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COMPILATION OF EXCITATION FUNCTIONS FOR THE PRODUCTION OF THE RADIONUCLIDES ^{123}I, ^{123}Xe AND ^{123}Cs BY CHARGED-PARTICLE INDUCED REACTIONS

A. Hashizume, Y. Tendow, K. Kitao*
RIKEN
(The Institute of Physical and Chemical Research)
Nuclear Data Group

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Abstract

Available experimental data of charged-particle induced nuclear reactions for the production of the radionuclides ^{123}I, ^{123}Xe and ^{123}Cs are reviewed and presented in graphical courves. Included are the reactions $^{124}Te(p,2n)^{123}I$, $^{127}I(p,5n)^{123}Xe$, $^{124}Xe(p,pn)^{123}Xe$, $^{122}Te(d,n)^{123}I$, $^{127}I(d,6n)^{123}Xe$, $^{127}I(d,p5n)^{123}I$, $^{121}Sb(a,2n)^{123}I$, $^{133}Cs(p,spallation)^{123}Xe$, $^{nat}Ba(p,spallation)^{123}Xe$, $^{nat}La(p,spallation)^{123}Xe$, $^{124}Xe(p,2n)^{123}Cs$, $^{nat}La(p,spallation)^{116-136}Cs$, $^{109}Ag(^{18}O,4n)^{123m}Cs$.

I. Introduction

Owing to the suitable nuclear decay properties, ^{123}I is considered one of the best radionuclides for in vivo diagnostic nuclear-medical studies using single-photon emission computed tomography. Although more than twenty kinds of reactions have been proposed for the production of ^{123}I, selection should be made from several essential points of view, that is, the cost of enriched isotope for a target, ease of recovery and recovery percentage of the isotope after irradiation, beam requirements whether the kind of incident beam and its energy are easily available, production yield rate, chemical separation yield, ease of chemical process after irradiation and impurities of other radioactive iodine isotopes in the final product. Among them, excitation function is one of important factors to determine the production method. The excitation functions to produce ^{123}I, ^{123}Xe and ^{123}Cs were compiled in this report.

II. Reactions to produce ^{123}I and ^{123}Xe

$^{124}Te(p,2n)$ reaction: This reaction has been used most extensively in the routine production of ^{123}I. Its excitation function was obtained by Kondo[1)] and is shown in Fig. 1. In the figure, 'ind' shows independent cross section. By using a 99.87 % isotopically enriched ^{124}Te target, cross sections were determined with uncertainties of 4-12 % except at the lowest

energy. The cross sections were also measured with a 91.86 % enriched isotope as a target.[1] As a whole, the cross sections were obtained at precision of about 10 %.

There are many reports concerning practical production yields of ^{123}I. The reported values are scattered in a wide range. A part of the reasons may be attributed to the loss of ^{123}I during irradiation. If the precaution is not taken, the product yield will be depend on the beam intensity because of loss of iodine during irradiation.

$^{127}I(p,5n)^{123}Xe$ reaction: The excitation functions have been reported by five different authors.[2-6] Their functions are shown in Fig. 2. The values reported by Lagunas-Solar et al.[6] are most elaborated ones by taking into account various errors in the measurement. Each author took precautions against the loss of the target or reaction products during irradiation. Paans and Wilkins have measured the beam current directly; Dikšić[4] and Syme[5] used monitor reactions such as $^{27}Al(p,3pn)^{24}Na$ and $^{12}C(p,pn)^{11}C$. One of the reasons for differences among these absolute cross sections may be attributed to beam current integration.

$^{124}Xe(p,pn)^{123}Xe$ reaction: The (p,pn) and (p,2n) reactions are important to obtain ^{123}Xe, ancestor of ^{123}I, from practical point of view. However their cross sections had not been measured until recently. In 1989, Kurenkov[7] measured cross sections between the proton energy 17 and 33 MeV with precision of about 18 % using 99.9 % isotopically enriched ^{124}Xe target. The excitation function is shown in Fig. 3. In his measurements, the threshold is not so clear. The yield curve obtained by Firouzbakht[8] with thin target shows sharp rise from 16 MeV to 20 MeV.

Deuteron induced reactions: The $^{122}Te(d,n)^{123}I$, $^{127}I(d,6n)^{123}Xe$ and $^{127}I(d,p5n)^{123}I$ reactions have been reported.[9,10] Zaidi[9] insisted that the $^{122}Te(d,n)$ reaction could produce ^{123}I with higher purity than obtaining from the

$^{124}Te(p,n)$ reaction. The cross sections are plotted in Fig. 4-6. There is only one measurement concerning the absolute value for (d,n) reaction.

Alpha induced reactions: The $^{121}Sb(\alpha,2n)^{123}I$, $^{123}Sb(\alpha,4n)^{123}I$ and also $^{122}Te(\alpha,3n)^{123}Xe$ reactions were drawn attention among alpha induced reactions. The excitation function for $^{121}Sb(\alpha,2n)^{123}I$ has been measured from the interest in comparing them with a nuclear reaction theory.[11] As shown in Fig. 7, absolute cross sections in the energy range from threshold to 27 MeV have been measured and compared with a statistical theory being taken into account the competition with γ-decay.

The production yield rate of $^{123}Sb(\alpha,4n)$ has been measured in the incident energy range between 50 and 75 MeV.[12]

The $^{122}Te(\alpha,3n)$ reaction[13] is one of methods to produce ^{123}Xe with small impurities such as ^{124}I, ^{125}I and others; however its cross section is not found in our survey.

Other reactions: Among other reactions explained above, ^{3}He induced reactions with ^{122}Te, and ^{123}Te targets have a high ^{123}Xe yield compared with alpha particle induced reactions.[14] However there are no reports on measurements of cross sections.

It is known that the spallation reaction induced by high energy protons have relatively high yield of ^{123}Xe. Peek[14] and Adilbish[15] reported spallation cross sections when ^{133}Cs, ^{nat}Ba and ^{nat}La were bombarded by high energy protons. The results are shown in Fig. 8-10. In the figure, 'cum' indicate that cross sections are cumulative. Adilbish[15] also reported ^{123}Xe producing cross sections when ^{127}I was bombarded by 660 MeV protons. The value is 3.8±0.4 mb. As there is one point for $^{127}I+p$ reaction, this deta is not presented in a figure. The cumulative cross sections for producing ^{123}Xe decrease slowly with increasing incident proton energies from 300 MeV to 660 MeV.

III. Reactions to produce ^{123}Cs

$^{124}Xe(p,2n)^{123}Cs$ reaction: The precursor of ^{123}Xe is ^{123}Cs ($T_{1/2}$=5.87 m). As ^{123}Cs is far apart from the nuclear stability line, the $^{124}Xe(p,2n)^{123}Cs$ reaction is an only possible reaction type with light and low energy ions. Yield curve including $^{123}Xe(p,pn)$ reaction was studied by Firouzbakht[7]. The cross sections were measured by Kurenkov[7] which was shown in Fig. 11. Sharp rise of curve is suggested from 16.0 MeV which is experimental threshold obtained by extrapolating to zero point in linear representation of excitation curve. The theoretical threshold obtained from Wapstra's table[16], is 15.58 MeV.

Spallation: High energy protons or ^{3}He incident ions combined with on line isotope separator have been used to produce ^{123}Cs, but there is only a report for absolute cross section measurements[17] in our survey. Cross sections to produce Cs isotopes by La + p(600 MeV) was shown in Fig. 12.

Heavy ion induced reactions: many combinations of targets and incident ions such as ^{10}B, ^{12}C, ^{14}N and ^{18}O have been utilized to produce ^{123}Cs. However, no cross section was reported in our survey except a relative value of excitation function for $^{109}Ag(^{18}O,4n)^{123m}Cs$ reaction.[18] Figure 13 shows relative cross sections for this reaction.

IV. Eye guide curves for excitation functions

The smooth lines in the Fig.1-10 are made for eye guide which were obtained by unweighted least squares fit to some order of poweres of exponent or a combination of several Gaussian distribution functions. In case of the $^{127}I(p,5n)^{123}Xe$ reaction, the curve between 68 and 85 MeV is not a real least squares fit but is connected smoothly by hand and this curve was replaced by a combination of Gaussian distribution functions. This procedure was needed because the experimental points were very dispersed between those obtained by Paans and by Dikšić. It seems there is no reason that sharp resonances are observed in this energy range

and in this mass region. More experimental data are necessary in this energy range to solve the discrepancies.

V. Experimental conditions

Kinds of reactions, beam energies employed and methods of degrading the energies and method of beam current measurements reported are shown in Table I. Here, each report has been numbered in the second column and these numbers correspond to the first column in Table II and III. The targets, kinds of radiation detectors used, stopping powers employed are shown in Table II. The half-lives, energies of radiations detected, their intensities employed and errors are shown in Table III.

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Table 1 Kinds of reactions and beam energies.

Reaction	No.	First Author	References	Incident Energy (MeV)	Minimum Energy (MeV)	Method of beam energy change	Beam current measurement
$^{124}Te(p,2n)^{123}I$	1	K.Kondo	(1)	28.19 ± 0.30 29.18 ± 0.29	9.95 ± 1.10 12.20 ± 0.80	Stacked foil	Faraday cup $^{63}Cu(p,n)^{63}Zn$
$^{127}I(p,5n)^{123}Xe$	2	S.R.Wilkins	(2)	62 ± 0.5	45.4	Stacked foil	Faraday cup
	3	A.M.J.Paans	(3)	66 < 0.6	46.4	By AVF cyclo.	Faraday cup
	4	M.Dikšić	(4)	85 ± 2	45.0	Changed radius in synchrocyclo	$^{12}C(p,pn)^{11}C$, $^{63}Cu(p,n)^{63}Zn$, $^{27}Al(p,3pn)^{24}Na$
	5	D.B.Syme	(5)	159.5 ± 0.5	38.0	Stacked foil	$^{12}C(p,pn)^{11}C$
	6	M.C.Lagunas-Solar	(6)	67.5 ± 0.5	38.6	Stacked foil	Faraday cup
$^{124}Xe(p,pn)^{123}Xe$	7	N.V.Kurenkov	(7)	34.7, 28.6, 27.5	17.2	Al degrader	Faraday cup Cu monitor
$^{133}Cs(p,spal)^{123}Xe$ $^{nat}Ba(p,spal)^{123}Xe$	8	N.F.Peek	(14)	590	320	Carbon degrader CsCl degrader	$^{27}Al(p,3np)^{24}Na$, $^{27}Al(p,x)^{22}Na$, $^{27}Al(p,x)^{7}Be$
$^{nat}La(p,spal)^{123}Xe$	9	M.Adilbish	(15)	660	-	-	$^{27}Al(p,3pn)^{24}Na$
$^{127}I(p,spal)^{123}Xe$	10	M.Adilbish	(15)	660	-	-	$^{27}Al(p,3pn)^{24}Na$
$^{122}Te(d,n)^{123}I$	11	J.H.Zaidi	(9)	14	7.4	Stacked foil	$^{51}V(d,2n)^{51}Cr$
$^{127}I(d,6n)^{123}Xe$	12	R.Weinreich O.W.B.Schult	(10) (10)	50 90 80 53	46.1	Stacked foil	$^{27}Al(d,p\alpha)^{24}Na$
$^{127}I(d,p5n)^{123}I$	13	R.Weinreich O.W.B.Schult	(10) (10)	90 80 53	55.1	Stacked foil	$^{27}Al(d,p\alpha)^{24}Na$
$^{121}Sb(\alpha,2n)^{123}I$	14	A.Calboreanu	(11)	27 ± 0.08	14.57 ± 0.60	Al degrader	Faraday cup
$^{124}Xe(p,2n)^{123}Cs$	15	N.V.Kurenkov	(7)	34.7, 28.6, 27.5	17.2	Al degrader	Faraday cup Cu foil monitor
$^{nat}La(p,spal)^{123}Cs$	16	H.L.Ravn	(17)	600	-	-	normalization to cross sections of $^{132,134,136}Cs$
$^{109}Ag(^{18}O,4n)^{123m}Cs$	17	Ch. Droste	(18)	105	57	Al degrader	Faraday cup

Table II Targets, stopping powers, detectors and half-lives

No.	First Author	Target	Stopping Power	Detector
1	K.Kondo	^{124}Te:91.86 %, 99.87 % 1.05±0.01 mg Te/cm^2 Stacked with Cu and Al foils	Williamson (19)	Ge(Li)
2	S.R.Wilkins	Litium Iodide covered by 0.051 mm Ta foil, 2 MeV thick. (Cooling He gas was checked for Xe activity)	Williamson (19)	Ge(Li), 2.6 keV(FWHM) at 1.33MeV
3	A.M.J.Paans	NaI, 1 Mev thickness covered by Al foils	-	Ge(Li),3.8 keV at 1.33 MeV
4	M.Dikšić	CuI, CHI_3 for E_p >45 MeV Ki and Al_2O_3 for E_p>45 MeV Thickness is 1 MeV at 50 MeV	-	Ge(Li), 3 keV at 1.33 MeV
5	D.B.Syme	KI, 0.33 g/cm^2 (about 1-2 MeV) Powder is compressed and sealed with thin adhesive tape (Xe losses were checked)	Barkas & Berger(20)	Ge(Li), 3 keV at 149 keV
6	M.C.Lagunas-Solar	NaI pressed into a circular cavity of Al(0.95 cm dia., 0.045 cm in thickness 35 stack was used (Xe losses were checked)	Janni (21)	Ge, 2.5 keV at 662 keV
7	N.V.Kurenkov	^{124}Xe gas in a capsule of 10 mm length, 5 mm diameter 1 atm., 280-300 um Al window	Janni (28)	Ge(Li)
8	N.F.Peek	$CsCl, BaCO_3, La_2O_3$ 0.171-0.707 g/cm^2 thickness 3 cm dia, in thin(0.5 mm) Al container	-	Ge(Li), 2 keV at 1 MeV
9	M.Adilbish	Aqueous solutions of $CsNO_3$, $Ba(NO_3)_2$, $La(NO_3)_3$	-	Ge(Li),2.6 keV at 159 keV
10	M.Adilbish	Aqueous solutions of LiI	-	Ge(Li),2.6 keV at 159 keV

Table II (continued)

No.	First Author	Target	Stopping Power	Detector
11	J.H.Zaidi	Natural Te and ^{122}Te(96.45 %) 4-4.5 mg/cm^2 thickness on 25 um, 10 um Ti backing	Williamson (19)	Ge(Li)
12	R.Weinreich O.W.B.Schult	NaI pellets(0.1 gr/cm^2) in polyethylen foils(7 mg/cm^2)	Williamson (19)	Ge(Li)
13	R.Weinreich O.W.B.Schult	Same as above	Williamson (10)	Ge(Li)
14	A.Calboreanu	0.2-0.4 mg/cm^2 Evaporated on Al backings	Williamson (10)	Ge(Li)
15	N.V.Kurenkov	^{124}Xe gas in a capsule of 10 mm length, 5 mm diameter 1 atm., 280-300 um Al window	Janni (28)	Ge(Li)
16	H.V.Ravn	70 g of La in Ta cylinder, 8cm long and 2 cm dia. Target were heated 1300 or 1400 $^{\circ}$C. Energy loss due to target thickness was 12 % for incident protons. Isoptope separator on line.	-	Ge(Li) 4-π plastic scintillator
17	Ch. Droste	Thin target, no detail is given by authors	-	Ge(Li)

Table III Intensities of gamma-rays used and erros for cross sections.

No.	Fist Author	Product	$T_{1/2}$	E_γ (keV)	I_γ (%)	Ref.for decay	Errors for cross sections		
1	K.Kondo	^{123}I	13.3h	159	83	(22)	Counting error	less than 3	%
							Target uniformity	less than 2	
							Recoil loss	very small	
							Overall error	12	
2	S.R.Wilkins	^{123}Xe	-	149	-	(22)	Beam and spectral integration	5	
							Target uniformity	6	
							Detector efficiecy	6.7	
							Decay scheme	3	
							γ-ray absorption correction	2	
							Overall error	12	
3	A.M.J.Paans	^{123}Xe	-	148.9	49.3	(22)	Ratio between Monitor(511 keV)		
				178.1	15.1		and 149 keV	3	
							Statistical error	5	
							Detector efficiency	10	
							Target uniformity	5	
							Dead time correction	less than 1	
							Current integration	less than 1	
							Overall error	12.5	
4	M.Diksic	^{123}Xe	2.1 h	178.1	19.5	(23)	Full-energy peak areas,		
				330.2	11.2		decay curve analysis, monitor		
				899.6	3.2		reactions are included.		
				1093.4	3.		Gamma-ray intensities, counter		
							efficiency, half-life are		
							relatively small and neglected.		
							Overall error	5.4-12.5	
5	D.B.Syme	^{123}Xe	1.99 h ± 0.018	149	50	(24)	Target thickness	2.0@	4.0*
							Self-absorption of gamma-ray	0.6@	2.0*
							Gamma detector calibration	2.0@	3.5*
							Observed activity	2.0@	2.0*
							Counting dead time	1.0@	2.0*
							Gamma-ray absolute abundance	small	
							Half-life	-	3.3*
							Sub total	3.7@	7.2*
							Monitor cross section	3.7@	7.1*
							Overall	5.2@	10.1*

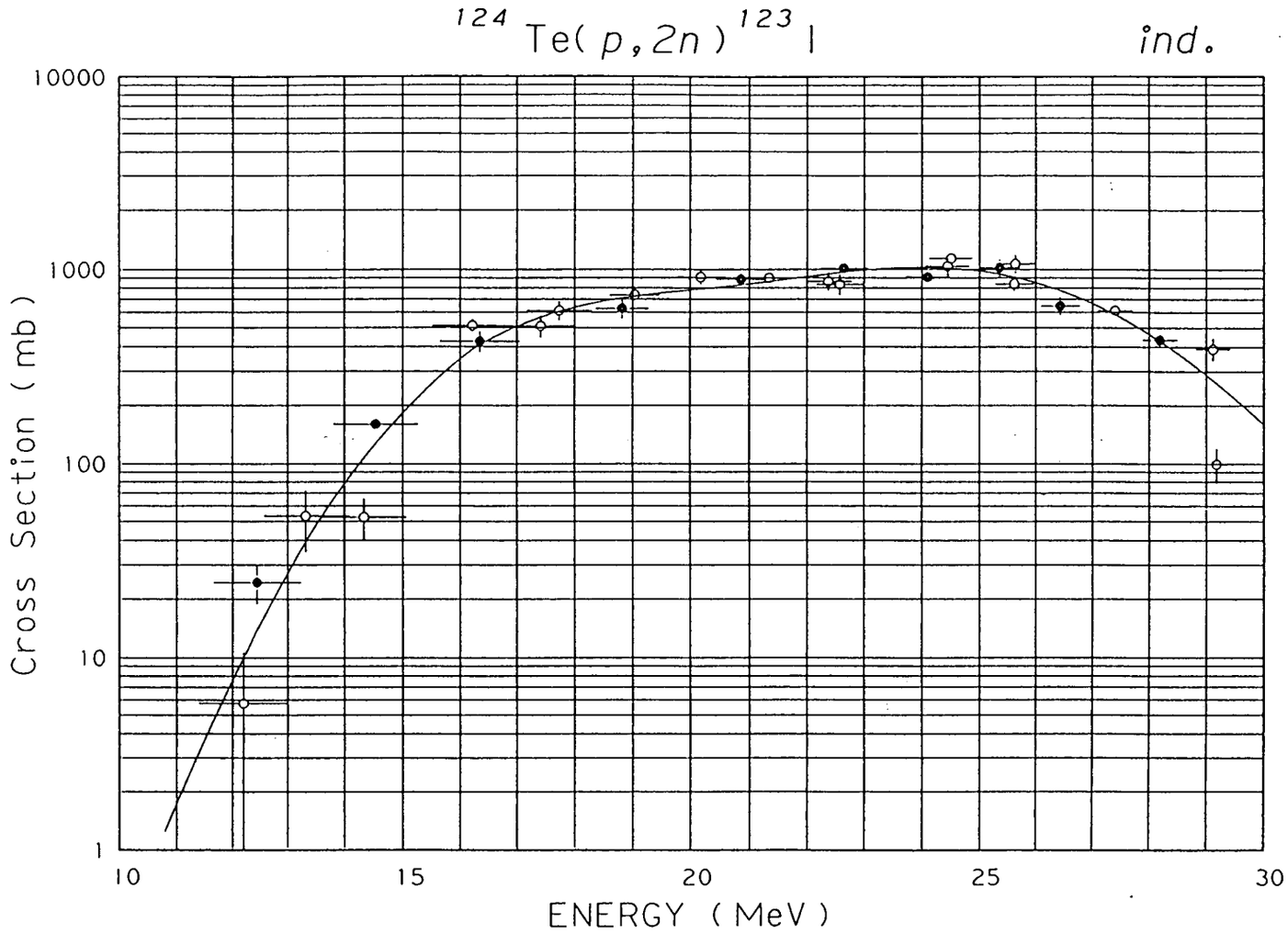
@ Root mean square errors
* systematic errors

Table III (continued)

No.	Fist Author	Product	$T_{1/2}$	E_γ (keV)	I_γ (%)	Ref.for decay	Errors for cross sections	
6	M.C.Lagunas-Solar	^{123}Xe	2.08 h	178 330	14.9 8.6	(25)	Incident beam energy 1 Range value 1 NaI target density 1 NaI target thickness 1 Total energy uncertainties 67 Mev 1 7.5 29 Beam-current integration 3 Calibration sources 3 Detector efficiency 5 Counting geometry 1 Decay constant 3 Gamma-ray abundances 5 Integration routine 3 Total uncertainty(one standard deviation) 9	(av.)
7	N.V.Kurenkov	^{123}Xe	2.08 h	148.91 177.99 330.19	49.0 14.9 8.6	-	Proton energy 2 Stopping power 2 Proton absorber thickness 1 Beaum current less than 3 Effect of beam intensity 5 Gas density 1 Capsule volume 3 Radionuclide assay and source geometry 1 Statistical error 3 Detector efficiency 10 Gamma-ray yield 10 Total error(others included) 18	
8	N.F.Peek	^{123}Xe	-	149	50	(24)	Standard source 2 Gamma-ray self-absorption dead time and secondary effect were considered. Over all 10	
9 10	M.Adilbish	^{123}Xe	2.08 h	148 178 330	50 16 8.6	-	No detail of errors are reported by the authors Overall error 5-16	
11	J.H.Zaidi	^{123}I	13.02 h	159	82.9	(25)	Overall error 10-12	
12	R.Weinreich O.W.B.Schult	^{123}Xe	2.1 h	149	53	(23)	Detector efficiency(relative) 3 Standard source 1	
13	R.Weinreich O.W.B.Schult	^{123}I	13.3 h	159	86	(26)	Detector efficiency 3 Standard source 1	

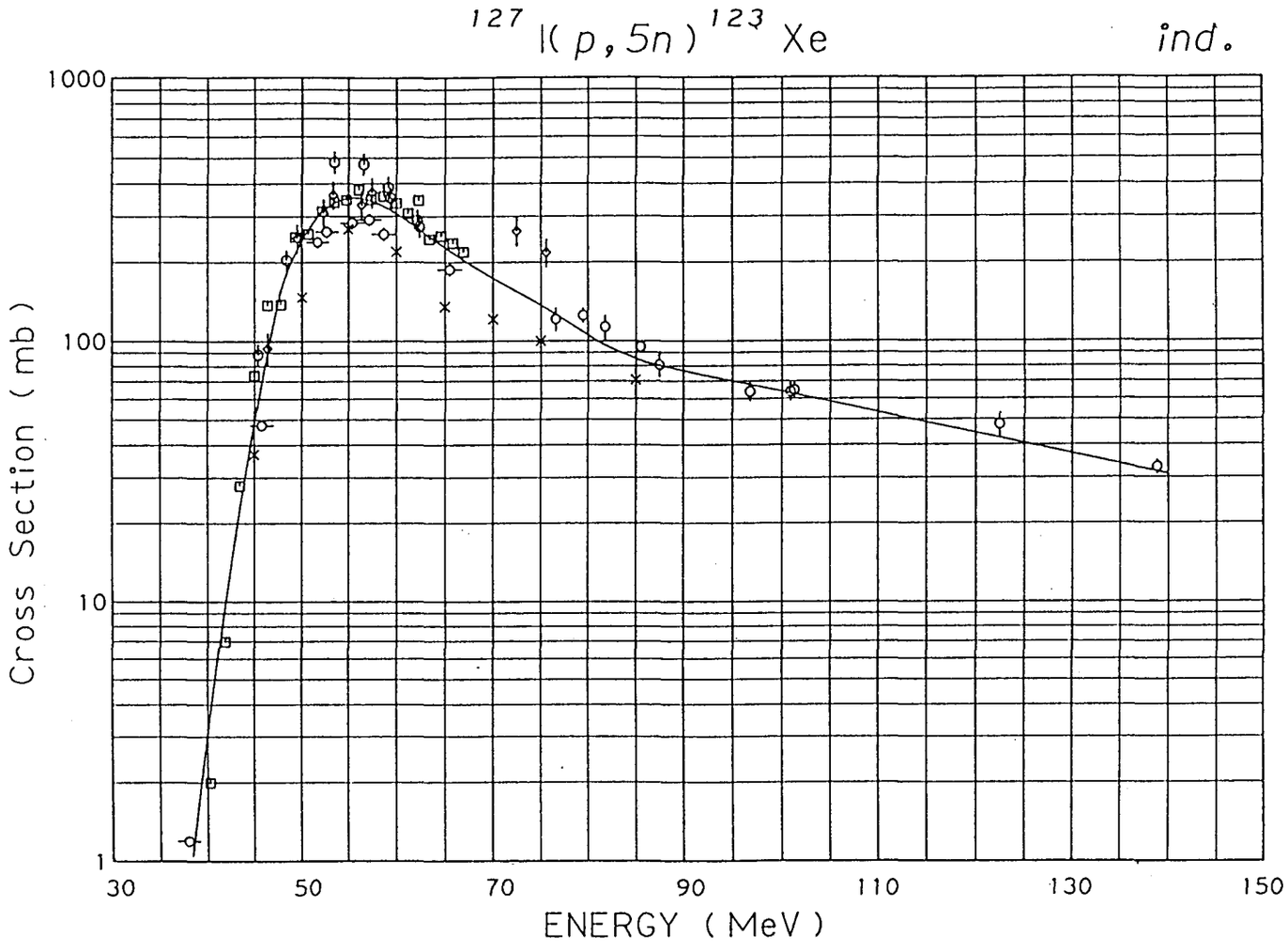
Table III (continued)

No.	Fist Author	Product	$T_{1/2}$	E_γ (keV)	I_γ (%)	Ref. for decay	Errors for cross sections	
14	A.Calboreanu	^{123}I	13.3 h	159	83	(27)	Counting error	<1
							Typical error	
							at 26.5 MeV	0.15
							18.9	1.2
							14.6	60
15	N.V.Kurenkov	^{123}Cs	5.87 m	97.36	14.5	-	Gamma-ray yield	14
				586.54	8.3		For other errors refer to No.7	
				741.31	2.4		Total error	12
16	H.V.Ravn	^{123}Cs	-	-	-	-	Efficiency fluctuations due to performance of the target, ion-souroe, source collection etc. are estimated	50
							Yield curve as a function of mass numbers are normalized using 9.4±0.8, 4.8±0.6 and 1.26±0.15 mb for ^{132}Cs, ^{134}Cs and ^{136}Cs respectively.	
							Suggested total errors	200
17	Ch. Droste	^{123m}Cs	1.6 s	99.5	-	-	Product was checked by cross bombardment of $^{115}In(^{12}C,4n)^{123}Cs$.	
							No detail is given by authors.	



K. Kondo (1) ϕ ^{124}Te with 91.86 isotopic enrichment
ϕ ^{124}Te with 99.87 isotopic enrichment

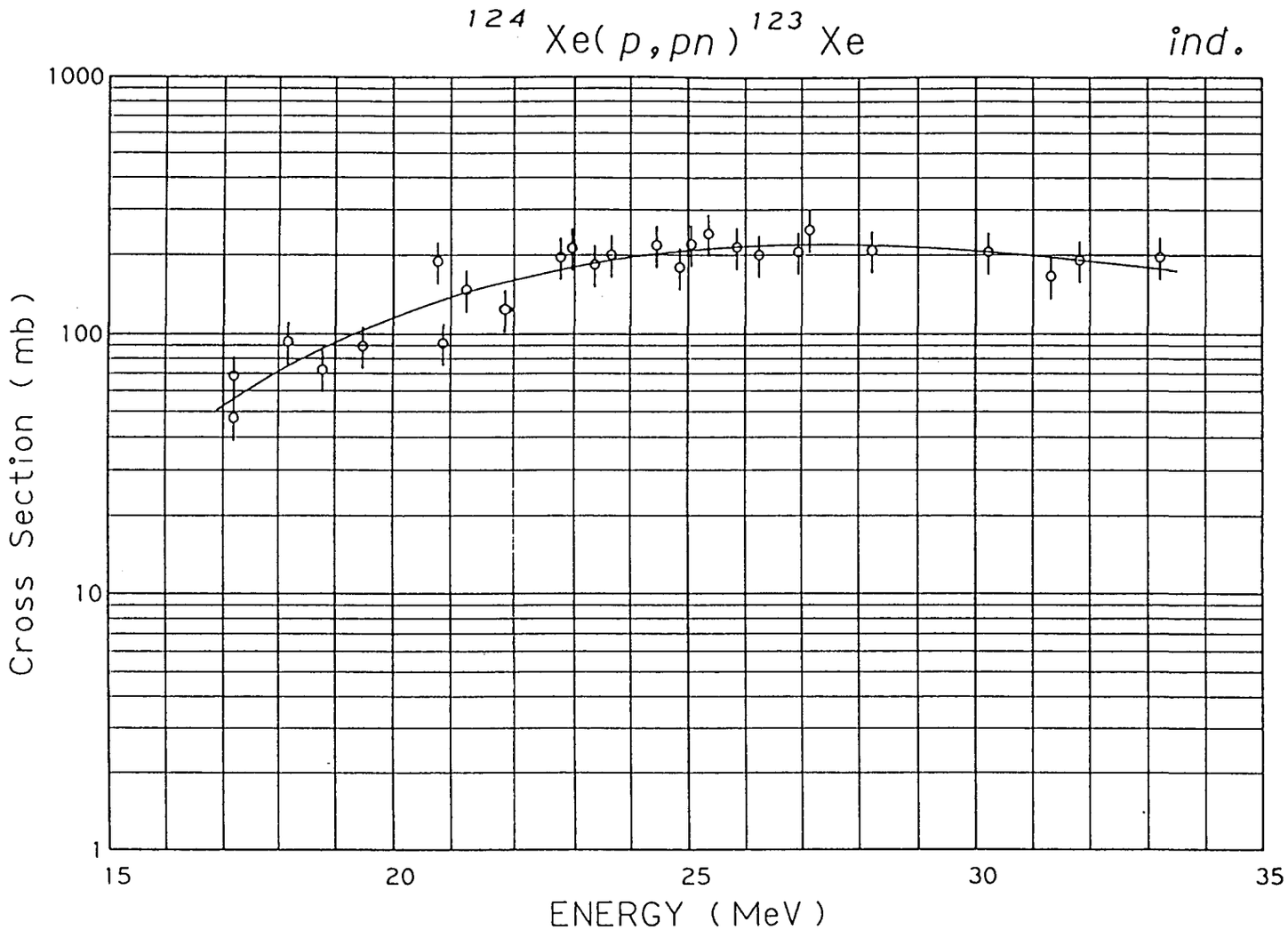
Fig. 1



S. R. Wilkins (2), A. M. J. Paans (3), M. Dikšić (4),

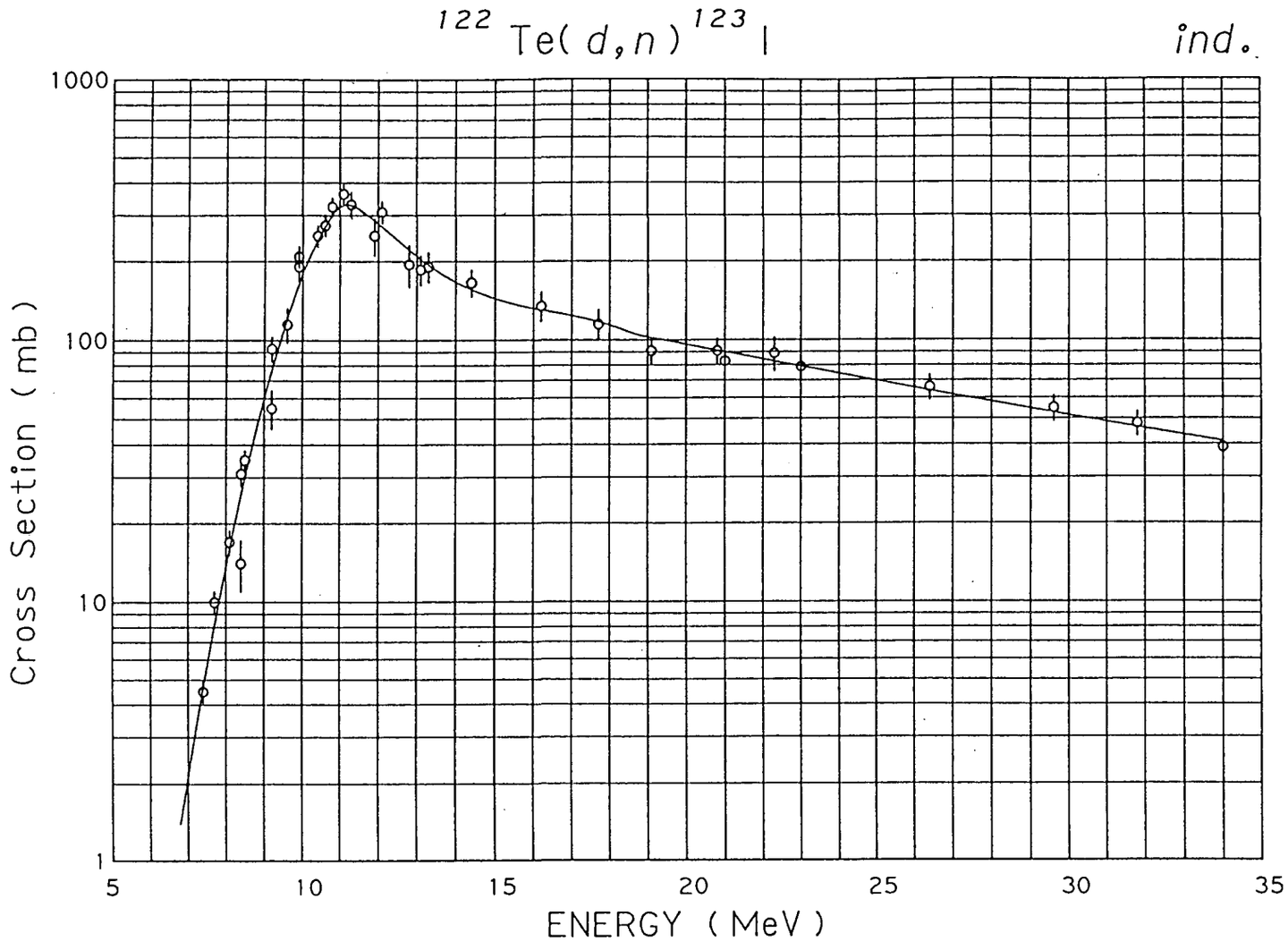
D. B. Svme (5), M. C. Lagunas-Solar (6)

Fig. 2



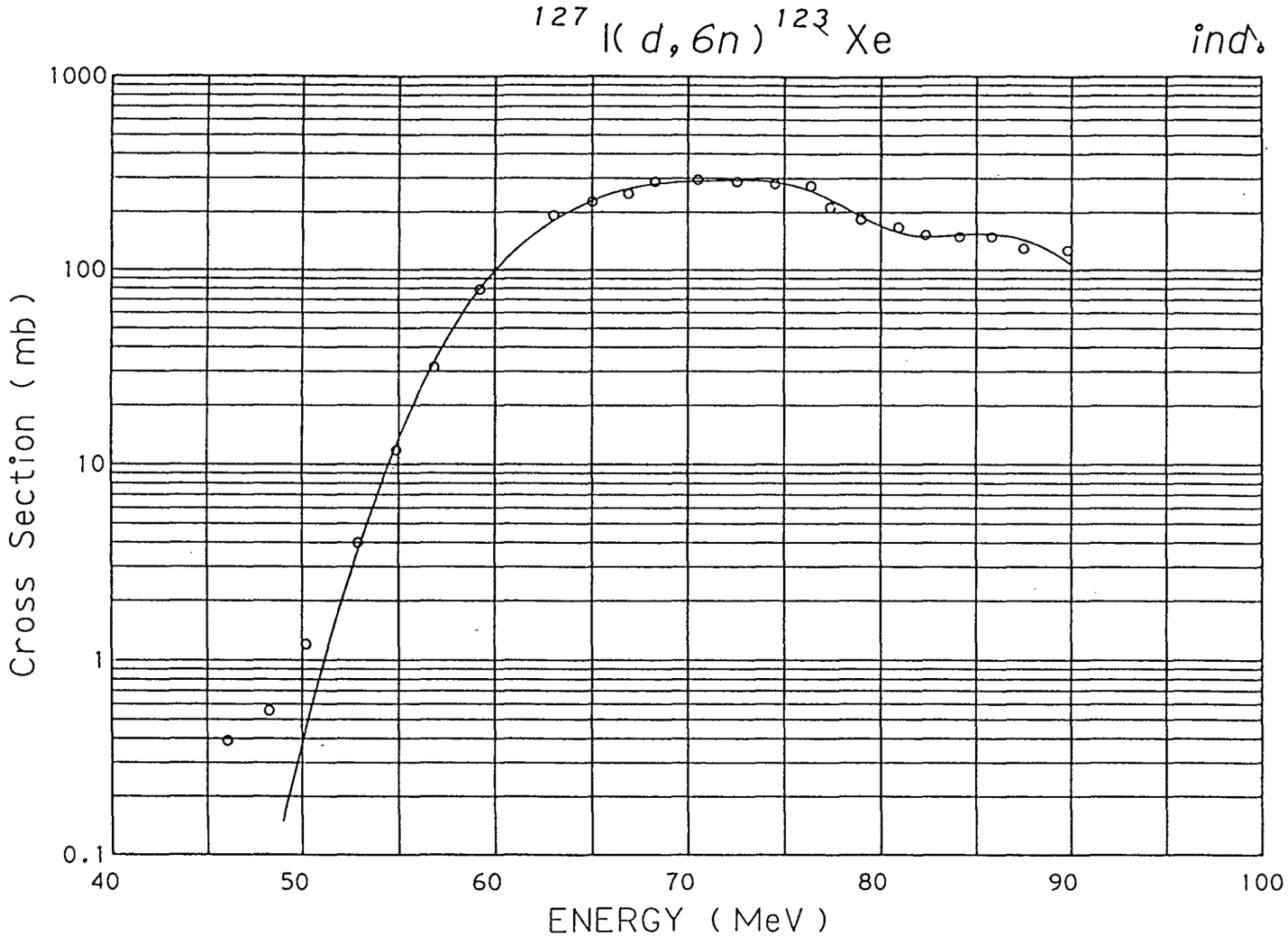
N. V. Kurenkov (7)

Fig. 3



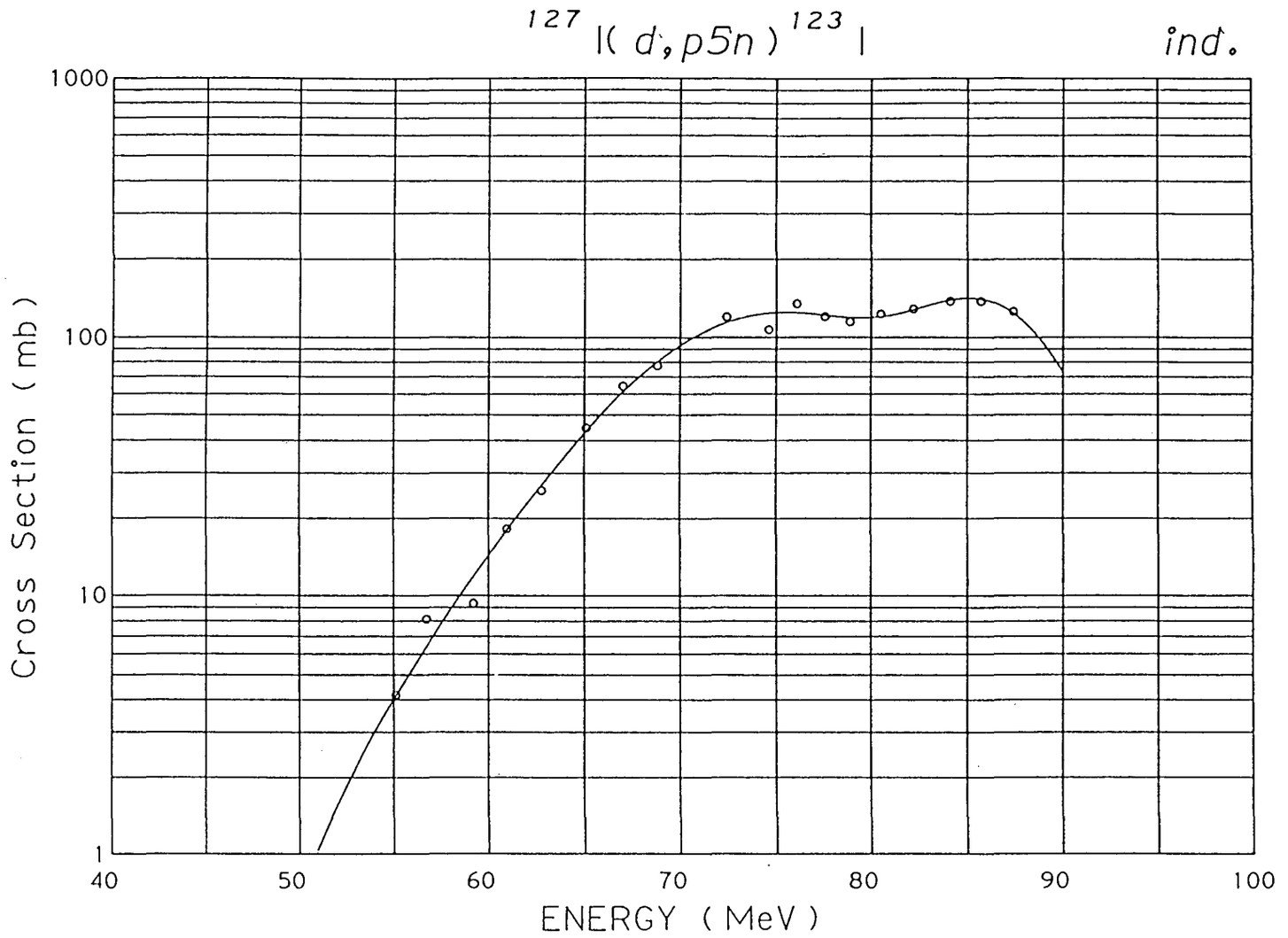
J. H. Zaidi (9)

Fig. 4



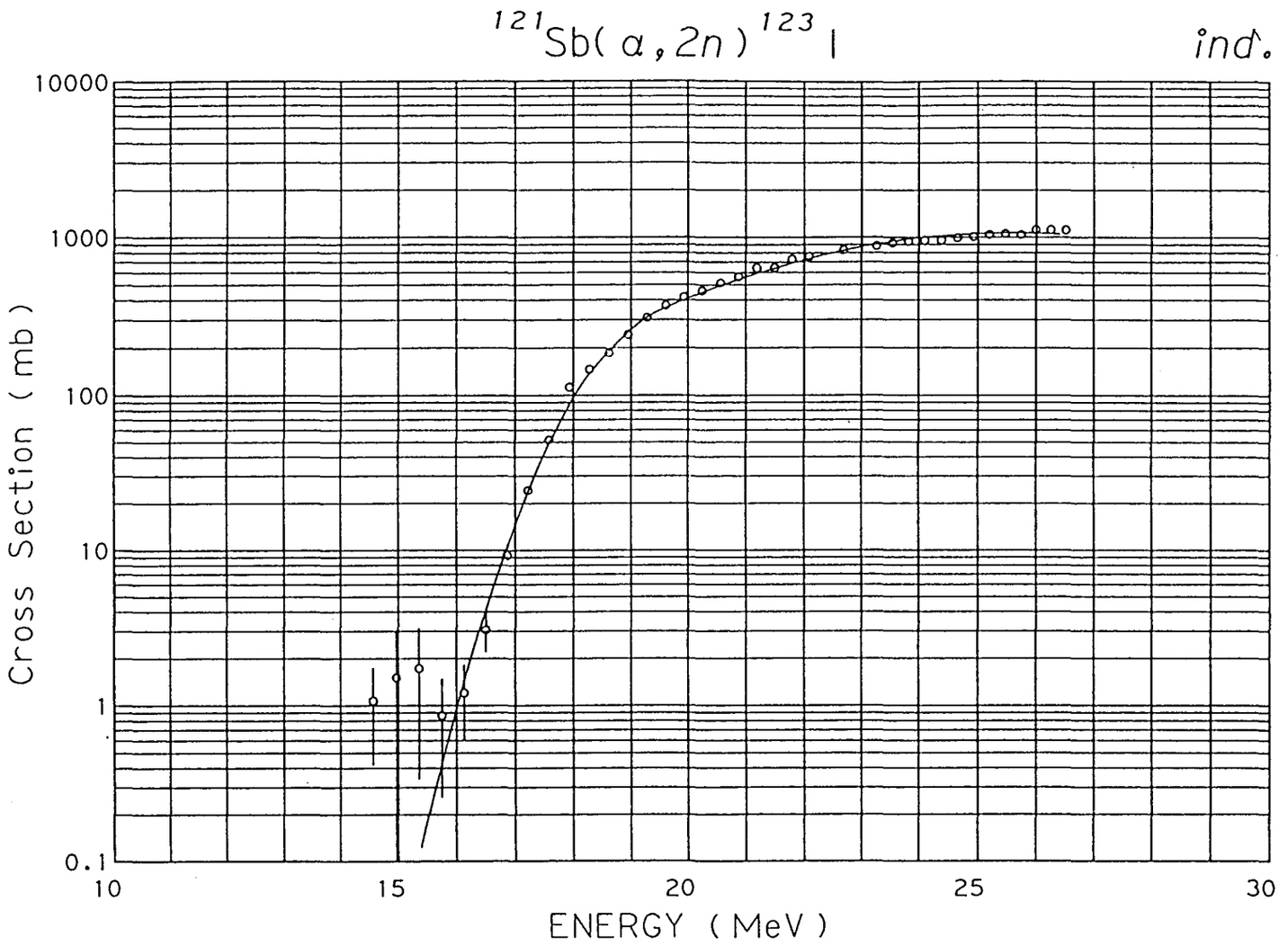
O. Schult (10)

Fig. 5



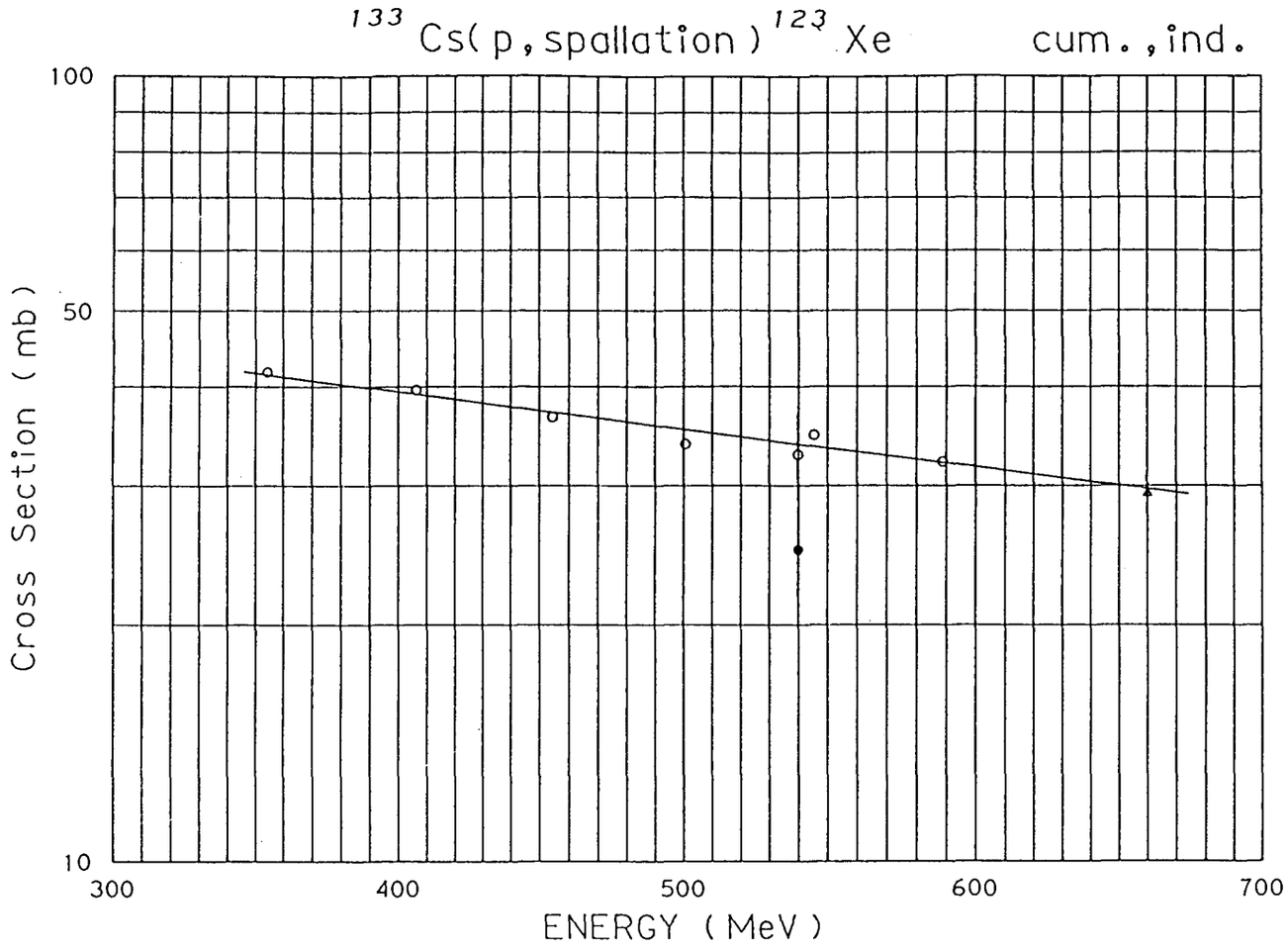
O. Schult (10)

Fig. 6



A. Calboreanu (11)

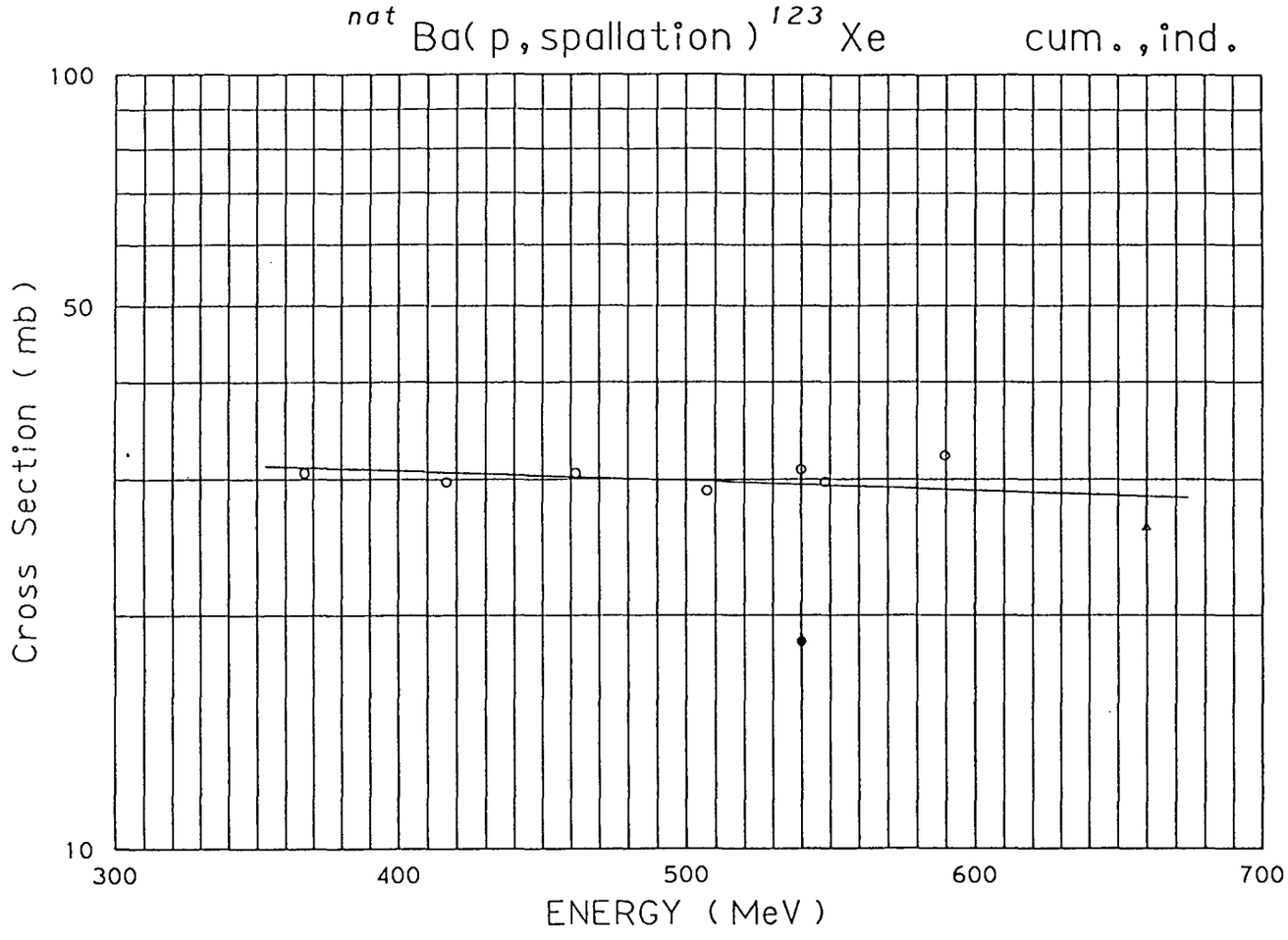
Fig. 7



○ N. F. Peek (14), a closed circle shows independent data.

▲ M. Adilbish (15)

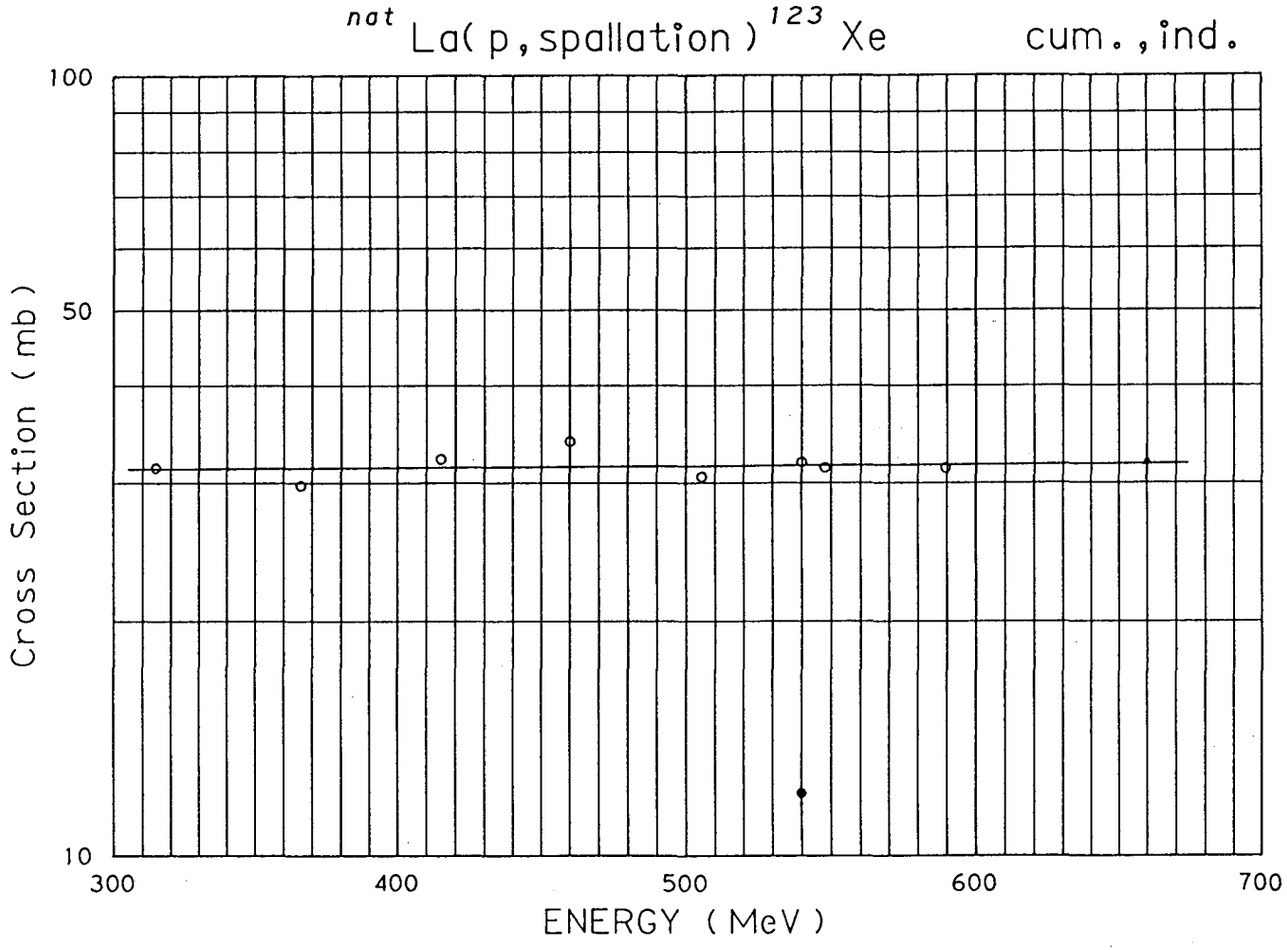
Fig. 8



o N. F. Peek (14), a closed circle shows independent data.

▲ M. Adilbish (15)

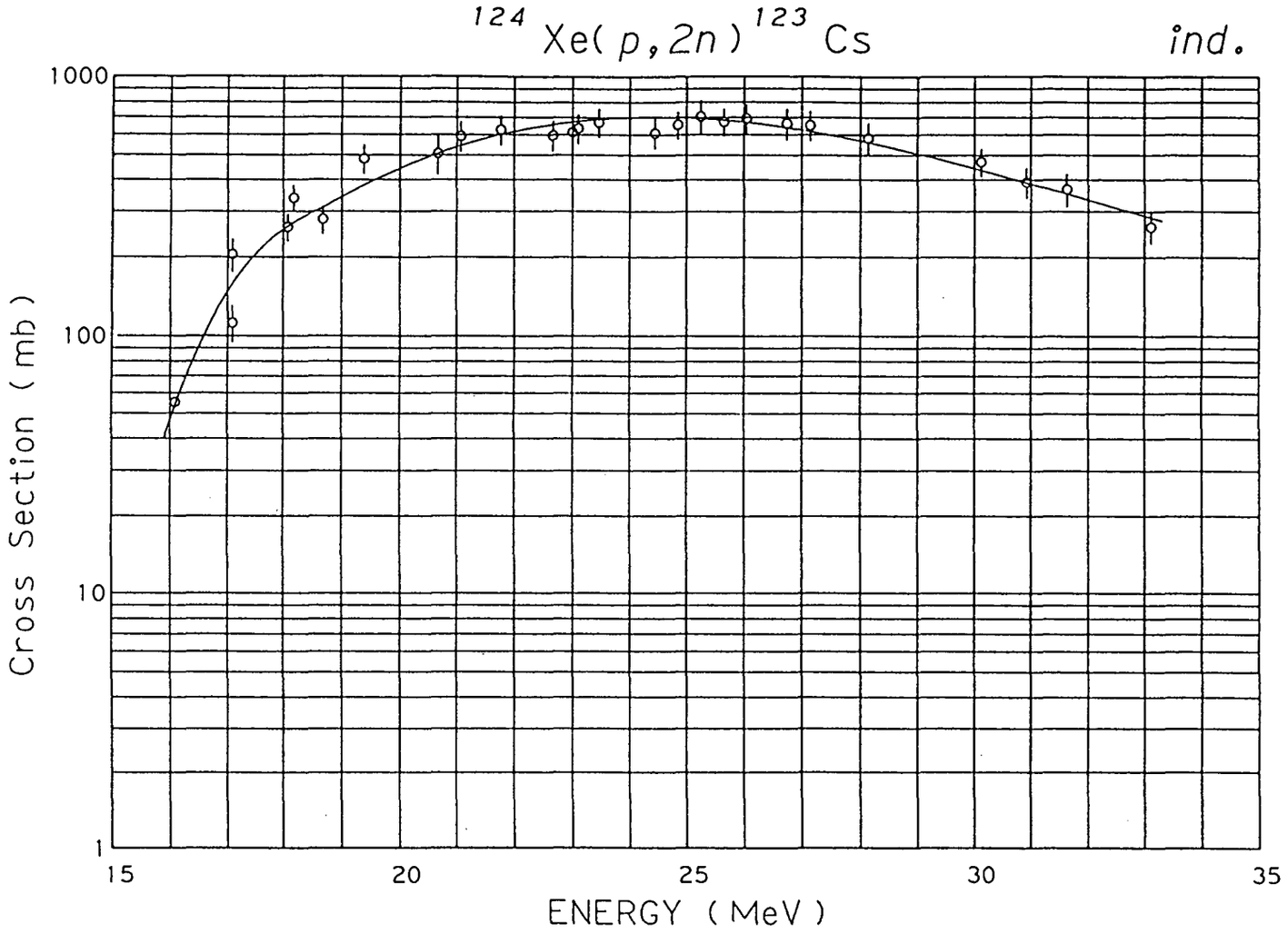
Fig. 9



○ N. F. Peek (14), a closed circle shows independent data.

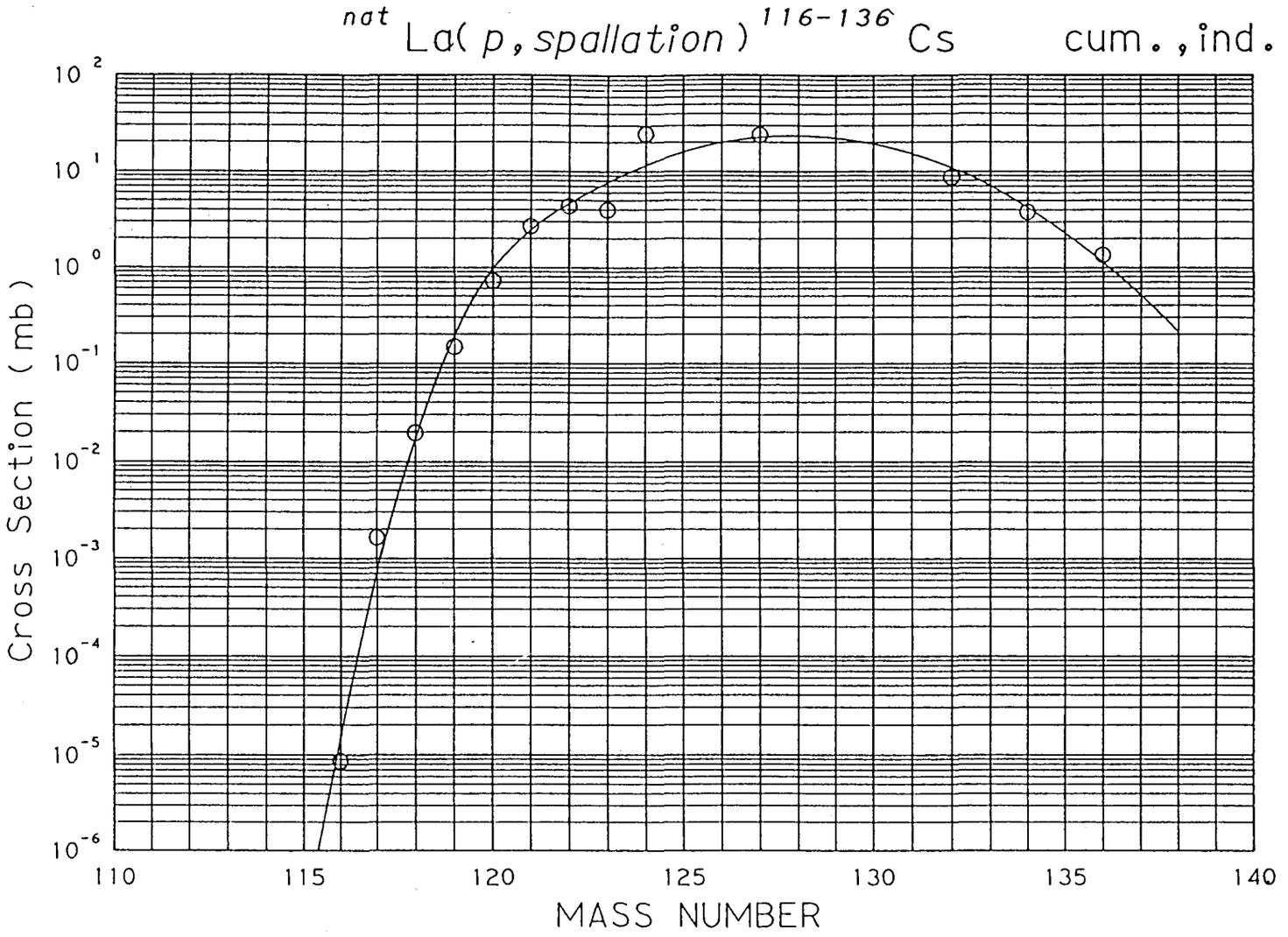
▲ M. Adilbish (15)

Fig. 10



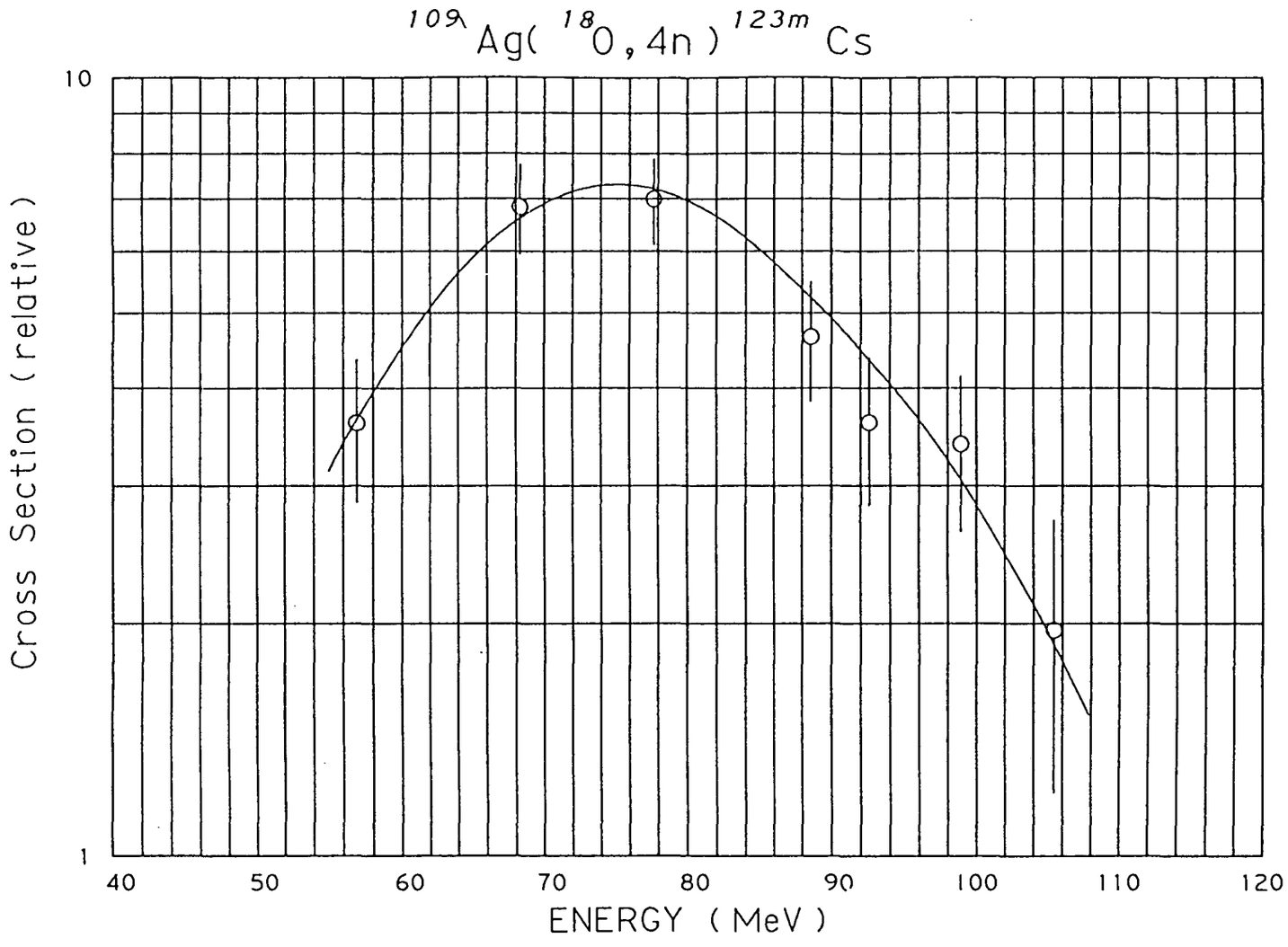
N. V. Kurenkov (7)

Fig. 11



H. L. Ravn (17)

Fig. 12



Ch. Droste (18)

Fig. 13