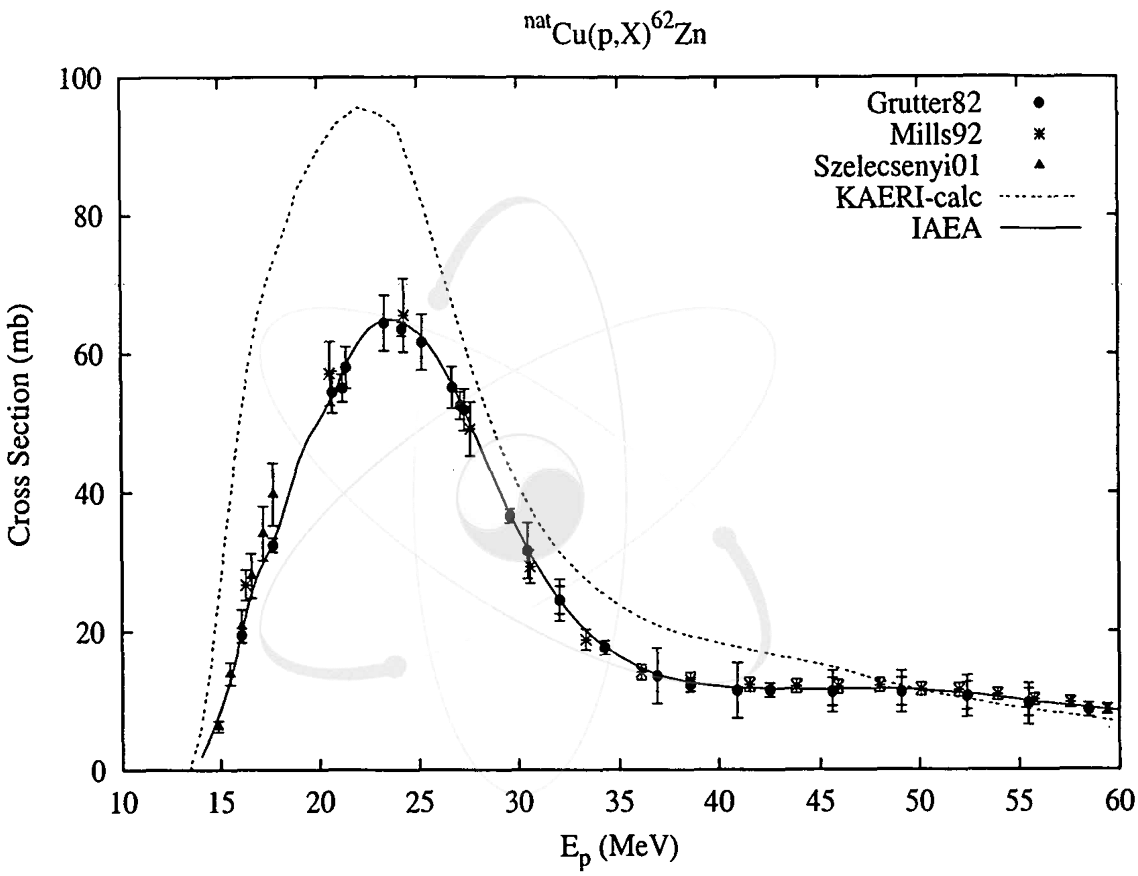
- Mills, S.J., Steyn, G.F., Nortier, F.M., Experimental and Theoretical Excitation Functions of Radionuclides Produced in the Proton Bombardment of Copper up to 200 MeV, Applied Radiation Isotopes 43 (1992) 1019 ; EXFOR A0507

3.6 $^{nat}Cu(p,X)^{62}Zn$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{nat}Cu(p,X)^{62}Zn$	9.26 h	596.7	25.7	14-60



Related documents:

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Experimental data:

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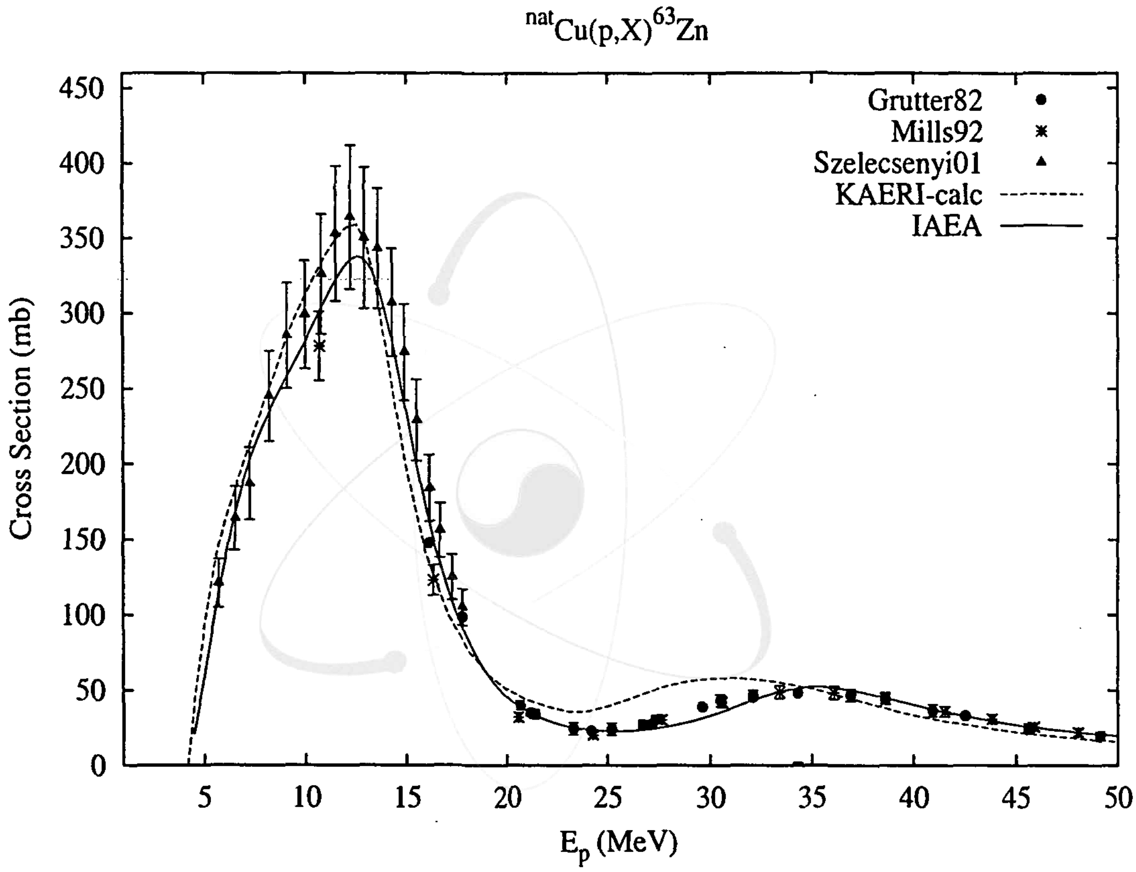
3.7 ^{nat}Cu(p,X)^{63}Zn

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{nat}Cu(p,X)^{63}Zn	38.1 min	669.8	8.4	4.5-50



Related documents:

- Kim, D., Evaluation of Proton Induced Reaction Data for Fe, Ni, Cu, and Zn isotopes up to 150 MeV at KAERI, Tech. Rep. NDL-03/01, KAERI, 2001.

Experimental data:

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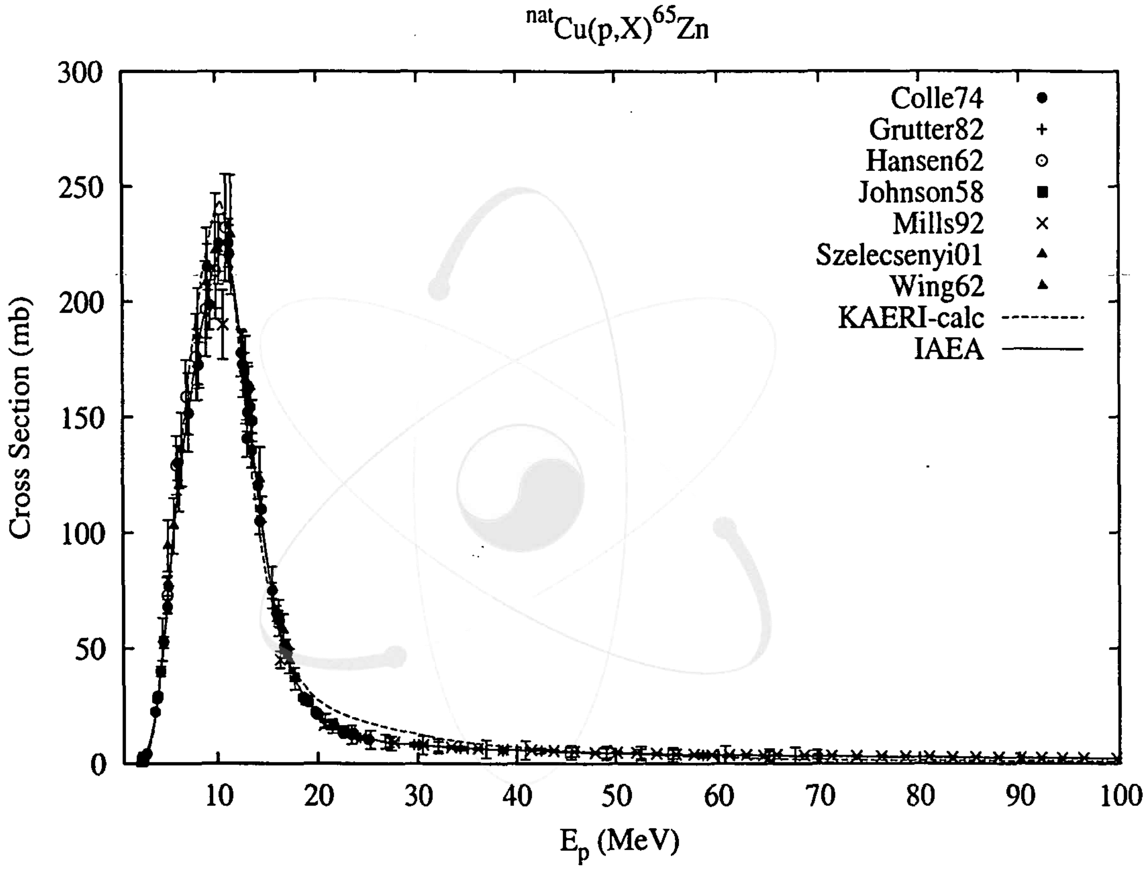
3.8 $^{nat}Cu(p,X)^{65}Zn$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines		Proton energy range (MeV)
		E_γ(keV)	I_γ (%)	
$^{nat}Cu(p,X)^{65}Zn$	244.10 d	1115.5	50.75	2.5-100



Related documents:

- Kim, D., Evaluation of Proton Induced Reaction Data for Fe, Ni, Cu, and Zn isotopes up to 150 MeV at KAERI, Tech. Rep. NDL-03/01, KAERI, 2001.

Experimental data:

- Barrandon, J.N., Debrum, J.L., Kohn, A., Spear, R.H., Etude du Dosage de Ti, V, Cr, Fe, Ni, Cu et Zn par Activation avec des Protons d'Energie Limitee a 20 MeV, Nuclear Intruments Methods 127 (1975) 269 ; EXFOR O0086

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4 Deuteron Beam Monitor Reactions

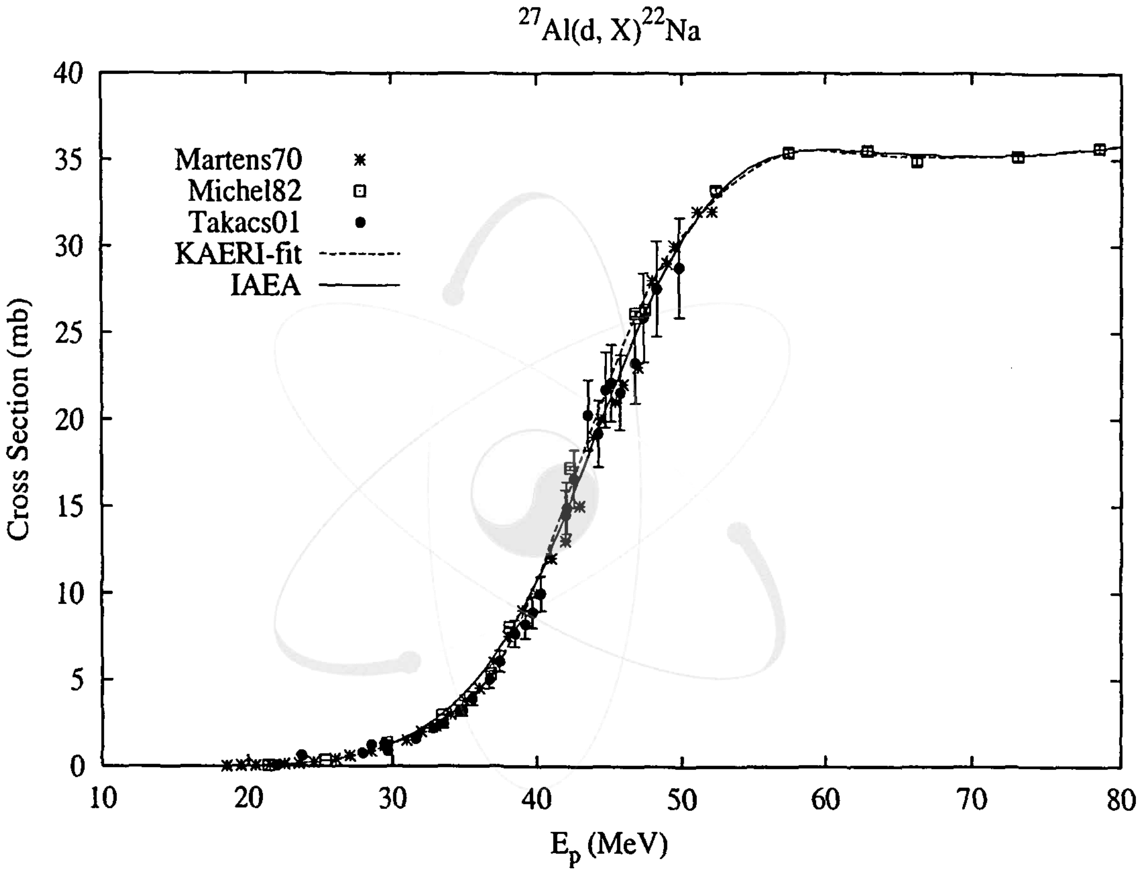
Table 2 lists 5 deuteron beam reactions evaluated, including the basic decay characteristics of roduct nuclei (half-lives, main γ-lines along with the intensities), and energy range of protons for which evaluations were performed.

表 2: Deuteron Beam Monitor Reactions

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Deuteron energy range (MeV)
$^{27}Al(d,X)^{22}Na$	2.60 a	1274.5	99.94	29.5-80
$^{27}Al(d,X)^{24}Na$	14.96 h	1368.6	100.0	15-80
		2754.0	99.94	
$^{nat}Ti(d,X)^{48}V$	15.98 d	983.5	99.99	9-50
		1312.0	97.49	
$^{nat}Fe(d,X)^{56}Co$	77.70 d	846.8	99.9	8-50
		1238.3	67.0	
$^{nat}Ni(d,X)^{61}Cu$	3.40 h	283.0	12.5	2.5-50
		656.0	10.66	

4.1 ^{27}Al(d,x)^{22}Na

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Deuteron energy range (MeV)
^{27}Al(d,X)^{22}Na	2.60 a	1274.5	99.94	29.5-80



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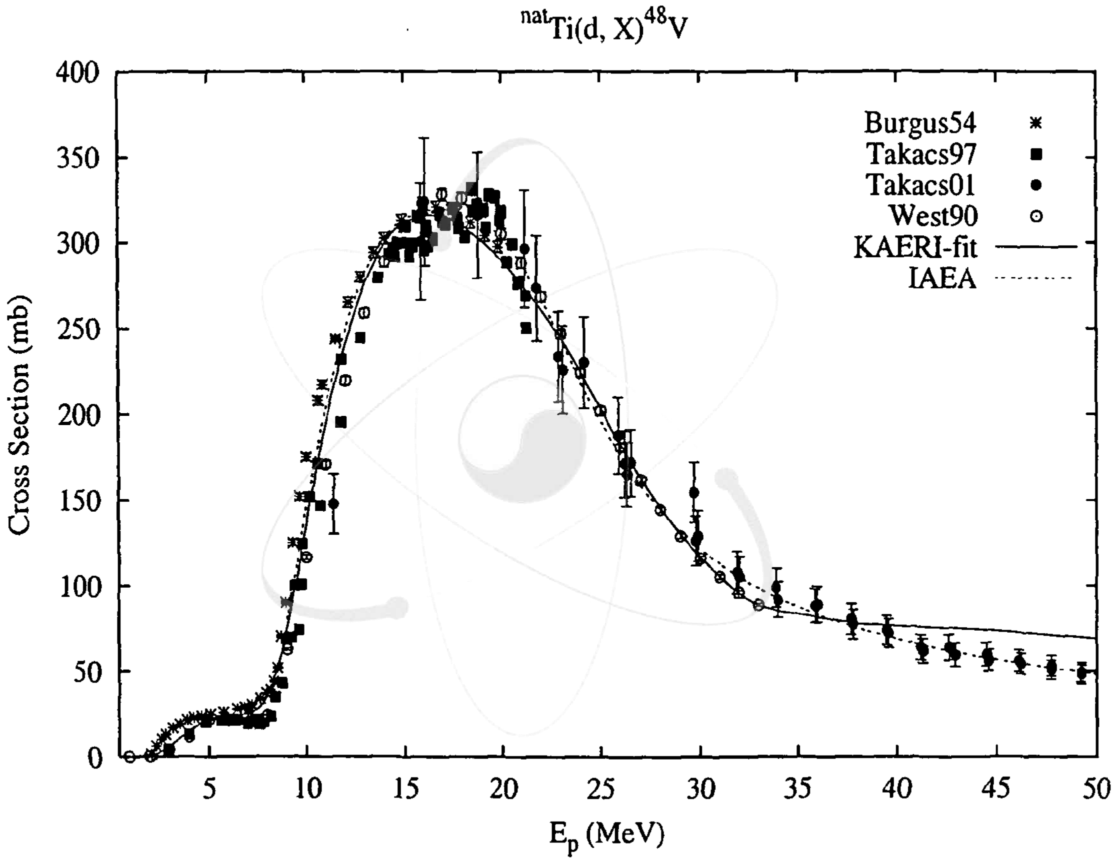
4.2 ^{nat}Ti(d,x)48V

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Deuteron energy range (MeV)
$^{nat}Ti(d,X)^{48}V$	15.98 d	983.5	99.99	9-50
		1312.0	97.49	



Related documents:

- Zhuang, Y.X., Evaluations and Calculations of N-14(d,n)O-15, Ne-nat(d,x)F-18, Ti-nat(d,x)V-48, Ti-nat(He-3,x)V-48, Ti-nat(a,x)Cr-51, Fe-nat(d,x)Co-56, Ni-nat(d,x) Cu-61, Zn-nat(p,xn)ga-66, Zn-nat(p,xn)Ga-67, Ga-69(p,2n)Ge-68, Cu-nat(He-3,x) Ga-66, Cu-nat(He-3,x)Ga-67 and I-127(p,5n)Xe-123 Reaction Excitation Functions, Tech. Rep. NDL-19/98, KAERI, 1998.

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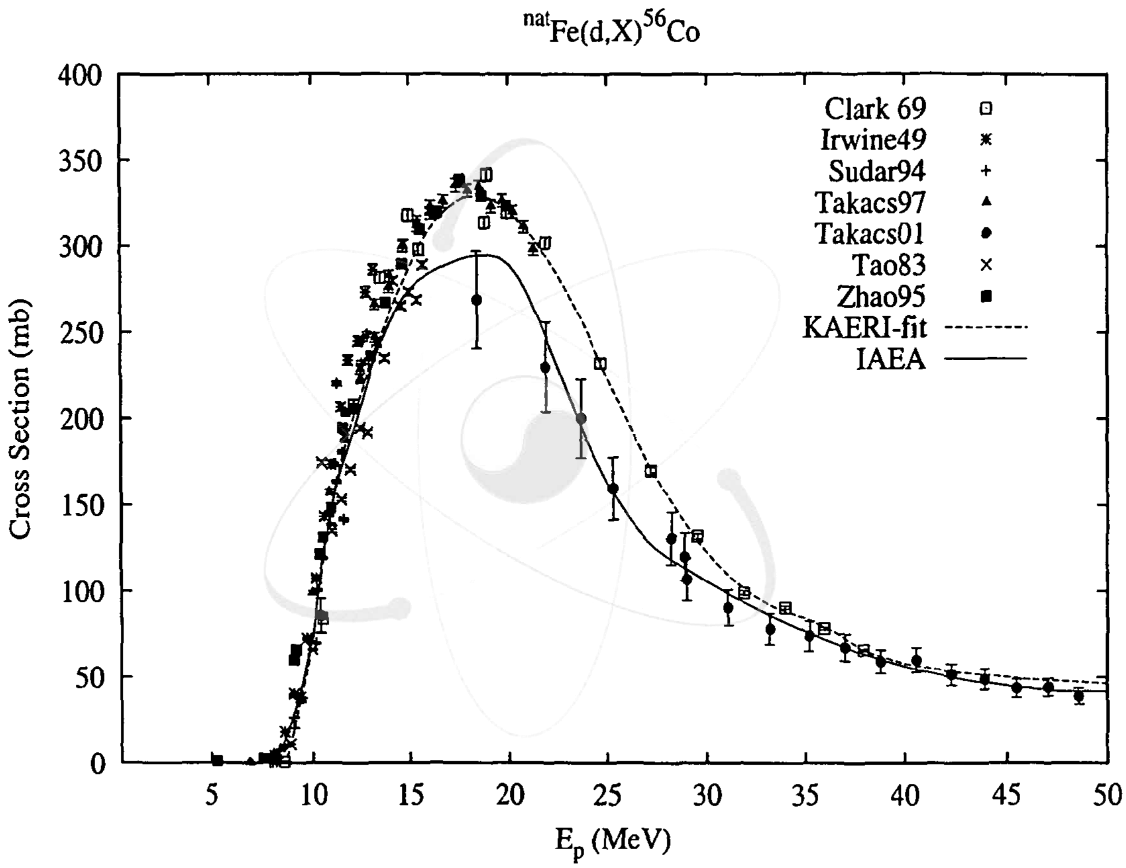
4.3 ^{nat}Fe(d,x)^{56}Co

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Deuteron energy range (MeV)
^{nat}Fe(d,X)^{56}Co	77.70 d	846.8	99.9	8-50
		1238.3	67.0	



Related documents:

- Zhuang, Y.X., Evaluations and Calculations of N-14(d,n)O-15, Ne-nat(d,x)F-18, Ti-nat(d,x)V-48, Ti-nat(He-3,x)V-48, Ti-nat(a,x)Cr-51, Fe-nat(d,x)Co-56, Ni-nat(d,x) Cu-61, Zn-nat(p,xn)ga-66, Zn-nat(p,xn)Ga-67, Ga-69(p,2n)Ge-68, Cu-nat(He-3,x) Ga-66, Cu-nat(He-3,x)Ga-67 and I-127(p,5n)Xe-123 Reaction Excitation Functions, Tech. Rep. NDL-19/98, KAERI, 1998.

Experimental data:

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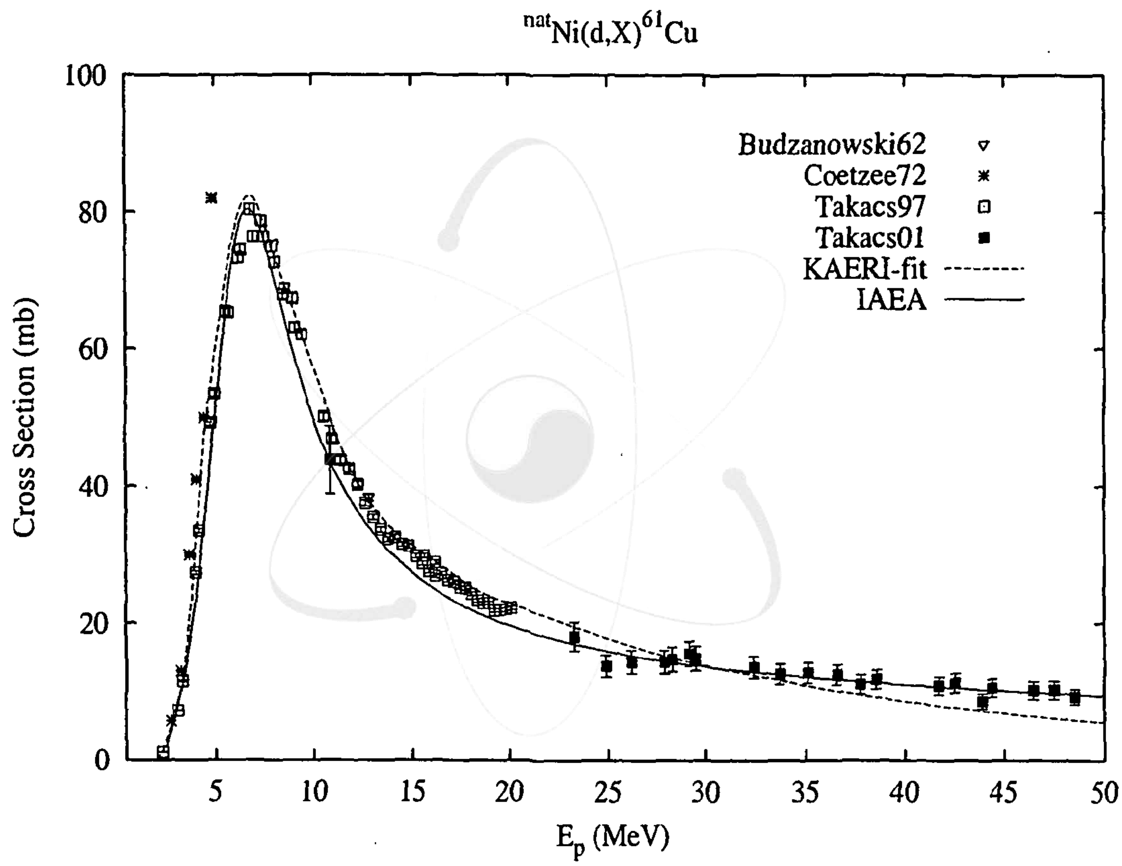
4.4 ^{nat}Ni(d,x)^{61}Cu

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines		Deuteron energy range (MeV)
		E_γ(keV)	I_γ (%)	
^{nat}Ni(d,X)^{61}Cu	3.40 h	283.0	12.5	2.5-50
		656.0	10.66	



Related documents:

- Zhuang, Y.X., Evaluations and Calculations of N-14(d,n)O-15, Ne-nat(d,x)F-18, Ti-nat(d,x)V-48, Ti-nat(He-3,x)V-48, Ti-nat(a,x)Cr-51, Fe-nat(d,x)Co-56, Ni-nat(d,x) Cu-61, Zn-nat(p,xn)ga-66, Zn-nat(p,xn)Ga-67, Ga-69(p,2n)Ge-68, Cu-nat(He-3,x) Ga-66, Cu-nat(He-3,x)Ga-67 and I-127(p,5n)Xe-123 Reaction Excitation Functions, Tech. Rep. NDL-19/98, KAERI, 1998.

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5 Helium-3 Beam Monitor Reactions

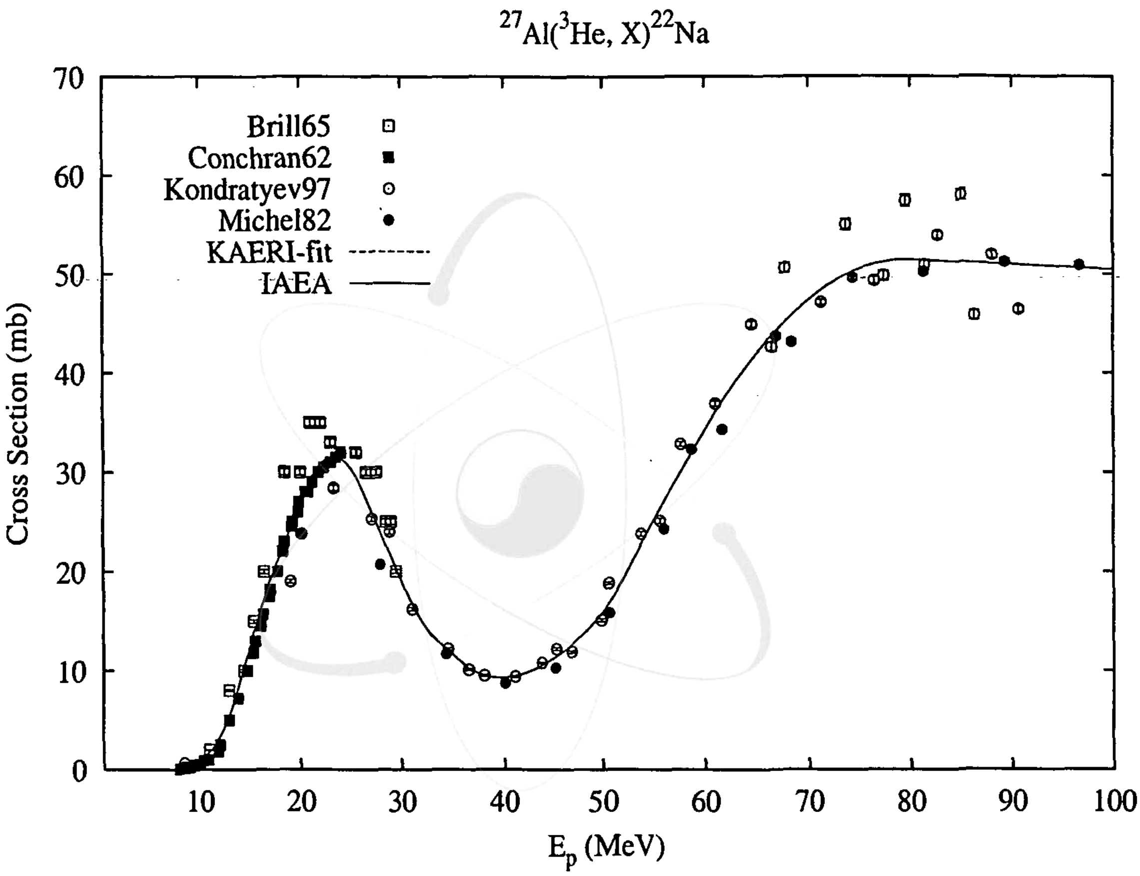
Table 3 lists 3 He-3 beam reactions evaluated, including the basic decay characteristics of roduct nuclei (half-lives, main γ-lines along with the intensities), and energy range of protons for which evaluations were performed.

표 3: ^{3}He Beam Monitor Reactions

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	^{3}He energy range (MeV)
$^{27}Al(^{3}He,X)^{22}Na$	2.60 a	1274.5	99.94	10-100
$^{27}Al(^{3}He,X)^{24}Na$	14.96 h	1368.6	100.0	25-100
		2754.0	99.94	
$^{nat}Ti(^{3}He,X)^{48}V$	15.98 d	983.5	99.99	16-100
		1312.0	97.49	

5.1 $^{27}Al(^{3}He,x)^{22}Na$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	^{3}He energy range (MeV)
$^{27}Al(^{3}He,X)^{22}Na$	2.60 a	1274.5	99.94	10-100



Related documents:

- Zhuang, Y.X., Evaluations and Calculations of Al-nat(He-3,x)Na-22, N-14(p,a)C-11 and Al-nat(d,x)Na-22 Reaction Excitation Functions, Tech. Rep. NDL-03/98, KAERI, 1998.

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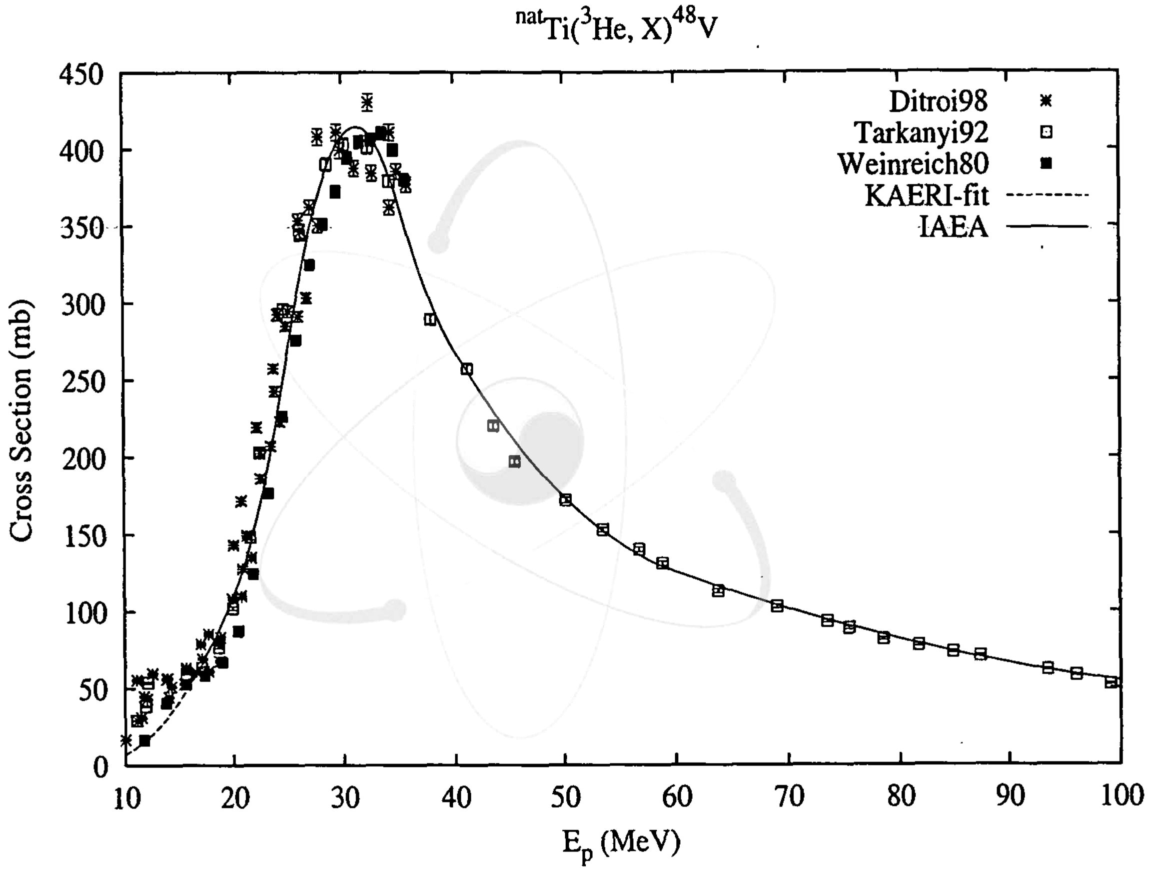
5.2 ^{nat}Ti(^{3}He,x)^{48}V

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	^{3}He energy range (MeV)
^{nat}Ti(^{3}He,X)^{48}V	15.98 d	983.5	99.99	16-100
		1312.0	97.49	



Related documents:

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Experimental data:

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6 Alpha Particle Beam Monitor Reactions

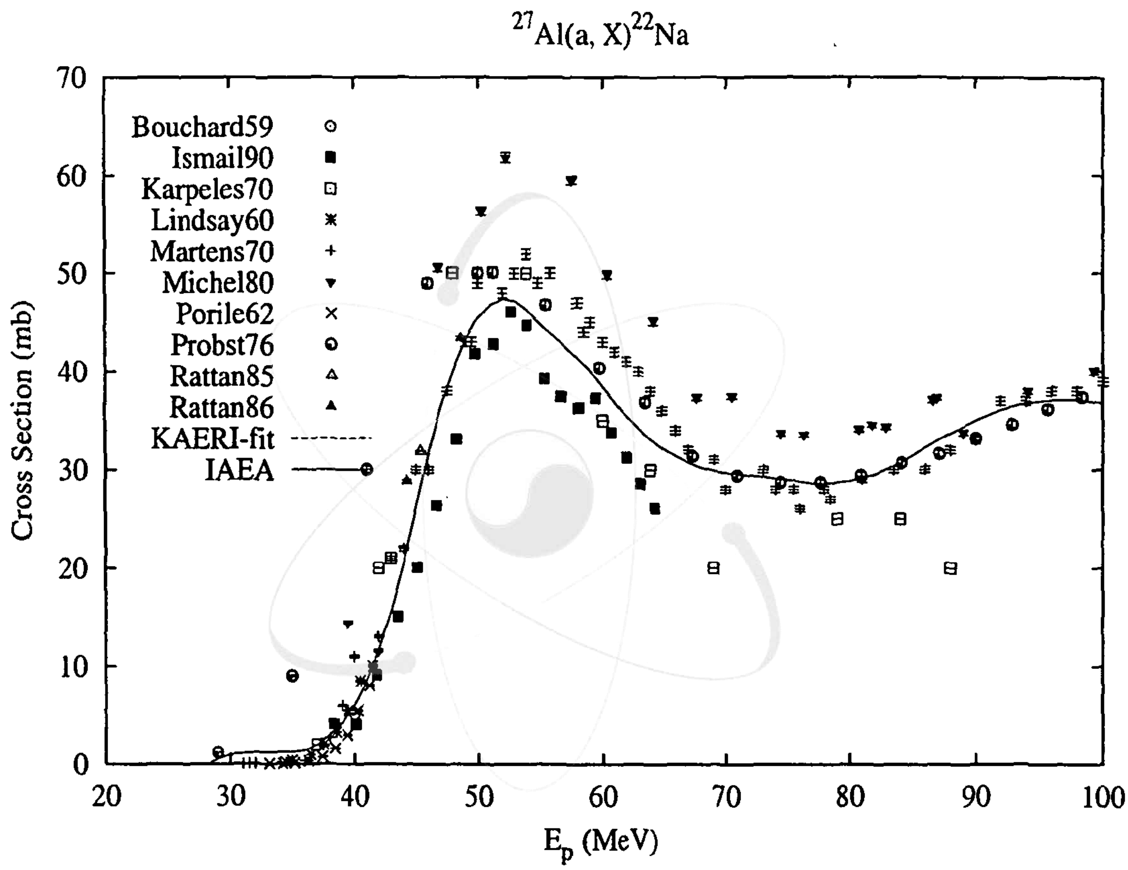
Table 4 lists 6 alpha-particle beam reactions evaluated, including the basic decay characteristics of roduct nuclei (half-lives, main γ-lines along with the intensities), and energy range of protons for which evaluations were performed.

表 4: α-particle Beam Monitor Reactions

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	^{alpha}-Particle energy range (MeV)
$^{27}Al(\alpha,X)^{22}Na$	2.60 a	1274.5	99.94	30-100
$^{27}Al(\alpha,X)^{24}Na$	14.96 h	1368.6	100.0	30-100
		2754.0	99.94	
$^{nat}Ti(\alpha,X)^{51}Cr$	27.70 d	320.1	9.83	5-40
$^{nat}Cu(\alpha,X)^{66}Ga$	9.49 h	1039.3	37.9	8-30
$^{nat}Cu(\alpha,X)^{67}Ga$	3.26 d	93.3	37.0	15-50
		184.6	20.4	
$^{nat}Cu(\alpha,X)^{65}Zn$	244.1 d	1115.5	50.75	15-50

6.1 ^{27}Al(a,x)^{22}Na

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	α-Particle energy range (MeV)
^{27}Al(α,X)^{22}Na	2.60 a	1274.5	99.94	30-100



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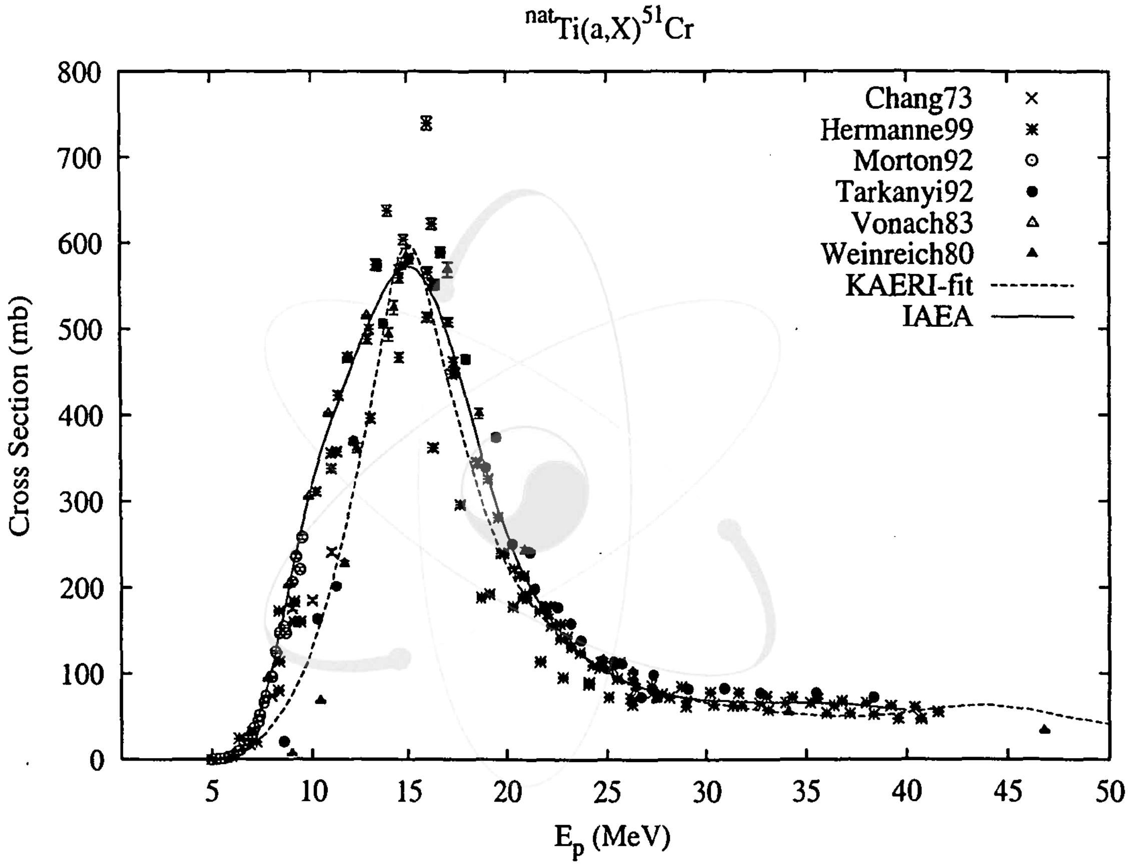
6.2 ^{nat}Ti(a,x)^{51}Cr

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	α-Particle energy range (MeV)
^{nat}Ti(α,X)^{51}Cr	27.70 d	320.1	9.83	5-40



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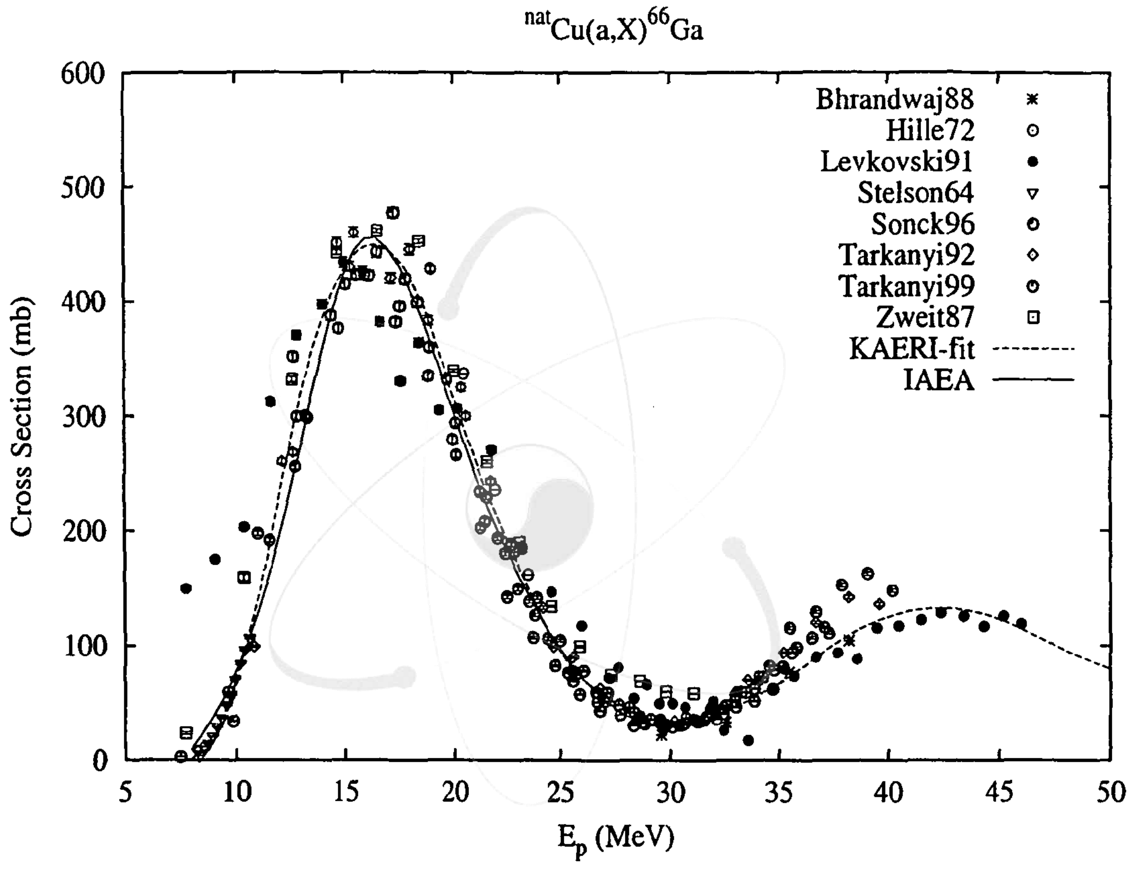
6.3 $^{nat}Cu(a,x)^{66}Ga$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	α-Particle energy range (MeV)
$^{nat}Cu(\alpha,X)^{66}Ga$	9.49 h	1039.3	37.9	8-30



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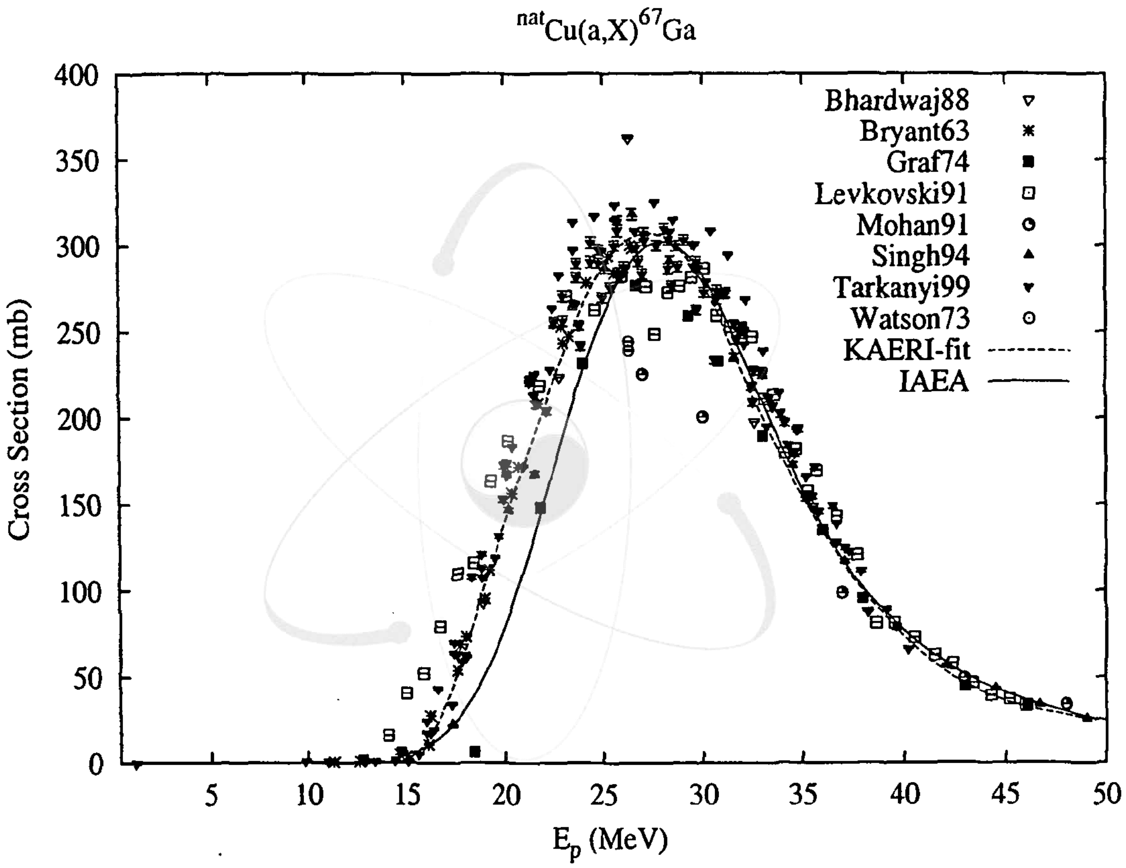
6.4 $^{nat}Cu(a,x)^{67}Ga$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	α-Particle energy range (MeV)
$^{nat}Cu(\alpha,X)^{67}Ga$	3.26 d	93.3	37.0	15-50
		184.6	20.4	



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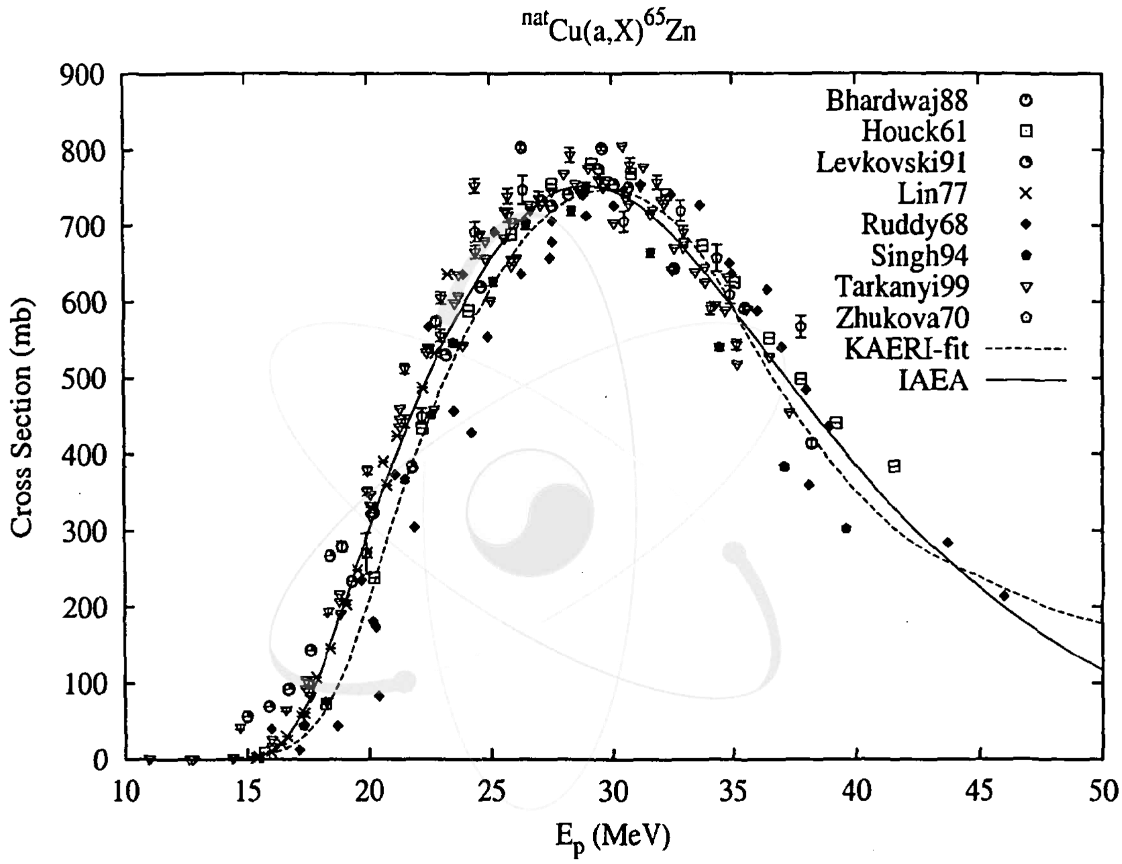
6.5 ^{nat}Cu(a,x)^{65}Zn

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	α-Particle energy range (MeV)
^{nat}Cu(α,X)^{65}Zn	244.1 d	1115.5	50.75	15-50



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7 Gamma Emitters

Table 5 shows the list of commonly used production reactions for gamma emitters including 16 reactions. Among them are 12 reactions for isotope production and 4 reactions deal with disturbing radionuclidic imprities. Only reactions occuring on the same targetisotope as the one used for the production are considered. Energies of incident particles cover the range from a few MeV up to 100 MeV.

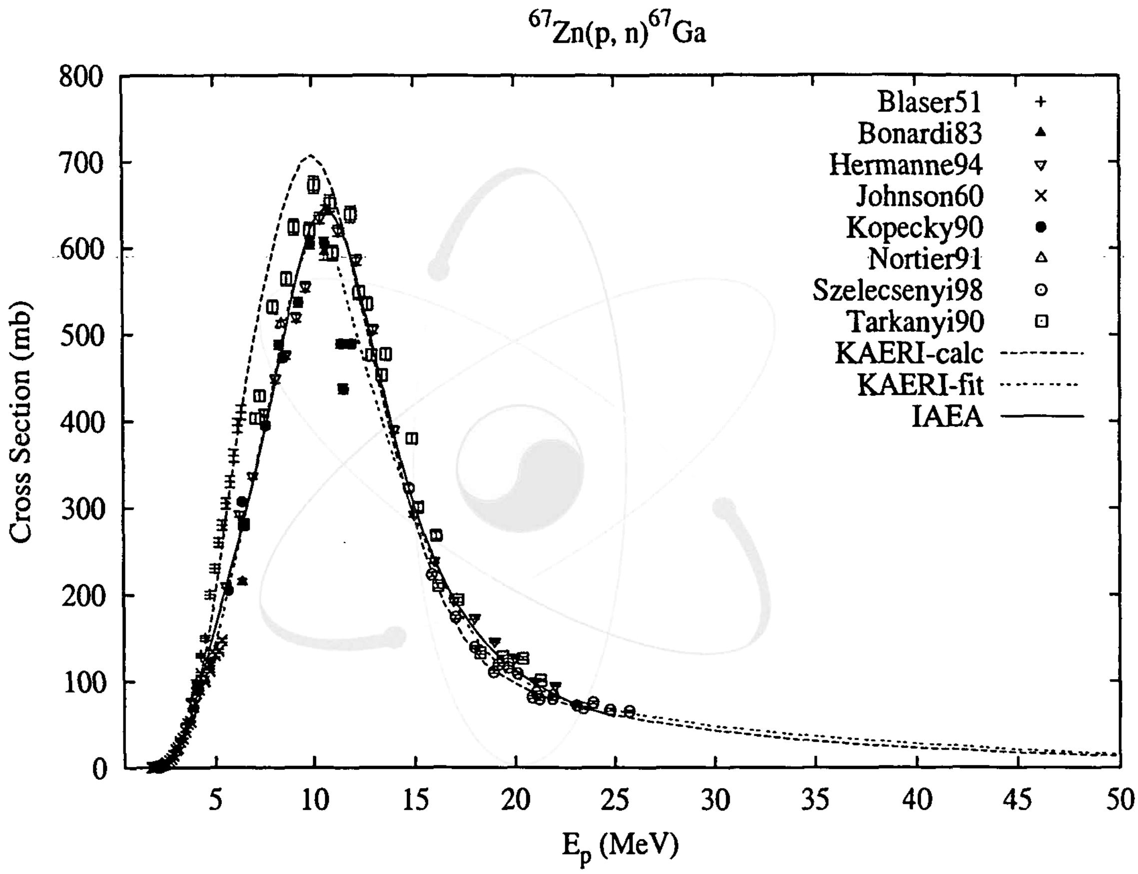
表 5: Commonly Used Production Reactions for Gamma Emitters. Denoted by Asterisk are Reactions Yielding Radionuclidic Impurities.

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{67}Zn(p,n)^{67}Ga$	3.26 d	93.3	37.0	2-25
		184.6	20.4	
$^{68}Zn(p,2n)^{67}Ga$	3.26 d	93.3	37.0	13-30
		184.6	20.4	
$^{nat}Kr(p,X)^{81}Rb$	4.58 h	190.4	64.3	14.5-80
$^{82}Kr(p,2n)^{81}Rb$	4.58 h	190.4	64.3	14.5-30
$^{111}Cd(p,n)^{111}In$	2.8 d	171.3	90.24	4-30
		254.4	94.0	
$^{112}Cd(p,2n)^{111}In$	2.8 d	171.3	90.24	11.5-35
		245.4	94.0	
$^{123}Te(p,n)^{123}I$	13.2 h	159.0	83.3	4-20
$^{124}Te(p,2n)^{123}I$	13.2 h	159.0	83.3	12-30
$^{124}Te(p,n)^{124}I$	4.18 d	602.7	61.0	5-30
$^{127}I(p,5n)^{123}Xe$	2.08 h	148.9	49.0	37-100
$^{127}I(p,3n)^{125}Xe$	16.9 h	188.4	54.9	20-100
$^{124}Xe(p,2n)^{123}Cs$	5.87 min	97.4	14.5	15.5-40
$^{124}Xe(p,pn)^{123}Xe$	2.08 h	148.9	49.0	16.5-40

Remark: ^{123}Xe decays into ^{123}I, ^{123}Cs decays into ^{123}Xe, ^{125}Xe decays into ^{125}I.

7.1 $^{67}Zn(p,n)^{67}Ga$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{67}Zn(p,n)^{67}Ga$	3.26 d	93.3	37.0	2-25
		184.6	20.4	



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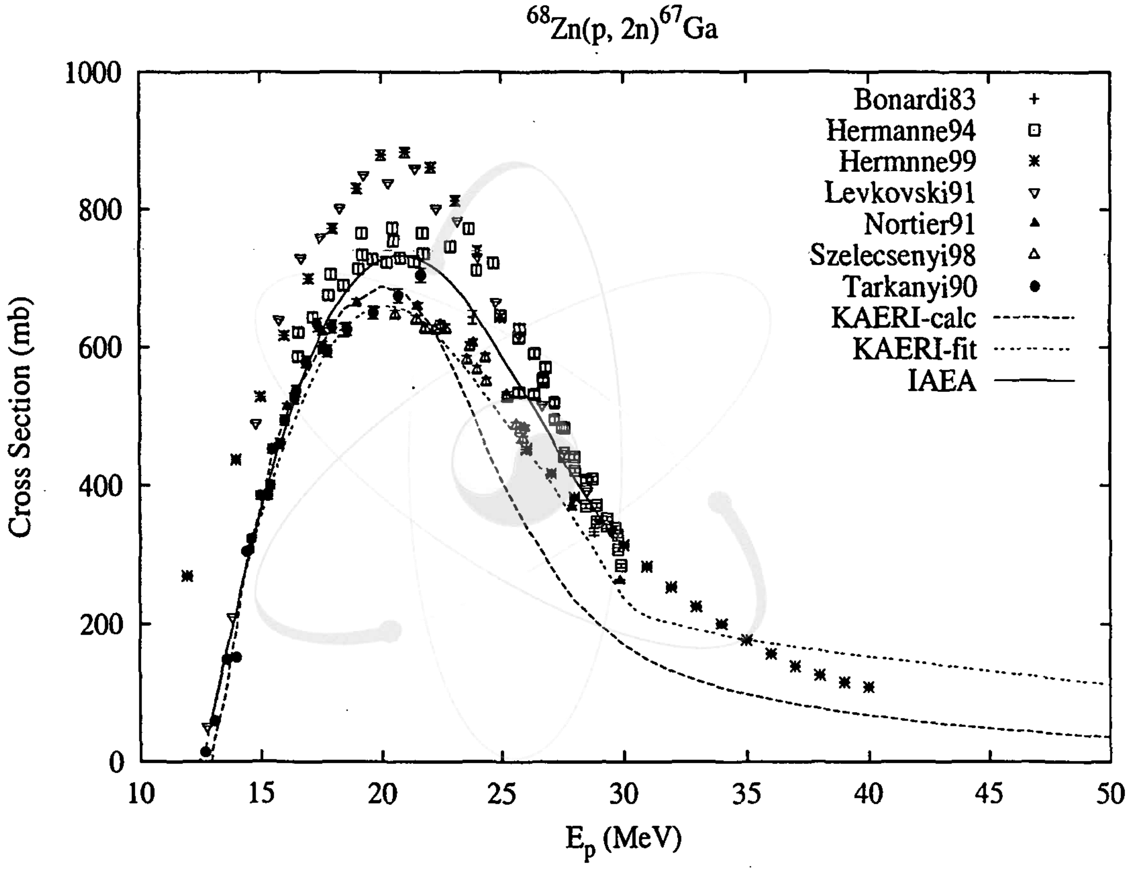
7.2 $^{68}Zn(p,2n)^{67}Ga$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{68}Zn(p,2n)^{67}Ga$	3.26 d	93.3	37.0	13-30
		184.6	20.4	



Related documents:

- Kim, D., Calculation and Evaluation of Proton Induced Reactions on N-14, O-18 and Zn-nat,66,67,68 up to 50 MeV, Tech. Rep. NDL-02/99, KAERI, 1999.
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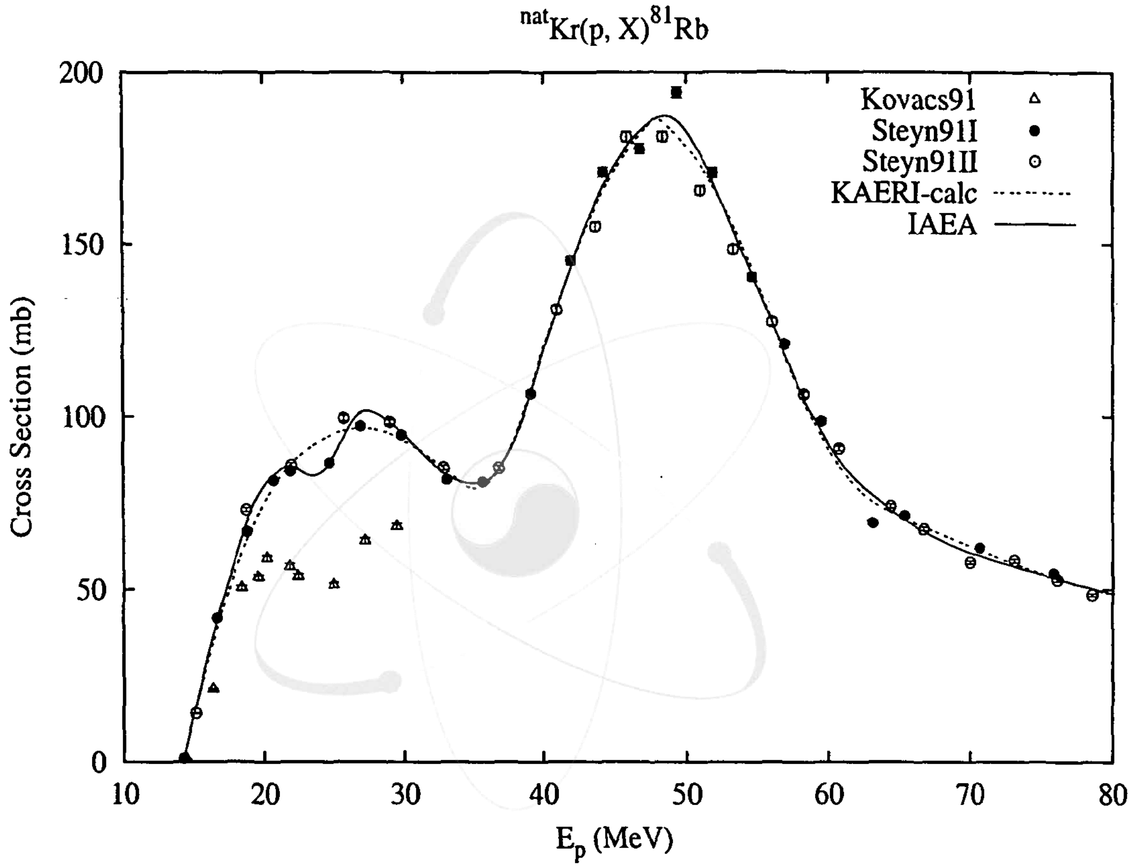
7.3 ^{nat}Kr(p,X)^{81}Rb

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{nat}Kr(p,X)^{81}Rb	4.58 h	190.4	64.3	14.5-80



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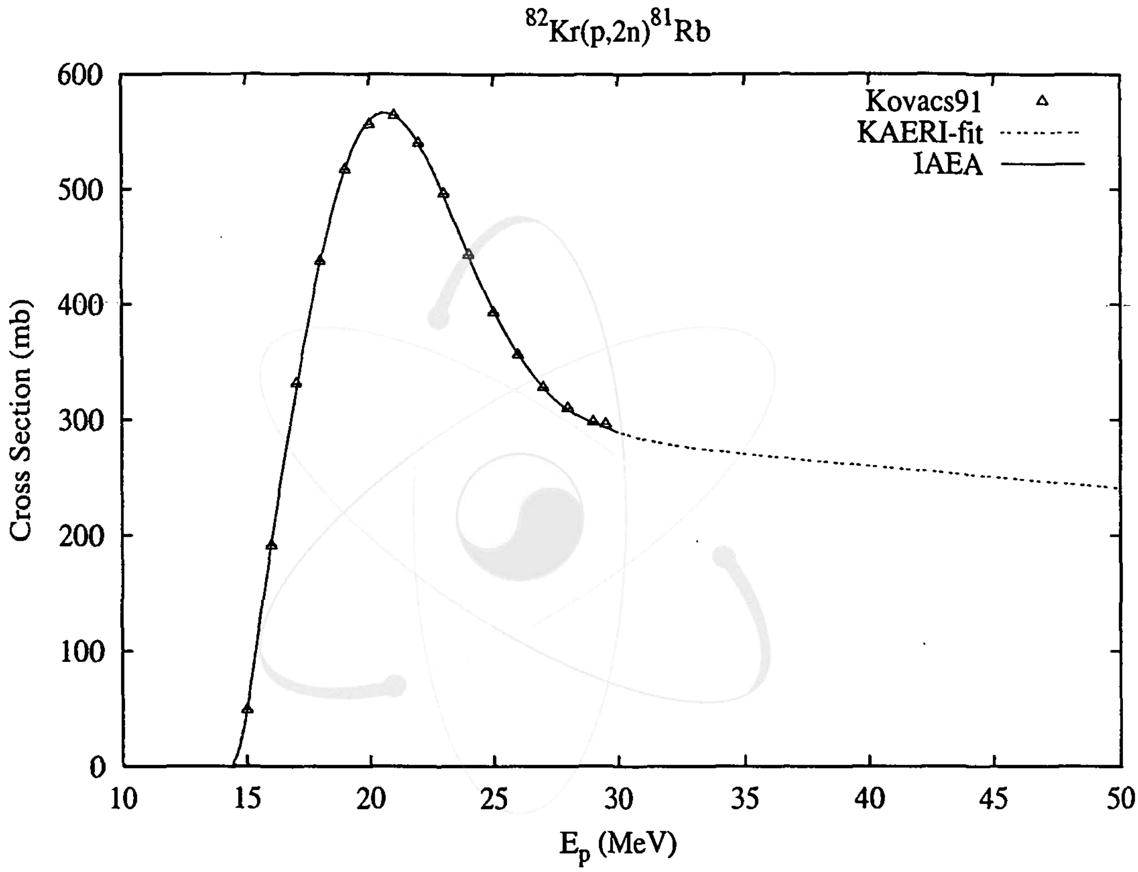
7.4 ^{82}Kr(p,2n)^{81}Rb

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{82}Kr(p,2n)^{81}Rb	4.58 h	190.4	64.3	14.5-30



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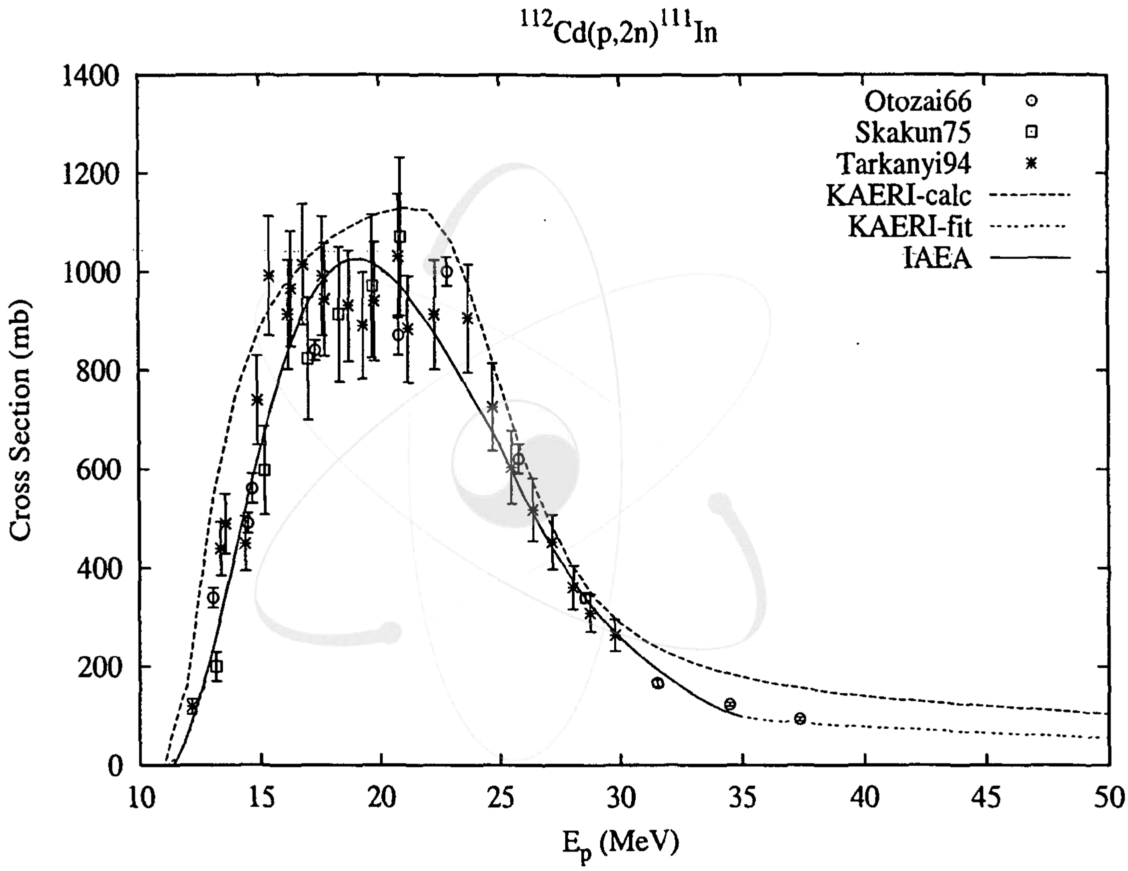
7.5 $^{112}Cd(p,2n)^{111}In$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{112}Cd(p,2n)^{111}In$	2.8 d	171.3	90.24	11.5-35
		245.4	94.0	



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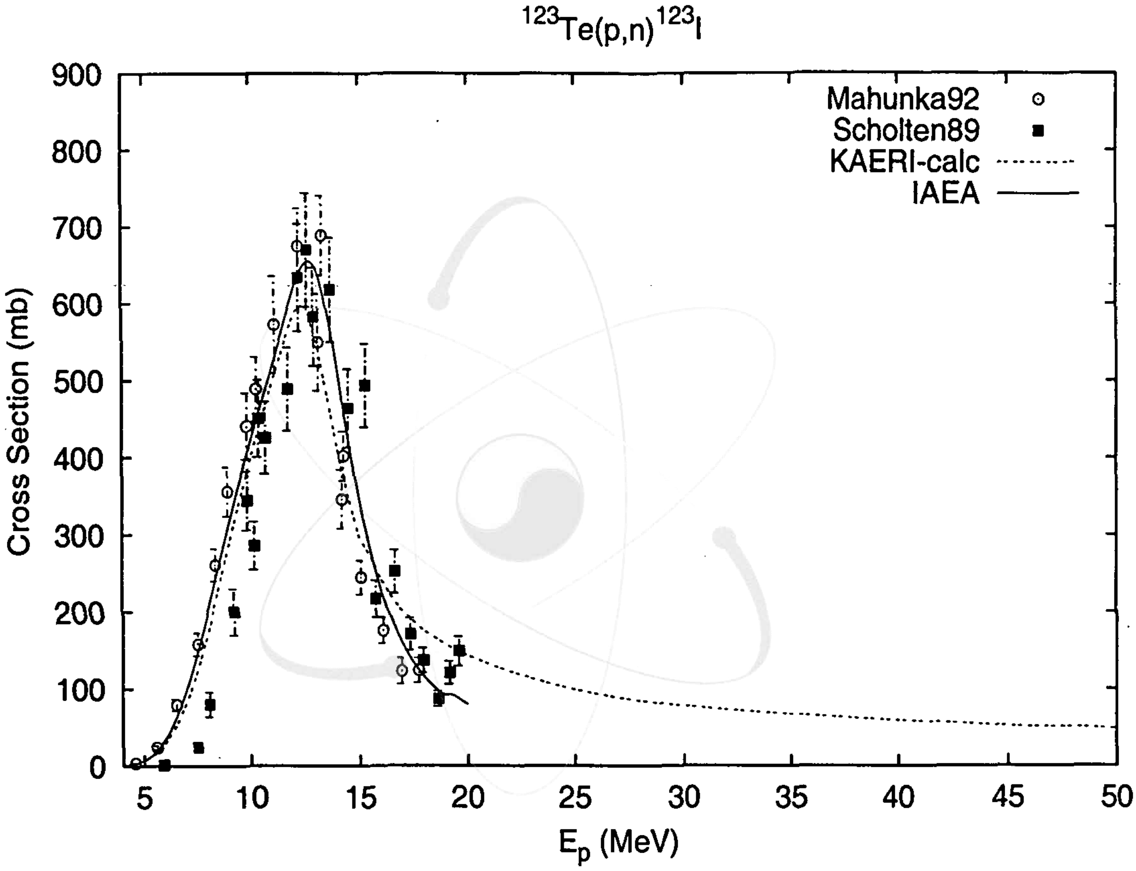
7.6 $^{123}Te(p,n)^{123}I$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{123}Te(p,n)^{123}I$	13.2 h	159.0	83.3	4-20



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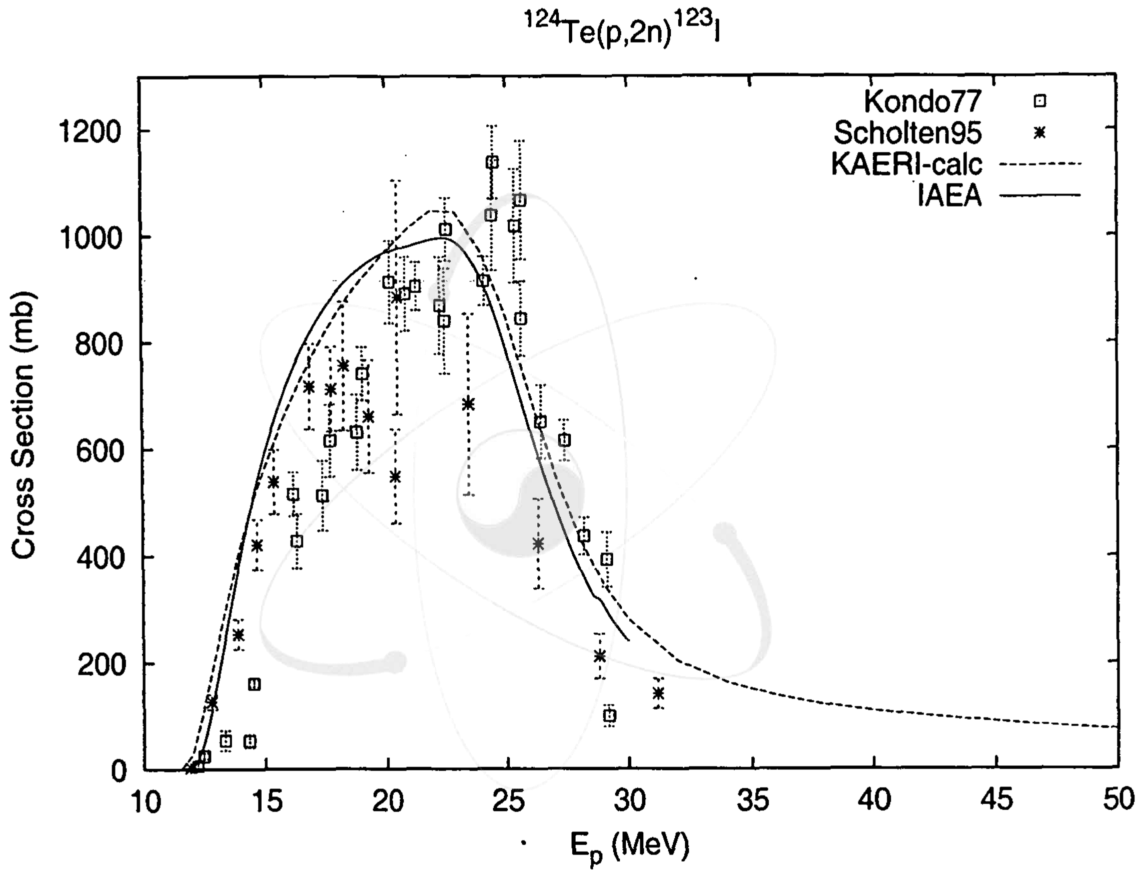
7.7 ^{124}Te(p,2n)^{123}I

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines		Proton energy range (MeV)
		E_γ(keV)	I_γ (%)	
^{124}Te(p,2n)^{123}I	13.2 h	159.0	83.3	12-30



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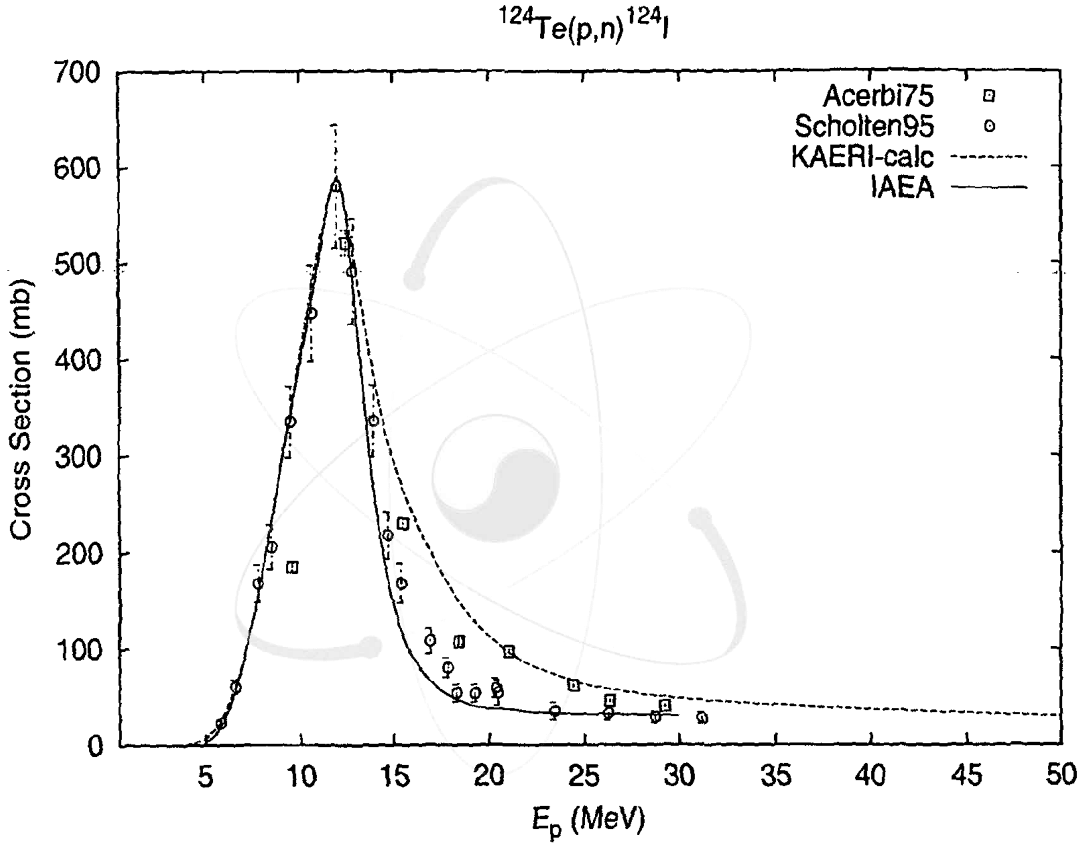
7.8 $^{124}Te(p,n)^{124}I$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
*$^{124}Te(p,n)^{124}I$	4.18 d	602.7	61.0	5-30



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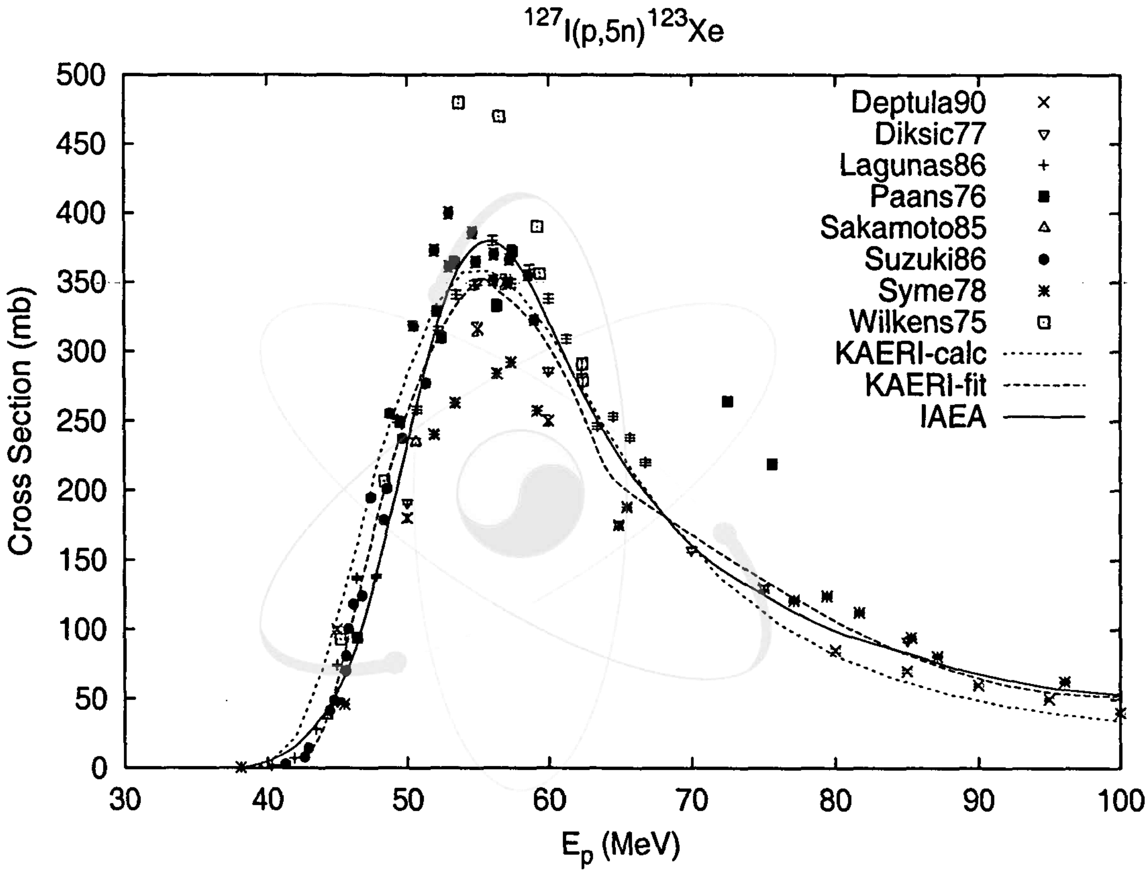
7.9 ^{127}I(p,5n)^{123}Xe → ^{123}I

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
^{127}I(p,5n)^{123}Xe	2.08 h	148.9	49.0	37-100



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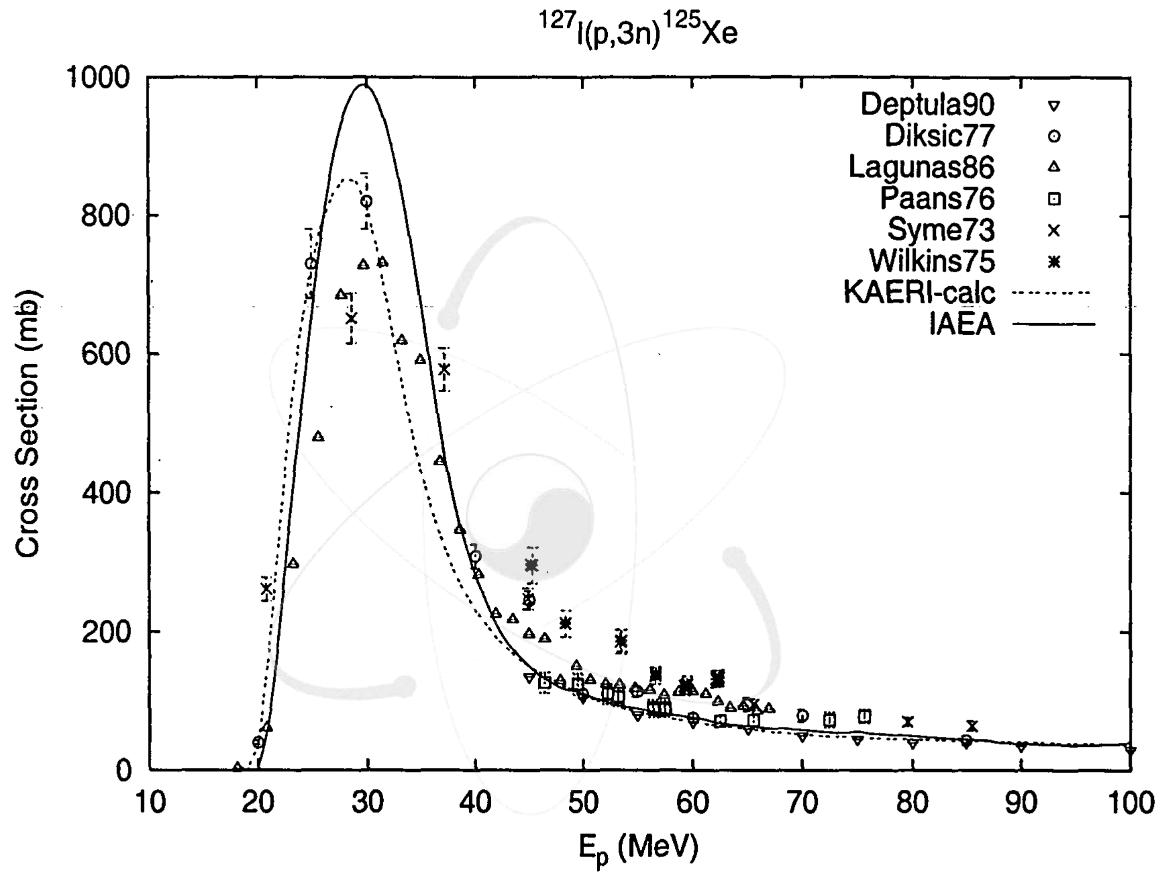
7.10 $^{127}I(p,3n)^{125}Xe \rightarrow {}^{125}I$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$*^{127}I(p,3n)^{125}Xe$	16.9 h	188.4	54.9	20-100



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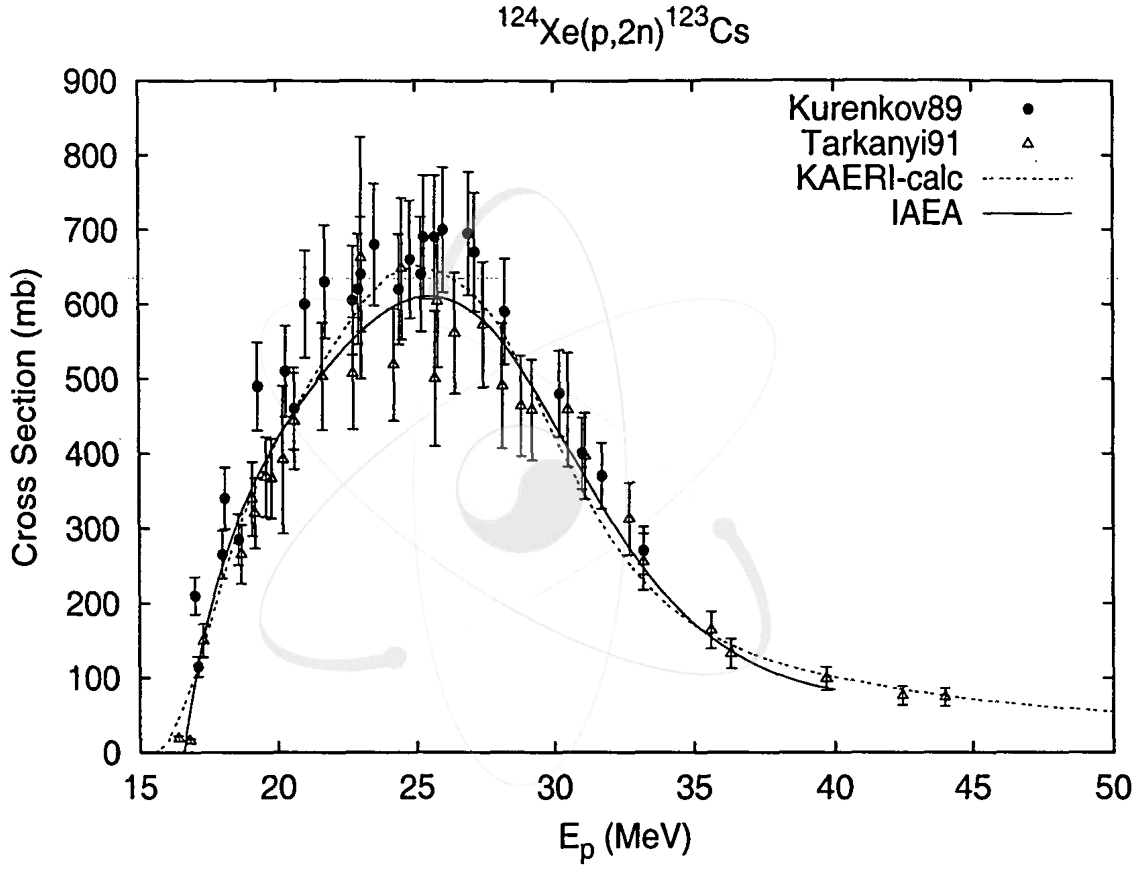
7.11 $^{124}Xe(p,2n)^{123}Cs \rightarrow {}^{123}Xe \rightarrow {}^{123}I$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{124}Xe(p,2n)^{123}Cs$	5.87 min	97.4	14.5	15.5-40



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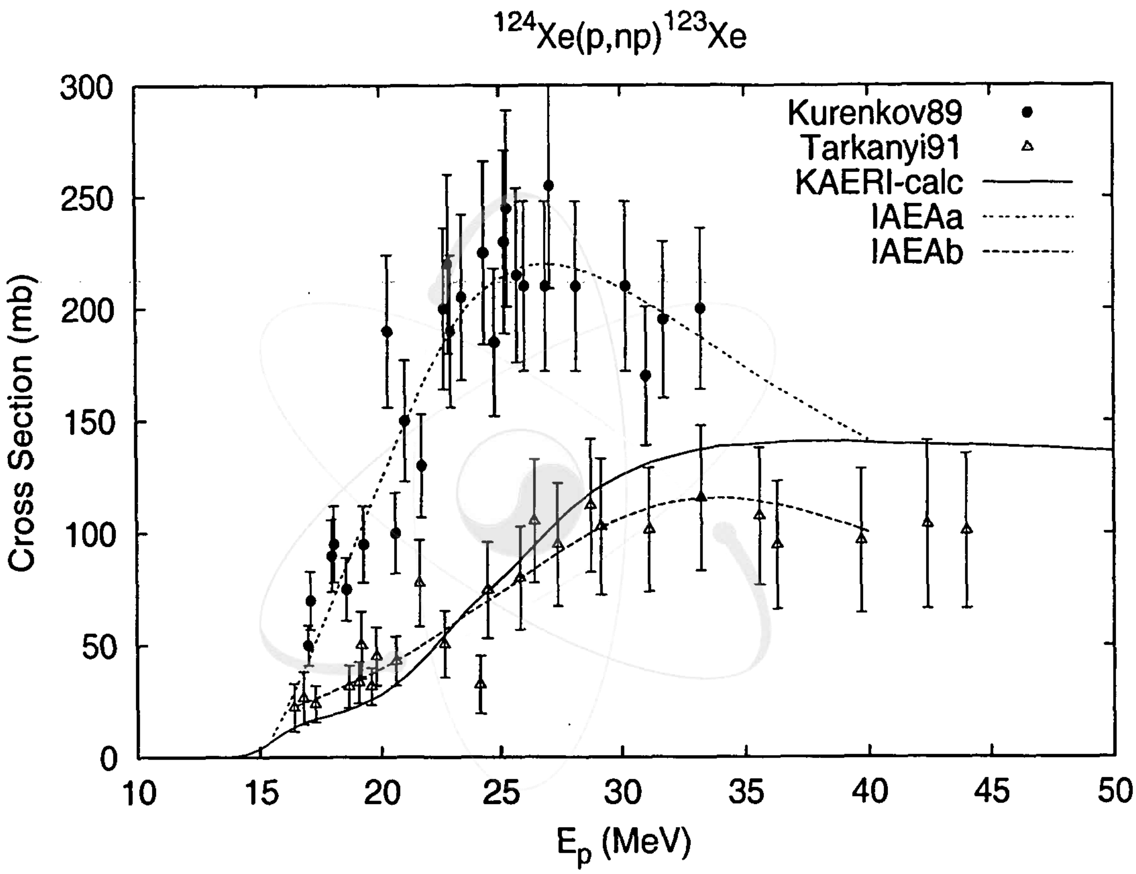
7.12 $^{124}Xe(p,pn)^{123}Xe \rightarrow {}^{123}I$

Reaction	$T_{1/2}$ of product nucleus	Main γ-lines E_γ(keV)	I_γ (%)	Proton energy range (MeV)
$^{124}Xe(p,pn)^{123}Xe$	2.08 h	148.9	49.0	16.5-40



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8 Positron Emitters

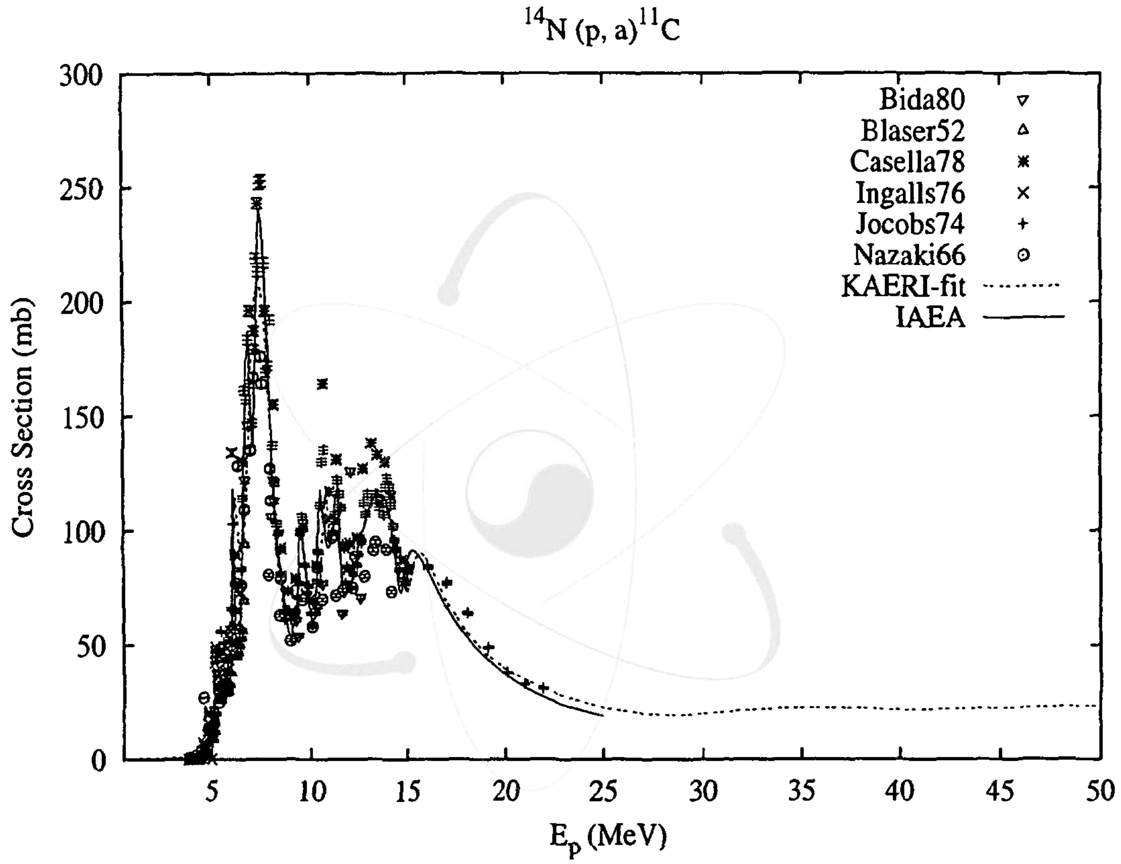
Table 6 shows the list of commonly used production reactions for positron emitters including 10 reactions. Among them are 6 reactions for production of short-lived "orgainc" positron emiters and 4 reactions to produce longer-lived isotopes for supply of PET radioisotopes via generators. and 4 reactions deal with disturbing radionuclidic imprities. Energies of incident particles cover the range froma few MeV up to 100 MeV.

表 6: Commonly Used Production Reactions for Positron Emitters.

Reaction	$T_{1/2}$ of product nucleus	β^+ branching (%)	Proton energy range (MeV)
$^{14}N(p,\alpha)^{11}N$	20.39 min	99.8	4-25
$^{16}O(p,\alpha)^{13}N$	9.96 min	99.8	6-20
$^{14}N(d,n)^{15}O$	2.04 min	99.9	1-15
$^{18}O(p,n)^{18}F$	109.8 min	97.0	2.5-20

8.1 $^{14}N(p,\alpha)^{11}C$

Reaction	$T_{1/2}$ of product nucleus	β^+ branching (%)	Proton energy range (MeV)
$^{14}N(p,\alpha)^{11}N$	20.39 min	99.8	4-25



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Experimental data:

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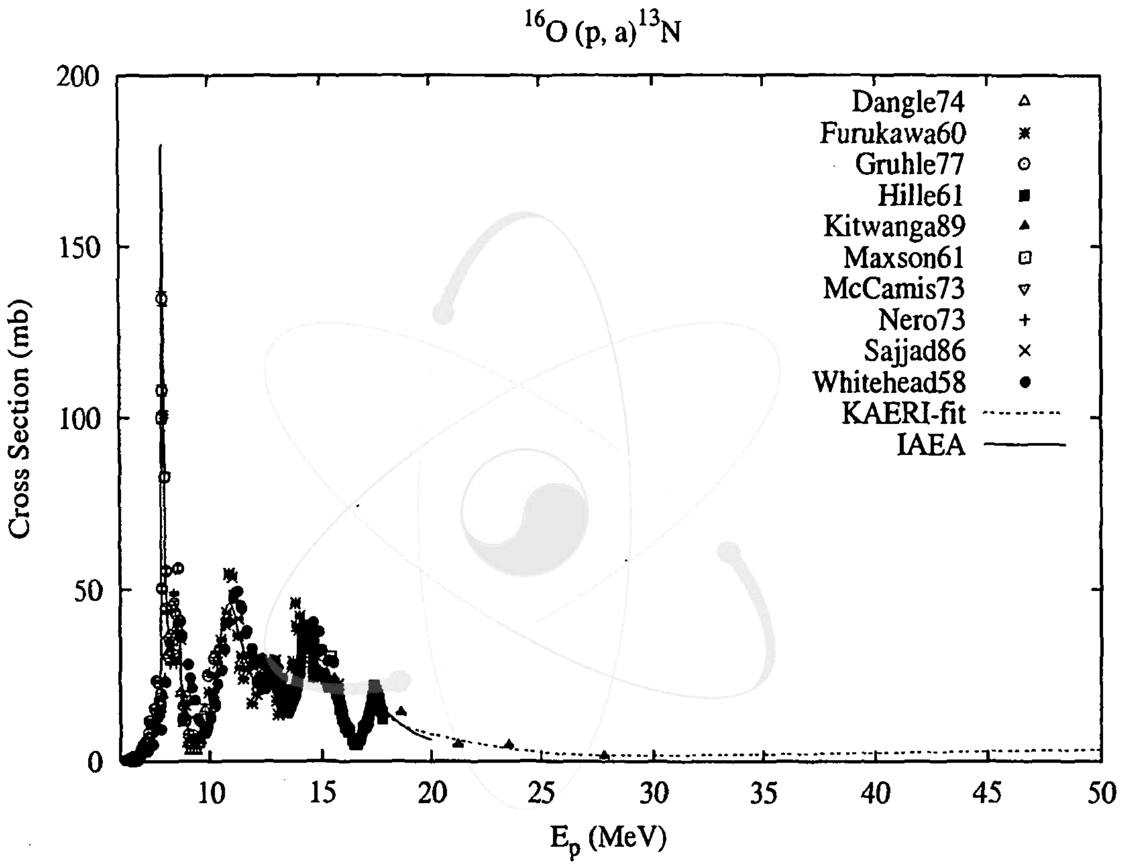
8.2 $^{16}O(p,\alpha)^{13}N$

Reaction	$T_{1/2}$ of product nucleus	β^+ branching (%)	Proton energy range (MeV)
$^{16}O(p,\alpha)^{13}N$	9.96 min	99.8	6-20



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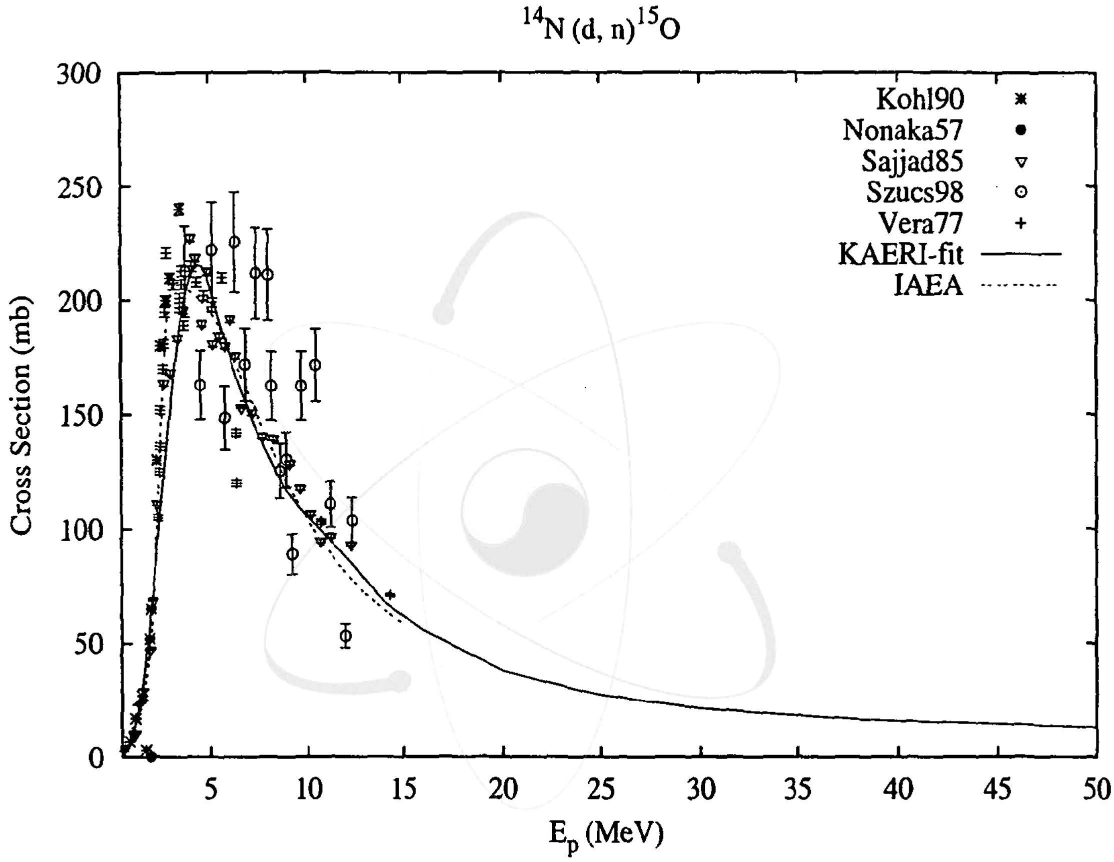
8.3 $^{14}N(d,n)^{15}O$

Reaction	$T_{1/2}$ of product nucleus	β^+ branching (%)	Proton energy range (MeV)
$^{14}N(d,n)^{15}O$	2.04 min	99.9	1-15



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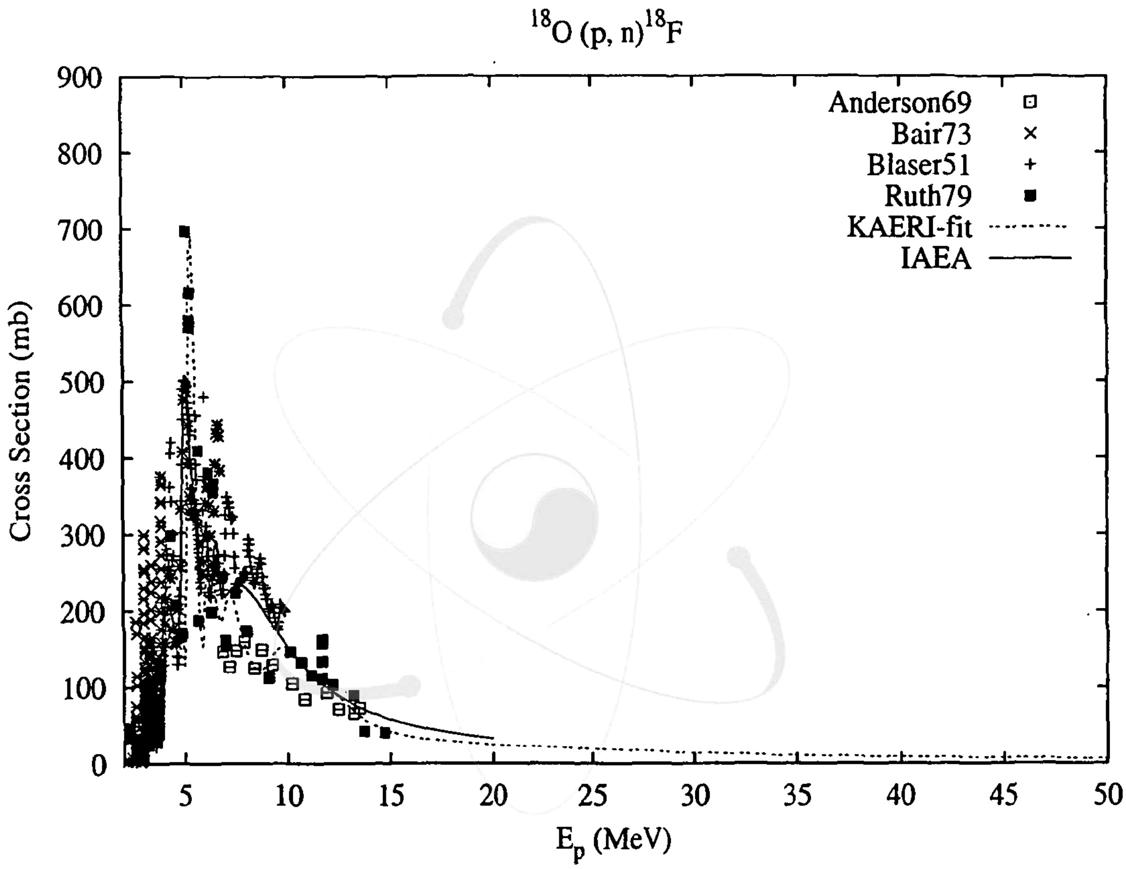
8.4 $^{18}O(p,n)^{18}F$

Reaction	$T_{1/2}$ of product nucleus	β^+ branching (%)	Proton energy range (MeV)
$^{18}O(p,n)^{18}F$	109.8 min	97.0	2.5-20



Related documents:

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Abstract (15-20 Lines)

This report summarizes information and figures describing the "KAERI Charged Particle Cross Section Library for Radioisotope production" The library contains proton-, deutron-, He-3-, and alpha-induced monitor cross sections, and gamma- and positron-emitter production cross sections. Experimental data and evaluation methods are described, and the evaluated cross sections are compared with those of the IAEA, MENDL, and LA150. The library has cross sections and emission spectra suitable for the transport analysis in the design of radioisotope production system, and are available at **http://atom.kaeri.re.kr/** in ENDF-6 format.

Subject Keywords (About 10 words)	nuclear data evaluation, charged particle nuclear reaction, medical radioisotpe production, gamma emiiter, positron emitter, ENDF-6 format

서 지 정 보 양 식			
수행기관보고서번호	위탁기관보고서번호	표준보고서번호	INIS 주제코드
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연구위탁기관		계약 번호			

초록 (15-20줄내외)

본 보고서는 한국원자력연구소 핵자료평가랩에서 생산한 “의료용 동위원소생산을 위한 하전입자 핵단면적 자료집” (KAERI Charged Particle Cross Section Library for Radioisotope production)을 기술한다. 본 자료집에는 양성자, 중양자, He-3, 및 알파입자의 모니터 핵반응과, 감마선원과 양전자선원을 생산하는 핵반응에 대한 평가핵자료를 수록하고 있다. 평가에 사용된 실험자료와 평가방법을 기술하였고 IAEA 등 타 기관에서 생산한 평가핵자료들과 비교하였다. 평가핵단면적은 동위원소 생산시설의 입자수송해석에 적합한 수송단면적의 형태의 ENDF-6형식으로 생산하였으며 **http://atom.kaeri.re.kr/** 에서 얻을 수 있다.

주제명키워드 (10단어내외)	핵자료평가, 하전입자핵반응, 의료용동위원소, 감마선원, 양전자선원, ENDF-6