A0033/76

DEZ,1976

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CROSS SECTIONS OF (γ,xn) REACTIONS IN COMPLEX NUCLEI AT INTERMEDIATE ENERGIES*

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ABSTRACT

Cross sections per equivalent quantum, in the energy range 0.3 GeV - 1.0 GeV, have been measured for ^{209}Bi$(\gamma,2n)$, ^{209}Bi$(\gamma,3n)$, ^{209}Bi$(\gamma,4n)$, ^{59}Co$(\gamma,2n)$, ^{59}Co$(\gamma,4n)$, and ^{51}V$(\gamma,3n)$ reactions. From the calculated mean absolute cross sections and the data already available in literature for (γ,xn) reactions $(x \geq 1)$, a cross section formula has been deduced which reproduces, within a factor of two, most of the experimental cross sections for target nuclei ranging between ^{9}Be and ^{238}U.

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[*] This work has been supported in part by the Brazilian Comissão Nacional de Energia Nuclear and by the Italian Consiglio Nazionale delle Ricerche.

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INTRODUCTION:

For energies above the π-meson photoproduction threshold, the interaction of photons with complex nuclei can yield a variety of nuclear reactions which have been roughly classified as direct reactions, spallation, fragmentation and fission. Among them, an important class of photonuclear reactions are those which lead to the formation of residual nuclei with a few neutrons lost by the target nuclei. Such reactions may contribute to some extent to the total photoabsorption cross section.

In the present work we are particularly interested in obtaining information about cross sections for the (γ,xn) reactions $(1 < x < 5)$ in complex nuclei (from ^{9}Be up to ^{209}Bi) at intermediate energies (0.2 - 1.0 GeV), since a comparison between the yields of such reactions and the (γ,n) reactions can lead to a better understanding of photonuclear interaction.

Cross sections for the (γ,xn) reactions $(x \geq 1)$ in complex nuclei at intermediate energies have been systematically measured in our laboratory [1-8] and by researchers at the Lund University [9-17]. Since the residual nuclei photoproduced in such reactions are radioactive, the activation analysis with gamma-spectrometry is entirely adequate for identifying the produced radionuclides and for obtaining the final cross sections. Moreover, semiempirical estimates of the cross sections based on the Rudstam's five-parameter formula [13,18], and the Monte Carlo intranuclear cascade-evaporation model have, in some cases, fitted the experimental cross sections quite well [2,19-21]. In the case of the (γ,n) reactions, the large amount of experimental data allowed us to analyse them in a systematic manner, and to construct semiempirical formulas which reproduce the experimental cross sections [1-2].

The purpose of the present work is to present some new data on mean cross sections in the energy range 0.3 - 1.0 GeV for the reactions ^{59}Co(γ,2n), ^{209}Bi(γ,2n), ^{51}V(γ,3n), ^{209}Bi(γ,3n), ^{59}Co(γ,4n) and ^{209}Bi(γ,4n). Results will be compared with those previously obtained by other authors and a systematic analysis of the available data in literature will be presented.

EXPERIMENTAL

The experiments were carried out at the Frascati 1 GeV Electron-synchrotron by using the uncollimated bremsstrahlung beams produced by collision of electrons accelerated to the desired energy on thin radiators. Different end-point energies of the bremsstrahlung spectra between 0.3 GeV and 1.0 GeV have been selected. The irradiation time during the exposures ranged between 8 hours for the reactions with produced radionuclides with short half-lives and 20 hours for those with produced radionuclides with long half-lives. In the case of ^{209}Bi(γ,2n) reaction more lengthy exposures were made. Dose measurements were carried out with polyethylene monitors, placed just in front of the samples, by means of the ^{12}C(γ,X)^{7}Be reaction [22]. As an average, typical values of the total number of equivalent quanta passed through the target samples were 2.0×10^{13} at 0.3 GeV and 2.0×10^{15} at 1.0 GeV. The time-dependent beam intensity variations were monitored by electronic devices. Corrections for the decay during the irradiation were taken into account for the photoproduced ^{55}Co.

The target samples were positioned at 1.5m in air from the beam exit window and irradiated at right angles with respect to the incident beam. In this way, the beam hits the targets with a cross-sectional diameter smaller than the size of the samples. Data concerning the target samples are listed in Table 1.

Counting of the samples after irradiations was carried out by means of a conventional γ-ray spectrometry line with a 70 cm^3 (nominal volume) true coaxial Ge-Li detector connected with a 1024-channel pulse-height analyser. The detector efficiency was experimentally determined by means of a number of standard calibrated γ-ray sources (supplied by the New England Nuclear Corporation, Boston, Mass., U.S.A.), whose effective standard deviation was less than 1%. Corrections for non-point sources have been taken into account. The identification of radionuclides was made from both half-life measurements and γ-ray energies in the spectra. For each reaction under investigation, the final radioactive produts of interest, as well as some related spectrometric data [23], are reported in Table 1.

RESULTS

The yields, expressed as cross sections per equivalent quantum, σ_Q, for the reactions studied in the present work are reported in Figs. 1 and 2. As can be seen, the smoothed curves indicate an increase in the cross section per equivalent quantum with increasing the bremsstrahlung end-point energy, E_o. A brief discussion about the errors involved in the cross section measurements can be found in previous papers [22,24]. For the sake of comparison, we also report in Fig. 1 the yields of the $^{51}V(\gamma,3n)$ reaction obtained by Blomqvist *et al.* [17]. Although the yields in Ref. [17] are slightly higher than our results, they exhibit, in the energy interval 0.25 - 0.60 GeV, a quite similar trend.

From the physical point of view, the magnitude of interest is the mean absolute cross section, $\bar{\sigma}_k$. In the energy range 0.3 - 1.0 GeV, the absolute cross sections have been obtained by means of the "square" approximation of the bremsstrahlung spectra. Since we have relatively few σ_Q measurements in this energy-range, a linear dependence of the σ_Q *versus* $\ln E_o$ has been assumed. In this way, the least-squares analysis gives the mean absolute cross section, $\bar{\sigma}_k$, for the reactions under investigation, according to

$$\bar{\sigma}_k = \frac{d\sigma_Q}{d\ln E_o} \quad . \qquad (1)$$

The results are listed in Table 2, where we also report all existing data on cross sections for the (γ,xn) reactions with $1 < x < 5$. Where not explicitly calculated by the authors quoted in this Table, mean values of σ_k have been deduced from the experimental σ_Q curves and by making use of eqn (1). In any case, corrections for the actual shape of the bremsstrahlung spectra have not been taken into account. As far as the $^{51}V(\gamma,3n)$ reaction is concerned, the results compare well with each other, if we consider the large errors involved in obtainig $\bar{\sigma}_k$ values and the different energy ranges considered.

DISCUSSION

Data now available allows us to make some considerations on specific (γ,xn) reactions for different target nuclei.

Figs. 3-5 are log-log plots of the absolute cross sections *versus* the mass number of the target nucleus, A_t, for the reactions $(\gamma,2n)$, $(\gamma,3n)$ and $(\gamma,4n)$, respectively. The experimental $\overline{\sigma}_k$ value for the $^{127}I(\gamma,2n)$ reaction [3] has not been considered in Fig. 3, since its value is considerably higher than the correspondent (γ,n) reaction cross section [1]. As a general rule, the (γ,xn) cross sections, $\overline{\sigma}_k$, increase with mass number, A_t, for all values of $1 < x < 5$. By least-squares fitting the experimental points, we obtained

$$\overline{\sigma}_k(\gamma,2n) = 2.58 \times 10^{-4}\, A_t^{1.88}\ \text{mb} \qquad (2)$$

$$\overline{\sigma}_k(\gamma,3n) = 3.05 \times 10^{-3}\, A_t^{1.17}\ \text{mb} \qquad (3)$$

$$\overline{\sigma}_k(\gamma,4n) = 3.20 \times 10^{-6}\, A_t^{2.45}\ \text{mb} \qquad (4)$$

A similar trend had been already found for the (γ,n) reactions [1], according to

$$\overline{\sigma}_k(\gamma,n) = 0.104\, A_t^{0.81}\ \text{mb} \quad . \qquad (5)$$

In this latter case, we have related the coefficient 0.104 mb to the cross sections of the primary photon-nucleon interactions ,

$$\gamma + \text{nucleon} \longrightarrow \text{nucleon} + \pi\text{-meson}. \qquad (6)$$

Furthermore, the $A_t^{0.81}$-dependence of the (γ,n) cross section strongly supports the idea of a volume-production model with some sort of suppression in the inner part of the nucleus, due to particle reabsorption processes (a pure nuclear surface interaction model would yield an $A_t^{2/3}$-dependence of the cross section). Such an interpretation of eqn (5) was possible since we regard a (γ,n) reaction as a simple direct or quasi-direct reaction.On the contrary, this is not the case for reactions such as $(\gamma,2n)$, $(\gamma,3n)$ and $(\gamma,4n)$, which must be properly described by a two-step cascade-evaporation mechanism. It is possible, however, that a large percentage of events leading to a $(\gamma,2n)$ reaction will occur in the rapid intranuclear cascade step initiated by the incoming photon. As a consequence, a physical interpretation of the numerical coefficients which appear in eqns (2-4) will be left for a future work, when estimates of the cross sections of the (γ,xn) reactions based on the Monte Carlo calculations will be available.

Owing to the large amount of experimental data collected in Table 2, it appears important to systematize the results in order to present the (γ,xn) reaction cross sections in a more practical manner. Since we are dealing with photoproduction of several isotopes belonging to the same target element, an attempt to represent the mean cross sections, $\bar{\sigma}_k$, was carried out, following a cross section distribution curve of the type

$$\bar{\sigma}_k = C_1 \exp\left[-C_2|A-A_p|^{\alpha}\right] , \qquad (7)$$

where A is the mass number of the product nuclide (A_p refers to the most probable mass number and defines the position of such a distribution) and C_1, C_2, and α are positive constants ($\alpha > 1$), C_2 representing the width of the distribution. In the case of the (γ,xn) reactions we are considering, we have

$$\begin{aligned} A &= A_t - x \\ A_p &= A_t - 1 \end{aligned} \qquad (8)$$

where x represents the number of neutrons lost by the target nucleus. Therefore, eqn (7) is rewritten as

$$\overline{\sigma}_k(\gamma,xn) = C_1 \exp\left[-C_2(x-1)^{\alpha}\right] \quad . \tag{9}$$

For $\alpha = 2$ (Gaussian distribution) the cross sections fall quite rapidly at the wings and therefore distributions with $1 < \alpha < 2$ which decrease more slowly, were investigated. From semi-log plots of all existing data in literature on $\overline{\sigma}_k(\gamma,xn)$ *versus* $(x-1)^{\alpha}$ $(x \geq 1)$ for each target nucleus (see Table 2 and Refs.[1,9, 13,15,19]), and by using a least-squares analysis, a value of α equal to 5/4 can be assumed. With this assumption, and by expressing the cross sections in millibarn, the A_t-dependence of the coefficients C_1 and C_2 was determined to be

$$C_1 = 0.187\, A_t^{0.684} \text{ mb} \quad . \tag{10}$$

$$C_2 = 37\, A_t^{-0.924} \quad . \tag{11}$$

Of course, according to eqn (9), the coefficient C_1 represents the (γ,n) cross section, which compares rather well with the experimental trend given by eqn (5). In this way, the (γ,xn) cross sections $(x \geq 1)$ can be deduced as

$$\overline{\sigma}_k(\gamma,xn) = 0.187\, A_t^{0.684} \exp\left[-37 A_t^{-0.924}(x-1)^{5/4}\right] \text{mb} \quad . \tag{12}$$

In the last column of Table 2 we list the calculated mean cross sections, $\overline{\sigma}_k$, according to eqn (12). About 75% of the experimental (γ,xn) cross sections $(1 < x < 5)$ are reproduced within a factor of 2. Taking into account all the experimental (γ,xn) cross sections $(x \geq 1)$, it is found that the cross section formula (eqn (12)) predicts 65% of the experimental cross sections also within a factor of 2. The agreement between calculated and experimental cross sections might be considered good if we remember that the range of cross sections covered is very large, as well as the range of target nuclei (from ^{9}Be up to ^{238}U). Furthermore, the experimental determinations are quite often very uncertain.

In Fig. 6 we represent the (γ,xn) cross section distributions for various target elements (^{12}C, ^{59}Co, ^{75}As, ^{127}I and ^{197}Au). The experimental points for ^{12}C, ^{59}Co and ^{75}As agree quite well with the calculated cross section distributions, while for ^{127}I and ^{197}Au, the curves deviate downward from the measured cross sections, mainly in the region of large numbers of neutrons lost by the target nuclei (say $x > 4$). Recently, a Monte Carlo calculation of photon induced intranuclear cascades at intermediate energies [21] has shown that, as an average, two or three neutrons are ejected from heavy target nuclei leading to residual nuclei with an average excitation energy of about 150 MeV. Therefore, a (γ,xn) reaction with $x \geq 4$ will surely occur during the cascade and evaporation steps. So, for these reactions, we should speak of a true spallation reaction. On the other hand, as the average number of emitted neutrons in the cascade step is about one for light nuclei and two for intermediate mass nuclei leading to residual nuclei with mean excitation energies of about 50 MeV and 100 MeV, respectively, it is more probable that for these nuclei a (γ,xn) reaction with $x < 4$ will take place in the rapid cascade stage. Thus, such reactions may be thought of as quasi-direct reactions. Due to the lack of experimental data on (γ,5n), (γ,6n), etc., reactions in more massive nuclei, it is reasonable to expect that the cross section distributions given by eqn (12) fit well with experimental data only in the region of $A_t \leq 100$ and $x \leq 4$. A more properly systematic description of true spallation reactions such as

^{127}I(γ,xn) and ^{197}Au(γ,xn) with a large number of neutrons lost, may be encountered on the basis of a general treatment of photon-induced spallation reactions. As a matter of fact, Jonsson and Lindgren [18] were successful in analysing the above photoreactions by a proper modification of the Rudstam's five-parameter formula.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the members of the Synchrotron staff of the Laboratori Nazionali di Frascati for assistance during irradiations. The critical reading of the manuscript and useful discussions with Prof. F. Salvetti are also gratefully acknowledged.

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Table 1. Data Concerning the Target Samples, Produced Radionuclides and Related Spectrometric Data.

Target Nucleus[a]	Chemical Compound	Form	Number of Nuclei *per* cm^2	Reaction	Produced Radionuclide	Half-life	E_γ (MeV)	Intensity (%)
^{209}Bi	Bi_2O_3	Powder[b]	1.2×10^{21}	$(\gamma,2n)$	^{207}Bi	30.2 y	0.570	98
							1.063	77
				$(\gamma,3n)$	^{206}Bi	6.24 d	0.880	72
							1.720	36
				$(\gamma,4n)$	^{205}Bi	15.31 d	1.766	27
^{59}Co	Metal	Foil[c]	2.0×10^{21}	$(\gamma,2n)$	^{57}Co	270 d	0.122	87
							0.136	11
				$(\gamma,4n)$	^{55}Co	18.2 h	0.480	12
^{51}V	Metal	Foil[c]	2.0×10^{21}	$(\gamma,3n)$	^{48}V	16 d	0.983	100
							1.312	97

[a] The bismuth and cobalt targets are monoisotopic; ^{51}V has an isotopic abundance of 99.75 %.

[b] Powders uniformly packed between two thin lucite disks (5 cm diameter).

[c] Thin metal foils in the form of disks (5 cm diameter).

Table 2. Mean Absolute Cross Sections for the (γ,xn) Reactions, with $1<x<5$, in Complex Nuclei at Intermediate Energies.

Target Nucleus	Reaction	Energy-Range (GeV)	Ref.	Cross Section, $\bar{\sigma}_k$(mb)	
				(Experimental)	(Calc. [a])
^{9}Be	$(\gamma,2n)$	0.3 - 1.0	8	0.021 ± 0.002	0.007
^{12}C	$(\gamma,2n)$	0.2 - 0.8	16	0.0277± 0.0004	0.025
^{16}O	$(\gamma,2n)$	0.2 - 0.8	16	0.0113± 0.0003	0.072
^{51}V	$(\gamma,3n)$	0.3 - 1.0	This work	0.23 ± 0.06	0.268
		0.25- 0.60	17	0.38 ± 0.04	0.268
^{55}Mn	$(\gamma,3n)$	0.3 - 1.0	7	0.41 ± 0.05	0.33
		0.3 - 0.8	11	0.311 ± 0.016	0.33
	$(\gamma,4n)$	0.3 - 1.0	7	0.053 ± 0.004	0.079
^{59}Co	$(\gamma,2n)$	0.4 - 1.0	This work	1 ± 1	1.3
	$(\gamma,4n)$	0.3 - 1.0	This work	0.06 ± 0.01	0.1
^{75}As	$(\gamma,3n)$	0.2 - 0.9	12	0.39	0.7
	$(\gamma,4n)$	0.2 - 0.9	12	0.24	0.24
^{89}Y	$(\gamma,3n)$	0.25- 1.0	14	0.47	1.0
^{103}Rh	$(\gamma,2n)$	0.4 - 0.9	4,6	5.1 ± 2.4	2.7
^{127}I	$(\gamma,2n)$	0.1 - 0.8	9	7.4[b]	3.4
		0.3 - 1.0	3	20 ± 7	3.4
	$(\gamma,3n)$	0.3 - 1.0	3	0.7 ± 0.2	1.9
		0.25- 0.9	9,10,13	1.6 ± 0.5	1.9
	$(\gamma,4n)$	0.25- 0.9	9,10,13	1.4 ± 0.4	1.0

Table 2. (continued)

^{197}Au	$(\gamma,2n)$	0.3 - 0.9	15	2 ± 2	5.2
		0.3 - 1.0	5	7 ± 5	5.2
	$(\gamma,3n)$	0.3 - 0.9	15	1.5 ± 0.4	3.6
^{209}Bi	$(\gamma,2n)$	0.3 - 1.0	This work	6 ± 1	5.5
	$(\gamma,3n)$	0.3 - 1.0	This work	2.0 ± 0.4	3.8
	$(\gamma,4n)$	0.3 - 1.0	This work	1.3 ± 0.2	2.5

[a] Calculated Values According to eqn (12).

[b] Deduced Value from the Interpolated σ_Q Curve as Indicated in Ref. [9].

FIGURE CAPTIONS

Fig. 1. Yields for the ^{59}Co(γ,2n), ^{51}V(γ,3n) and ^{59}Co(γ,4n) reactions. Open circles: present experiment; filled circles: experimental data for the ^{51}V(γ,3n) reaction as in Ref. [17]. Smooth curves are drawn "by eye" through the experimental points.

Fig. 2. Yields for the ^{209}Bi(γ,xn) reactions $(1 < x < 5)$.. Smooth curves are drawn "by eye" through the experimental points.

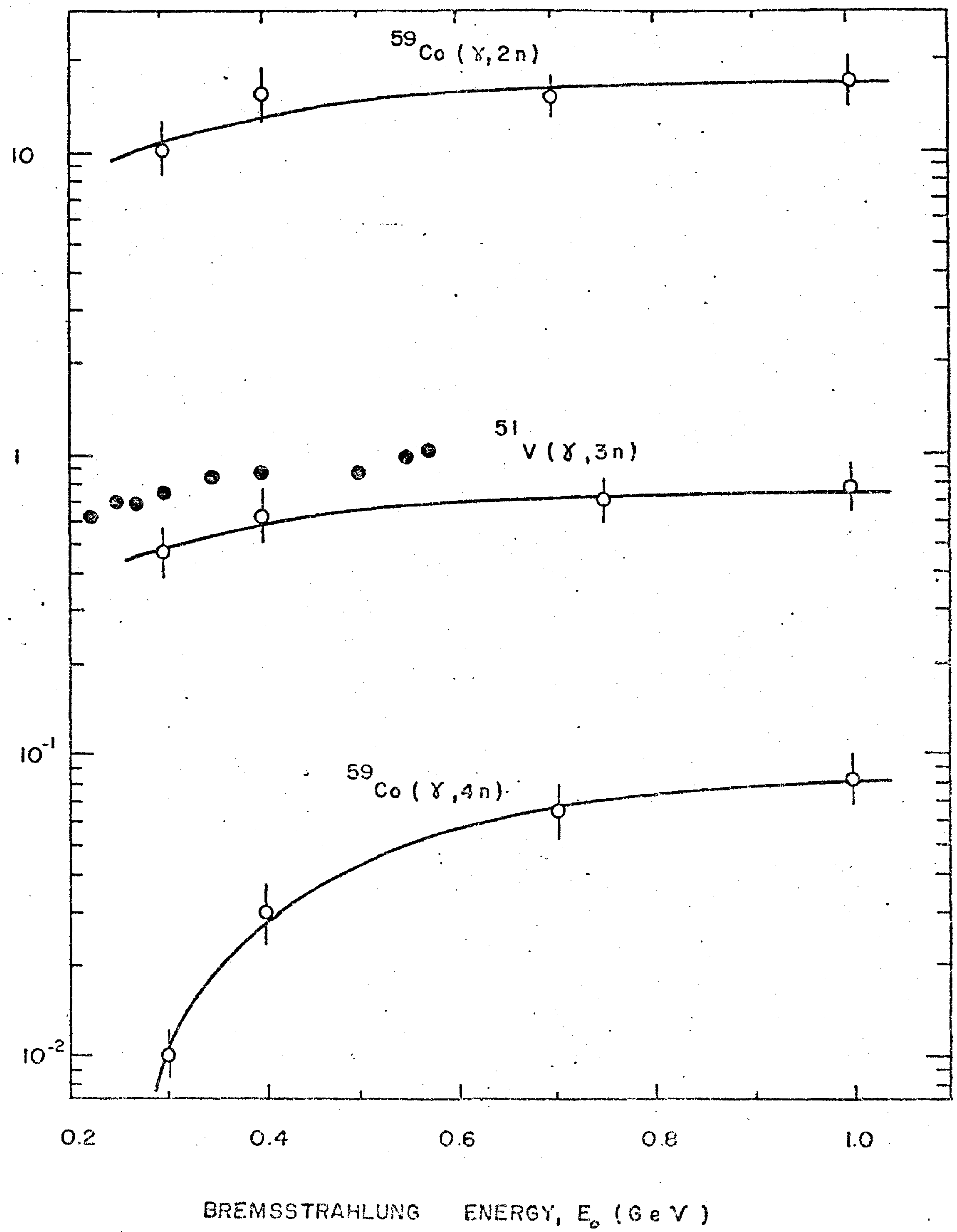
Fig. 3. Experimentally determined mean absolute cross sections, $\bar{\sigma}_k$, for the (γ,2n) reactions *versus* the mass number, A_t, of the target nucleus. Filled circles are taken from our earlier experiments: ^{9}Be, Ref. [8]; ^{103}Rh, Ref. [4,6]; ^{197}Au, Ref. [5]. Open circles : ^{12}C and ^{16}O, Ref. [16]; ^{197}Au, Ref. [15]. Filled triangles are the results of the present work for ^{59}Co and ^{209}Bi. The straight line is a least squares-fit of the experimental points.

Fig. 4. The same as in Fig. 3 for the (γ,3n) reactions. Filled circles are taken from our earlier experiments: ^{55}Mn, Ref. [7]; ^{127}I, Ref. [3]. Open circles: ^{51}V , Ref. [17]; ^{55}Mn, Ref. [11]; ^{75}As, Ref. [12]; ^{89}Y , Ref. [14]; ^{127}I, Ref. [9,10,13]; ^{197}Au, Ref. [15] . Filled triangles are the results of the present work for ^{51}V and ^{209}Bi. The straight line is a least-squares fit of the experimental points.

Fig. 5. The same as in Fig. 3 for the (γ,4n) reactions. Filled circle is taken from our earlier experiment : ^{55}Mn, Ref. [7]. Open circles: ^{75}As, Ref. [12]; ^{127}I, Ref. [9,10,13]. Filled triangles are the results of

the present work for ^{59}Co and ^{209}Bi. The straight line is a least-squares fit of the experimental points.

Fig. 6. Cross section distributions for the (γ,xn) reactions ($x \geq 1$) at intermediate energies (0.2-1.0 GeV). Experimental data are taken from: filled circle: ^{12}C, Ref. [1]; open circles: ^{12}C, Ref. [1,16]; filled squares: ^{59}Co, this work and Ref. [1]; open square: ^{59}Co, Ref. [1]; filled rhomb: ^{75}As, Ref. [1]; open rhombs: ^{75}As, Ref. [12]; filled reversed triangles: ^{127}I, Ref. [1,3]; open reversed triangles: ^{127}I, Ref. [1,9,10,13]; filled triangles: ^{197}Au, Ref. [1,5]; open triangles: ^{197}Au, Ref. [15]. The full lines represent the calculated cross section distributions according to eqn (12).



^{59}Co (γ, 2n)
^{51}V (γ, 3n)
^{59}Co (γ, 4n)
10
1
10^{-1}
10^{-2}
0.2
0.4
0.6
0.8
1.0
BREMSSTRAHLUNG ENERGY, E_o (GeV)

Fig. 1

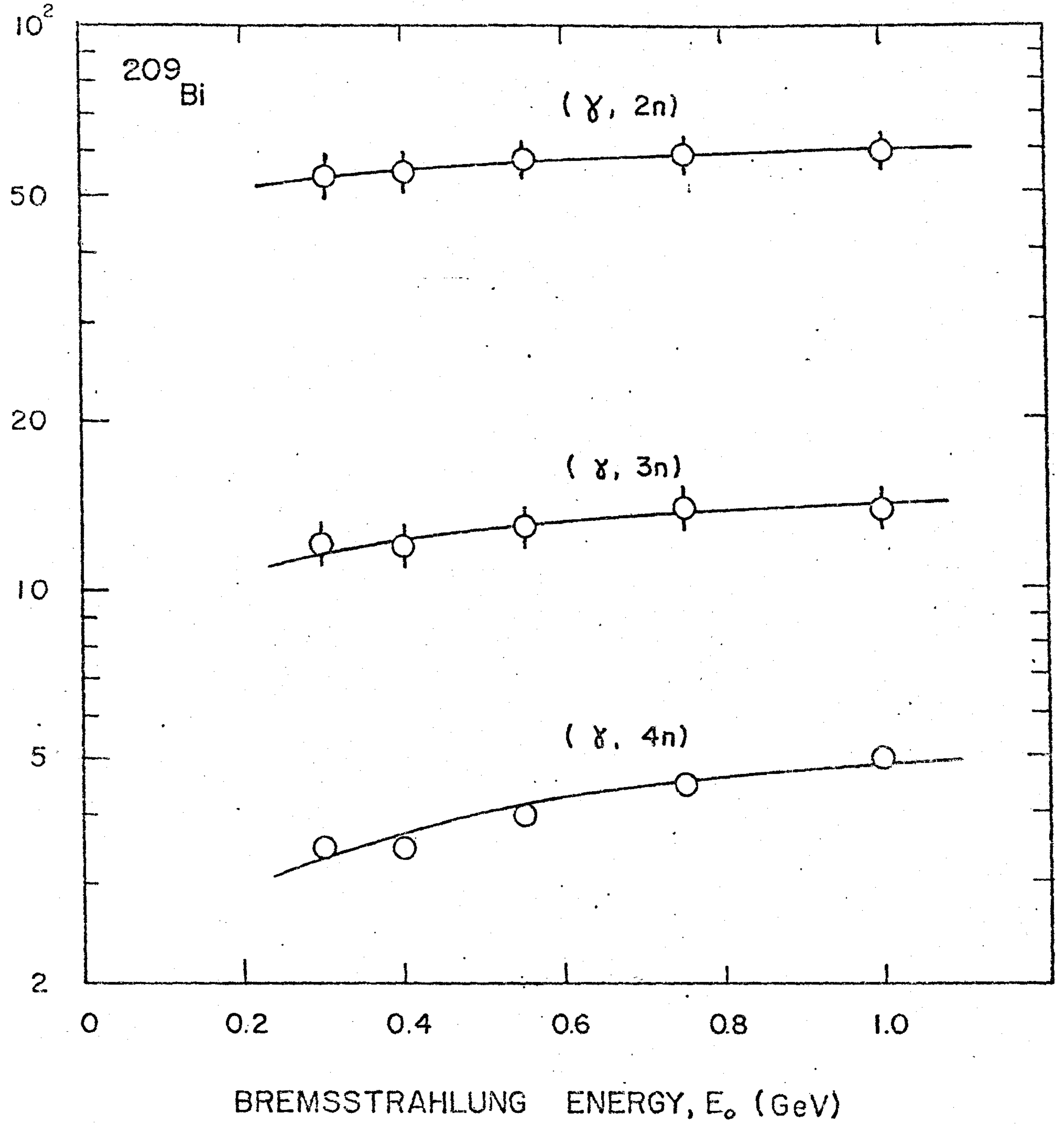

^{209}Bi
(γ, 2n)
(γ, 3n)
(γ, 4n)
10^2
50
20
10
5
2
0
0.2
0.4
0.6
0.8
1.0
BREMSSTRAHLUNG ENERGY, E$_o$ (GeV)

Fig. 2

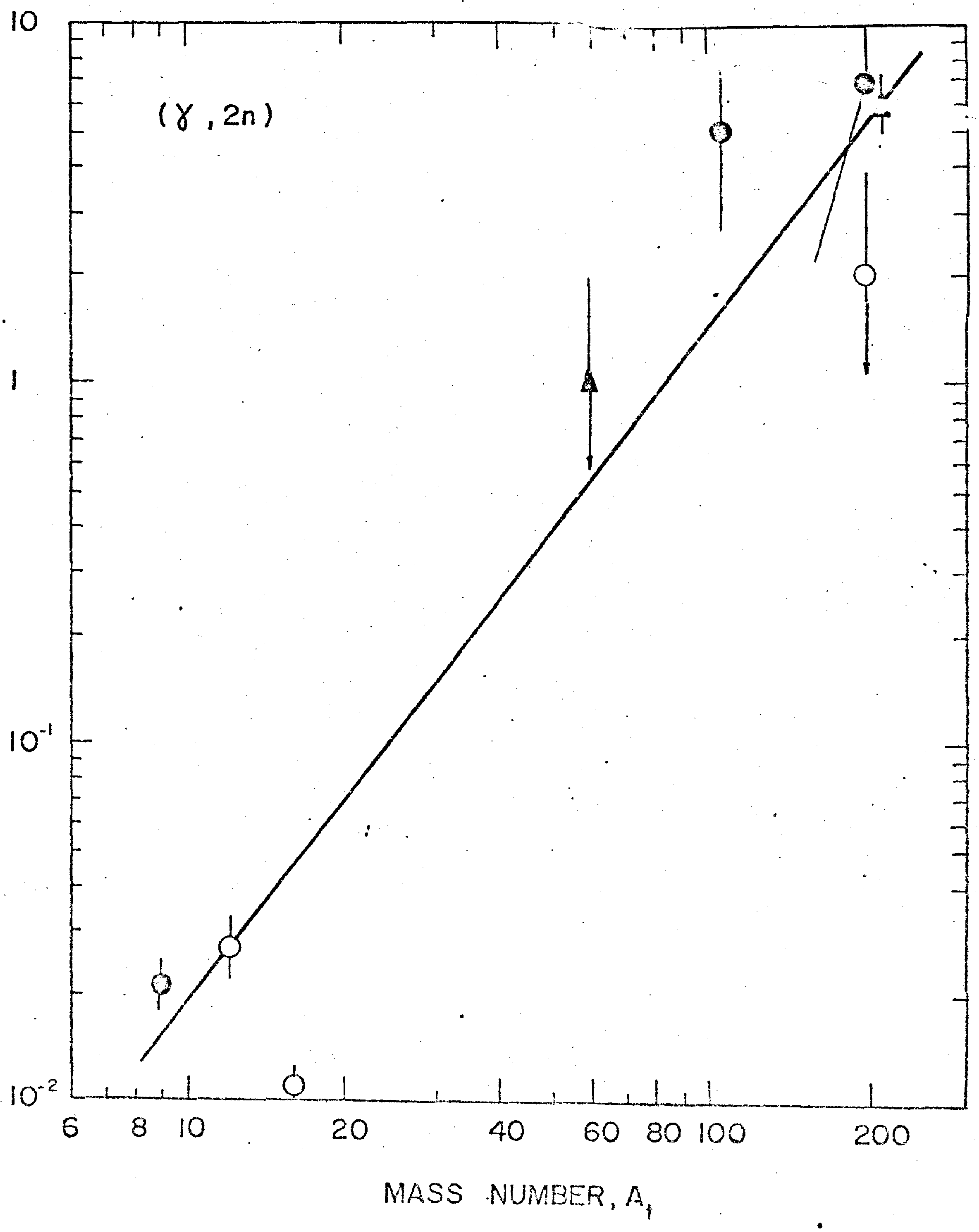


Fig. 3

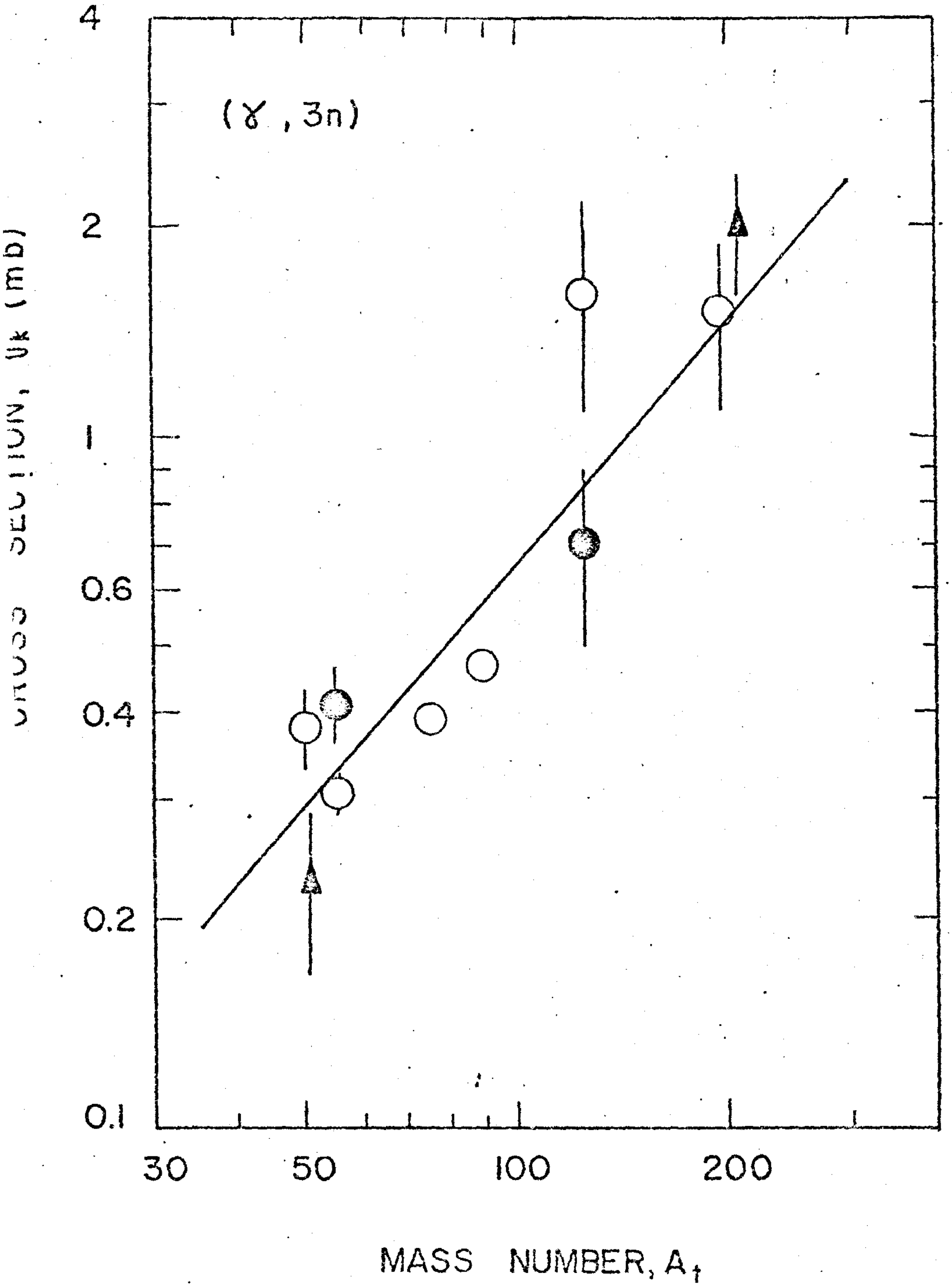

(γ , 3n)
CROSS SECTION, σk (mb)
4
2
1
0.6
0.4
0.2
0.1
30
50
100
200
MASS NUMBER, A_t

Fig. 4

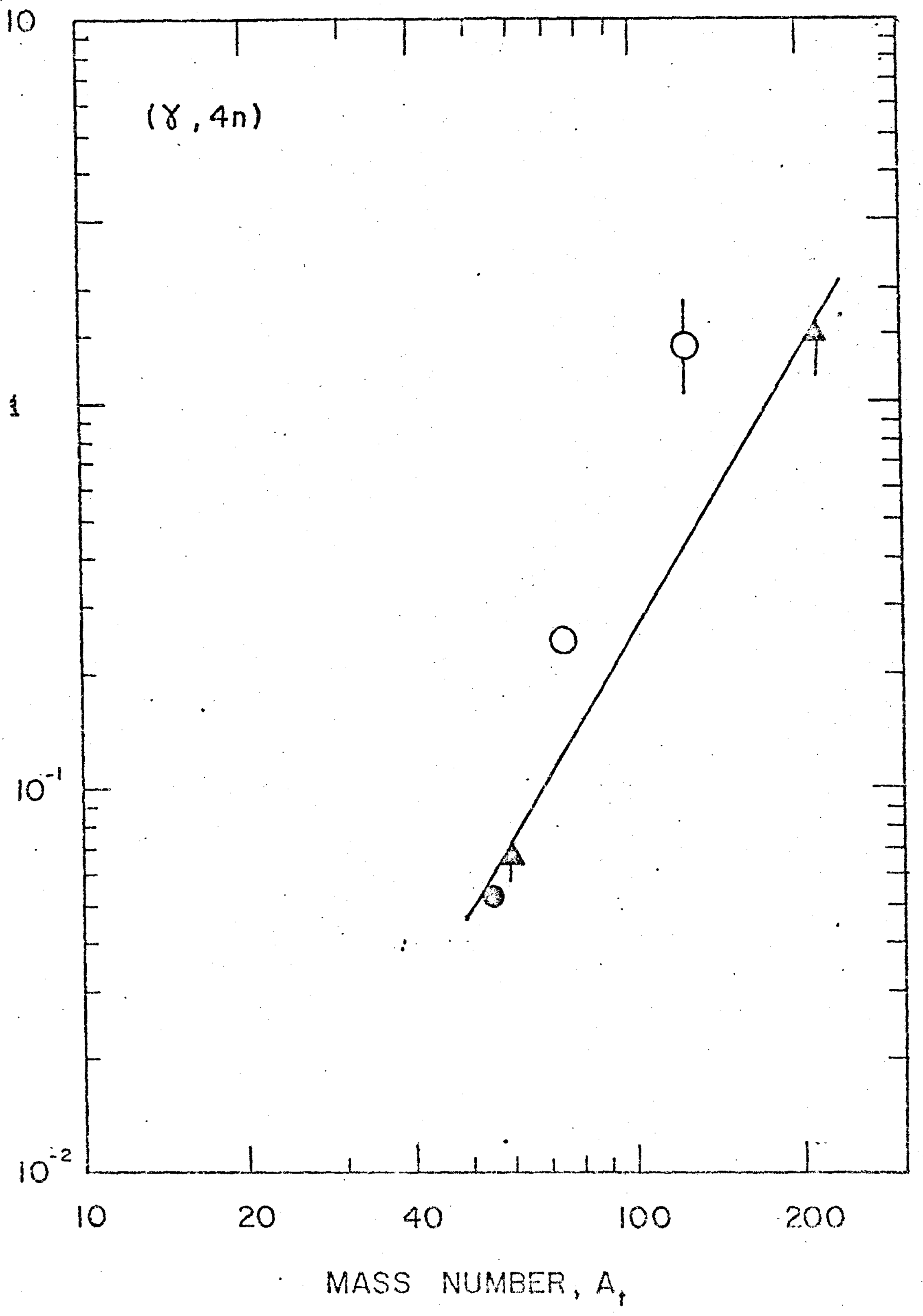


Fig. 5

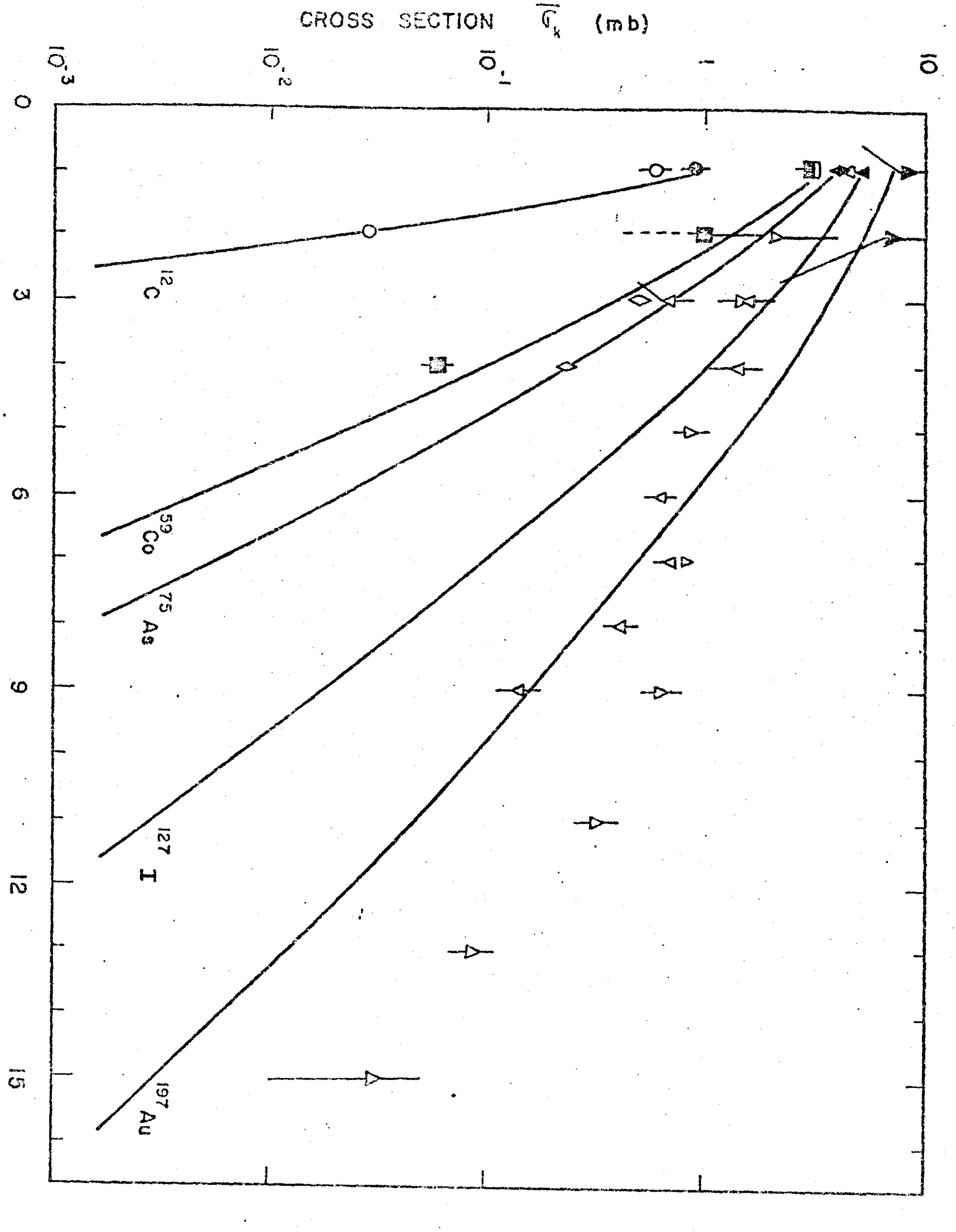

CROSS SECTION $\overline{\sigma}_k$ (mb)
10^{-3}
10^{-2}
10^{-1}
1
10
0
3
6
9
12
15
^{12}C
^{59}Co
^{75}As
^{127}I
^{197}Au

Fig. 6