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Simple Nuclear Reactions of Ga^{69} and Ga^{71} with High-Energy Protons*

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Abstract

Excitation functions in the energy range of 0.5-2.9 Bev have been measured for several (p,xn), (p,pxn), and (p,3pxn) reactions of Ga^{69} and Ga^{71}. The cross-section for the (p,pn) reactions are about 57 mb at 2.9 Bev and 69 mb at 0.5 Bev. The cross-sections for the (p,pxn) reactions decrease monotonically as x increases and are some 30-250 times larger than the isobaric (p,xn) reaction cross sections. The results are compared with Monte Carlo cascade and evaporation calculations. Good agreement is obtained at 0.5 Bev except in the case of the (p,pn) reaction. In the Bev region the agreement is less widespread. The (p,pn) cross-sections are compared with a calculation that takes the effects of shell structure and a diffuse nuclear surface into account. Some preliminary conclusions about the availability of the 1 f 7/2 shell for (p,pn) reactions in this mass region are drawn on the basis of this comparison.

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DISCLAIMER

I. INTRODUCTION

The interaction of high-energy protons with complex nuclei is considered to proceed by a cascade-evaporation mechanism. The various features of the cascade process have been investigated by means of Monte Carlo calculations.[1] The results of such calculations,[1] when coupled with an evaporation calculation, provide information that may be directly compared with the results of spallation experiments. A large number of experimental studies[2] have been performed in recent years in order to provide data for comparison with the above calculations.

The present study falls in this category. Previous work in the medium element region has shown reasonable agreement in the overall mass yield distribution obtained experimentally with that obtained from the Monte Carlo cascade calculation coupled with an evaporation calculation. This agreement is particularly widespread at a bombarding energy of less than 0.5 Bev. On the other hand, the calculation has a very marked lack of success in predicting the cross-sections of (p,pn) and (p,2p) reactions at all energies. It is found that the calculated values are too low by factors ranging from 2 to 9.[3] In view of this situation it was thought worthwhile to examine some reactions in which several nucleons are emitted in order to determine if the lack of agreement between experiment and calculation observed for (p,pn) and (p,2p) reactions also carried over to other simple reactions. Cross sections were thus measured for several (p,xn), (p,pxn), and (p,3pxn) reactions of Ga^{69} and Ga^{71} at 0.5, 1.5, and 2.9 Bev. The choice of these nuclides as targets proved convenient because the mass region under consideration has been thoroughly investigated by means of low-energy nuclear reaction studies. In particular, excitation functions have been measured for a number of reactions of Cu^{63},[4] Cu^{65},[4] Zn^{64},[5] and Zn^{70},[6] with 10-40 Mev alpha particles. The results of these studies have recently been compared with the predictions of evaporation

theory.[7] Good overall agreement has been found for a particular choice of values for the parameters of importance in evaporation calculations. Since the excitation energies involved in the present study cover the same range as those in the low-energy studies it thus becomes possible to use the residual nuclei from the high-energy cascade process given by the Monte Carlo calculations as the starting nuclei for an evaporation calculation based on experimental data. A detailed comparison of calculated and experimental cross sections thus becomes possible.

II. EXPERIMENTAL

The irradiations were performed in the circulating beam of the Cosmotron. The beam intensity was monitored by means of the $Al^{27}(p,3pn)$ reaction. The cross-section for this reaction was taken as 11.0 mb at 0.5 Bev, 9.5 mb at 1.5 Bev, and 9.0 mb at 2.9 Bev.[8] The target assemblies were irradiated for periods ranging from 3 to 40 minutes. In the course of this study a total of 33 irradiations was performed.

The targets consisted of highly enriched gallium isotopes (Ga^{69}-98.4 atom percent, Ga^{71}-98.1 atom percent).[9] Targets were prepared by electroplating gallium to a thickness of approximately 2 mg/cm^2 onto thin (2 mg/cm^2) nickel foils. The target foils were positioned during bombardment so that atoms recoiling out of the target in a forward direction stopped in the nickel backing. The activity loss due to backward recoil emission was checked by including in the target assembly a foil to stop backward recoils and was found to be negligibly small. This procedure was usually not followed as the absence of a backward recoil catcher facilitated the process of cutting the target assembly after irradiation. The activity induced in the nickel backing foil was checked in a separate experiment. It was found for all nuclides of interest in thisstudy, that the contribution of the nickel foil was less than 0.5% of that of the gallium target. The targets were inspected visually for uniformity and it was found

that there usually was some variation in target thickness. The intensity of the proton beam striking the target was, however, found to be uniform to within 20% over the target area so that small inhomogeneities in thickness had little effect on the accuracy of the measurement.

The target assembly consisted of an aluminum monitor foil (2.5 mg/cm^2), an aluminum guard foil (1.7 mg/cm^2), and the target foil. The guard foil was included in order to prevent any recoiling atoms produced in the nickel foil from penetrating the monitor foil. Following the irradiation, a circular punch was used to stamp out discs with a diameter of 6 mm. The activity of Na^{24} in the monitor foil was determined by assay of the foil with a beta proportional counter. The counter had previously been calibrated for Na^{24} by β-γ coincidence measurements. A correction was applied for the loss of Na^{24} recoils from the aluminum foil by use of the results of Cumming and Poskanzer.[10] This correction amounted to less than 3% in all cases.

The target foil was subjected to radiochemical analysis and germanium gallium, and copper were separated by previously used procedures.[5] The target foil was usually dissolved in a distilling flask containing 6N HCl, $KClO_3$, and the appropriate carriers. Germanium was distilled as the tetrachloride and purified by precipitation with H_2S and further distillation. Gallium was separated from the distillation residue by repeated extraction into i-propyl ether from 7N HCl and back extraction into water. Separation from iron was effected by reducing the latter to Fe^{++} with $SnCl_2$ prior to each extraction. Copper was separated and decontaminated by use of an anion exchange column, $Fe(OH)_3$ scavengings, and precipitation of CuCNS. The chemical yields were determined after completion of the activity measurements by spectrophotometric determination.

The activity measurements were performed with both beta proportional and NaI scintillation counters. Self absorption curves were determined for all isotopes whose activities were measured with beta proportional counters. The various nuclides were identified by their half-lives and by their γ-ray spectra. The latter were determined with the aid of a 100-channel pulse-height analyzer. The various counters used in this study were calibrated for all nuclides of interest. The calibration for positron emitters was performed by 0.51 Mev - 0.51 Mev γ coincidence measurements. The coincidence rate was compared with that of a calibrated Na^{22} source. The calibration for γ-ray emitters was performed by measurements of the γ-ray spectrum in low geometry with a 3-inch detector connected to a 100-channel pulse-height analyzer. The overall efficiency of the counter was determined as a function of γ-ray energy with the aid of a number of standard sources. The calibration for nuclides decaying predominantly by β^- emission was performed by 4π beta counting. The various counting and calibration procedures are summarized in Table I. The branching ratios for particular radiations that were used as a basis of cross-section determinations are listed. These values were taken from the NRC compilation[11] or from more recent studies.[12] The listed half-lives are the best literature values and are in agreement with our experimental values. The analysis of the counting data was performed with the use of these half-lives. The data were analyzed with the aid of an IBM-704 computer by use of a least-squares program.[13]

Table I. Counting and calibration procedures

Nuclide	Half-Life	Counting Procedure	Calibration Procedure	Calibration Radiation
Ge^{66}	2.5 hr	BP[a]	0.51-0.51	β^+ - 76%[d]
Ge^{67}	19 min	BP	0.51-0.51	β^+ - 93%
Ge^{68}	208 d	BP	0.51-0.51	see Ga^{68}[e]
Ge^{69}	40.4 hr	BP	0.51-0.51	β^+ - 33%
Ga^{65}	15 min	GW[b]	0.51-0.51	β^+ - 81%
Ga^{66}	9.5 hr	GW	0.51-0.51	β^+ - 50.5%
Ga^{67}	78 hr	G[c]	γ	182+206 kev γ - 30%
Ga^{68}	68 min	GW	0.51-0.51	β^+ - 87.5%
Ga^{70}	21 min	BP	$4\pi\ \beta$	β^- - 100%
Cu^{67}	61 hr	G	γ	182 kev γ - 44%

[a] Beta proportional counter

[b] Gamma-ray well counter

[c] 3-inch NaI detector connected to 100 channel analyzer

[d] Ge^{66} also calibrated by measurement of Ga^{66} daughter

[e] Ge^{68} is in equilibrium with Ga^{68}

III. RESULTS

The measured isotopic cross-sections are presented in Table II. The number of separate determinations of each cross-section is listed in parenthesis. The errors for each cross-section include both the standard deviation from the mean value as well as an estimate of systematic errors. In the case of Ga^{65}, where only one measurement was made, an estimate of the error is given. It is seen that the errors range from approximately 10 to 30 percent. The uncertainty in the cross-section for the $Al^{27}(p,3pn)$ reaction is not included in this estimate. The uncertainty in the bombarding energy may be as much as 10% at 0.5 Bev, but should be negligible at the higher energies. The listed cross-sections refer in all cases to the independent formation of the nuclide in question. It was necessary to apply a correction in the case of some of the gallium nuclides for their formation from the decay of the corresponding germanium nuclides. This correction is largest for the (p,p2n) reaction where it only amounts to at most 2%.

The cross-sections for the (p,xn) reactions are seen to be quite small. These reactions have much higher cross-sections at lower energies and the question of the contribution to the observed yields due to low-energy secondary protons becomes important. An estimate of this contribution made from values of the primary cross-section,[14] proton multiplicity, and energy-spectra indicated that for the target assembly thickness used in this study the secondary contribution should be an order of magnitude lower than the observed results in all cases. This estimate was checked in an experiment in which the thickness of the target assembly was increased by a factor of three. No difference in cross-section was noted in agreement with

Table II. Experimental cross-sections in millibarns

Target	Reaction[a]	Energy 0.5 Bev	1.5 Bev	2.9 Bev
Ga^{69}	(p,n)	1.8 ± 0.3 (3)[b]	0.5 ± 0.1 (4)	0.5 ± 0.1 (3)
	(p,2n)	2.3 ± 0.6 (3)	0.7 ± 0.2 (4)	0.6 ± 0.2 (3)
	(p,3n)	1.0 ± 0.2 (3)	0.3 ± 0.1 (4)	0.3 ± 0.1 (3)
	(p,4n)	0.14 ± 0.03 (3)	0.04 ± 0.01 (4)	0.04 ± 0.01 (3)
	(p,3p)	1.4 ± 0.2 (4)	1.3 ± 0.2 (3)	1.3 ± 0.2 (4)
	(p,pn)	70 ± 8 (3)	60 ± 7 (3)	57 ± 8 (3)
	(p,p2n)	26.0 ± 3.0 (3)	19.8 ± 2.4 (3)	18.0 ± 2.1 (4)
	(p,p3n)	17.6 ± 2.0 (3)	11.6 ± 1.6 (3)	9.8 ± 1.8 (3)
	(p,p4n)		1.7 ± 0.3 (1)	
Ga^{71}	(p,pn)	69 ± 8 (3)	63 ± 9 (3)	58 ± 7 (3)
	(p,p3n)	36 ± 4 (3)	21.7 ± 2.7 (3)	22.2 ± 3.4 (3)
	(p,p4n)	16.2 ± 1.7 (4)	8.7 ± 1.1 (3)	8.4 ± 0.9 (4)
	(p,p5n)	10.2 ± 1.0 (4)	5.0 ± 0.5 (4)	4.8 ± 0.6 (4)
	(p,p6n)	≤ 0.4 (1)	≤ 0.3 (1)	
	(p,pα)	8.9 ± 1.3 (2)	6.8 ± 1.0 (2)	7.6 ± 1.1 (2)

[a] The nomenclature used in designating all these reactions is not intended to imply a particular reaction mechanism.

[b] The numbers in parenthesis refer to the number of separate determinations of each cross section.

the above estimate. The cross-sections for the other reactions were also in agreement with the thin-target results indicating that the contribution of other secondary reactions such as (n,xn) or (n,2pxn) was also negligible.

The results are presented in the form of excitation functions in Figs. 1-3. It is seen that the cross-sections for the (p,pn) reactions are nearly independent of energy and approximately equal for both target nuclides. Previous studies of (p,pn) reactions in this mass region indicate a similar magnitude and energy dependence for the measured cross-sections.[3] The cross-sections for the (p,pxn) reactions are seen to decrease monotonically as the number of emitted neutrons increases. The cross-sections for the (p,xn) reactions are much smaller than those for the corresponding (p,pxn) reactions. In addition, the (p,xn) reactions show a strong energy dependence below 1.5 Bev.

Several isobaric yields have been measured for A = 67, representing the Ga^{69}(p,3 nucleon) and Ga^{71}(p,5 nucleon) reactions. In the case of Ga^{69} the maximum observed yield occurs for the (p,p2n) reaction. The cross-sections for the (p,3p) and (p,3n) reactions are lower by factors ranging from approximately 15 to 60. In the case of Ga^{71}, nearly equal yields are obtained for Ga^{67} and Cu^{67} indicating that when x becomes as large as 4, the (p,pxn) reaction may no longer have the highest isobaric yield.

IV. DISCUSSION

In this section the experimental results will be compared with the predictions of Monte Carlo cascade and evaporation calculations. Cascade calculations have been carried out for a Cu^{64} target nucleus and incident protons with energies of 0.46, 0.69, 0.94, and 1.84 Bev.[1] In view of the small difference in the distributions of residual nuclei and excitation

energy predicted by the calculation for Cu^{64} and Ru^{100}, the results for Cu^{64} have been used without correction. The residual nuclei were, of course, shifted in charge and mass number to correspond to the difference in charge and mass between Cu^{64} and Ga^{69} or Ga^{71}. Approximately 850 cascades were available at each energy.[15] Since the cascade calculation was carried out with a nuclear radius parameter of 1.3 fermis, a single cascade event in the calculation corresponds to a cross-section of approximately 1 mb. It was found that cascades leading to the deposition of more than about 100 Mev of excitation energy did not lead to the formation of any of the experimentally observed nuclei. These cascades were consequently not used for the evaporation calculation.

The evaporation calculation was performed in the manner outlined by Dostrovsky, Fraenkel and Friedlander.[7] The relative emission widths for different particles were obtained in that study with a level density expression of the form $W(E)\alpha \exp\left[2(a\{E-\delta\})^{1/2}\right]$. The best values of the level density parameter, a, and the characteristic energy, δ, were obtained by fitting the calculated values to the large number of excitation functions that have been measured in this particular mass region.[4-6] Dostrovsky et al[7] were thus able to fit the measured cross-sections in the region of the peak of the excitation functions to within about 30% with a particular set of δ values for the various residual nuclides and for $a = A/20$. The best value of the nuclear radius parameter for the above values of a and δ was found to be 1.5 fermis.

The residual nuclei from the cascade calculation were used as the starting nuclei for the Monte Carlo evaporation calculation. The values given by Dostrovsky et al[7] were used for all the parameters in question. The branching ratios for the evaporation process were obtained on the basis of 10 evaporation runs for each starting nucleus. The statistical uncertainty

of the calculated values thus reflects mainly the statistical uncertainty of the results of the cascade calculations.

The calculated and experimental cross-sections are compared in Figs. 4-7. The calculated values are given by the shaded areas. The width of the latter corresponds to two standard deviations. The experimental cross-sections for the (p,pxn) reactions were obtained by interpolation and extrapolation from the measured excitation functions . This procedure does not appreciably increase the uncertainty of the experimental values in view of the slight energy dependence exhibited by the excitation functions. The comparison for the (p,xn) reactions is made at 0.5 and 1.5 Bev. The calculated values were obtained by a combination of the results for 0.46 and 0.69 Bev, and 0.94 and 1.84 Bev, respectively. This procedure is justified by the lack of systematic energy dependence of the calculated cross-sections within each of the above energy intervals.

It is seen that the calculated (p,pn) cross-sections are lower than the observed values by factors ranging from about 3 at 0.46 Bev to about 6 at 1.84 Bev. Both the magnitude and energy dependence of this discrepancy have been observed previously.[3] This discrepancy has not as yet been satisfactorily resolved although there is evidence that it is at least partly due to the assumption made in the cascade calculation of a constant nuclear density up to a sharp boundary.

The other (p,pxn) reactions may be divided into two groups on the basis of this comparison. The calculated and experimental cross-sections for the (p,p4n), (p,p5n), and (p,p6n) reactions show agreement within their respective uncertainties at all energies. The actual agreement isusually to within better than a factor of two. The (p,p2n) and (p,p3n) cross-sections show an equally good agreement at 0.46 Bev but at 0.94 and 1.84 Bev the

experimental values are larger than the calculated values by factors ranging from 2 to 5.

It is instructive to compare these results with other measurements of (p,pxn) reaction cross-sections. Ladenbauer and Winsberg[16] have recently measured excitation functions for (p,pxn) reactions on I^{127} and compared their results with a cascade-evaporation calculation. Good agreement between experiment and calculation is reported for a number of reactions ranging from (p,p2n) to (p,p7n) for bombarding energies below 1 Bev. On the other hand, the calculated cross-sections for all these reactions are much lower than the experimental values above 1 Bev. Lindner and Turkevich[17] have reported good agreement between experimental and calculated values for (p,pxn) (x = 6,8-10) reactions on U^{238} at 0.34 Bev. On the other hand, Pate and Poskanzer[18] report that the calculated values for the same cross-sections at 1.8 Bev are much lower than their experimental values at this energy. It thus appears that, in the Bev region, the relative number of cascades leading to low deposition energies and involving the knocking-out of only a few nucleons is underestimated in the cascade calculations. This effect is undoubtedly due to causes other than those responsible for the low calculated (p,pn) cross-sections since it is only observed in the Bev region. It has been attributed[18] to an overestimate of the importance of meson processes resulting from the lack of information about the details of meson dynamics at the time of the cascade calculation.[1] The calculation shows, in fact, that cascades involving meson emission generally do not result in residual nuclei capable of leading to the overall emission of only a few nucleons. The fact that the results for gallium are in less extensive disagreement with the calculation than the results for iodine and uranium is consistent with this viewpoint since meson processes are of less importance in a light nucleus.[1]

The effect of the evaporation process on the relative cross-sections of (p,pxn) reactions may also be considered. A plot of the ratio of (p,pxn) and (p,pn) cross sections as a function of x is shown in Fig. 8 for 2 Bev protons on I^{127} and 1.5 Bev protons on Ga^{69} and Ga^{71}. It is seen that the decrease in cross-section with increasing neutron emission is fastest for Ga^{69} and slowest for I^{127}. This difference in behavior can be attributed to differences in the values of some of the parameters governing the evaporation process. The larger Coulomb barrier at iodine thus inhibits the evaporation of charged particles more effectively than in the case of gallium, thereby decreasing the competition from (p,2pxn) reactions. The difference between Ga^{69} and Ga^{71} may be ascribed to a separation energy effect. The ratio of neutron to proton separation energies for gallium nuclides increases with decreasing mass number. Since the residual nuclei from the cascade process will on the average have a greater mass number for a Ga^{71} target nucleus, it follows that the evaporation of a given number of nucleons is more likely to result in a gallium end product in the case of Ga^{71}.

The (p,n) reaction can occur through a single interaction of the incident proton with a target neutron by means of an elastic, inelastic, or charge-exchange scattering process. The (p,2n) reaction can occur through a two-step mechanism involving a (p,n) reaction followed by neutron evaporation or through a multi-step cascade process involving the direct emission of two neutrons. The other (p,xn) reactions are usually the result of a combination of evaporation and cascade processes. It is seen in Fig. 6 that, within the rather large statistical uncertainties, the calculated and experimental cross-sections are in agreement bothat 0.5 and 1.5 Bev. The cross-section ratio for the (p,xn) and the corresponding (p,p(x-1)n) reactions at 0.5 Bev is 0.033, 0.039, and 0.008 for x = 2, 3, and 4, respectively. At 3 Bev these ratios are lower than

at 0.5 Bev by a factor of 2 to 3. Th se very low ratios are due primarily to two factors. The (p,pxn) reactions can occur as the result of interactions in which the incident proton loses only a small fraction of its energy in traversing the nucleus whereas in (p,xn) reactions the proton must transfer practically all its energy to one or more neutrons. Furthermore, the cascade calculation indicates that in a substantial number of cases the product of a (p,pxn) reaction is formed directly in the cascade process, particularly when $x < 3$. The (p,xn) reactions, on the other hand, usually involve the evaporation of one or two neutrons and competition of charged particle evaporation reduces the cross-sections even further. The experimental and calculated cross-sections for the (p,3n) and (p,p2n) reactions at 0.46 Bev are in significantly good agreement, and the statistics of the cascade calculations are sufficiently good, that it is possible to estimate the relative effect of the above two factors. It is thus found that the cross-section for the (p,3n) reaction is lower than that for the (p,p2n) reaction by about a factor of 3.5 because of the greater effect of charged particle evaporation in the deexcitation of germanium nuclides. The remaining factor of about 7 in the ratio of these two cross-sections is due to the intrinsic greater probability of cascades in which one proton is emitted.

The experimental and calculated excitation functions for the formation of Cu^{67} are shown in Fig. 7. The calculated cross-sections for the Ga^{69}(p,3p) reaction are very low, and within the rather large statistical uncertainties, are in agreement with the experimental values. The calculation indicates that cascades involving the emission of two protons followed by the evaporation of one additional proton are of importance for this reaction. The direct formation of Cu^{67} by a (p,3p) cascade probably also contributes to the observed yield.

Several mechanisms may be responsible for the formation of Cu^{67} from Ga^{71}. These include the emission of single nucleons in the cascade and evaporation stages of the reaction, the evaporation of an alpha particle following a (p,p') cascade, and a direct (p,pα) cascade in which an alpha particle is knocked out of the nucleus in similar fashion to the (p,pn) knock-on process. This last mechanism is not allowed for in the cascade calculation since the latter only considers the emission of single nucleons.. On the other hand, there is some experimental evidence indicating that alpha particles are emitted in the course of the nuclear cascade.[19] The results of the comparison indicate that the experimental cross-sections are indeed larger than the calculated values but the magnitude of the disagreement is not sufficiently large to draw any conclusions about the emission of alpha particles in the cascade process. The calculation indicates that the main mechanisms responsible for the formation of Cu^{67} are (p,3pn) and (p,3p) cascades followed by the evaporation of one or two neutrons, respectively. The evaporation of an alpha particle following a (p,p') cascade is of less importance.

A calculation of (p,pn) cross-sections in the Bev region has been performed recently by Benioff.[20] This calculation is based on a model that assumes a diffuse nuclear surface and also takes shell-structure effects into account. It is possible to calculate cross-sections for the (p,pn) reactions of Ga^{69} and Ga^{71} using Benioff's formalism. The neutron shells that are available for (p,pn) reactions in this mass region are listed by Benioff. There is some uncertainty about the availability of the $1f_{7/2}$ shell since there is a substantial energy difference between this shell and the top neutron shell in this mass region. The removal of a $1f_{7/2}$ neutron may consequently lead to a state that is unstable to further particle emission. The calculated

values have therefore been computed both by including and excluding the contribution of the $1f_{7/2}$ shell. The calculated values are based on a half density nuclear radius parameter of 1.07 fermis as given by the results of electron scattering experiments.[21] The results of this comparison at 3 Bev are given in Table III. The cross-section for the $As^{75}(p,pn)$ reaction has been measured recently by Kaufman[22] and is included in this comparison. It is seen that the calculated cross-sections for the gallium nuclides are in agreement with the experimental values if the $1f_{7/2}$ shell is assumed to be available. The results for As^{75}, on the other hand, are consistent with the unavailability of this shell. The possibility of observing a decrease in (p,pn) reaction cross-sections in this mass region due to the sudden unavailability of the $1f_{7/2}$ shell has been discussed by Grover.[23] While the results in Table III are suggestive, it is clear that further and more accurate measurements in this mass region are necessary.

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Table III. Comparison of Experimental and Calculated (p,pn) Reaction Cross-Sections at 3 Bev.

Target	Experimental Cross-Section	Calculated Cross-Section	
		$1f_{7/2}$ shell available	$1f_{7/2}$ shell unavailable
Ga^{69}	57 ± 8 mb	56 mb	33 mb
Ga^{71}	58 ± 7	63	41
As^{75}	47 ± 5	67	47

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Fig. 1. Excitation functions for $Ga^{71}(p,pxn)$ reactions.

Fig. 2. Excitation functions for $Ga^{69}(p,pxn)$, $Ga^{69}(p,3p)$ and $Ga^{71}(p,p\alpha)$ reactions.

Fig. 3. Excitation functions for $Ga^{69}(p,xn)$ reactions. Some of the points have been displaced in energy for greater clarity.

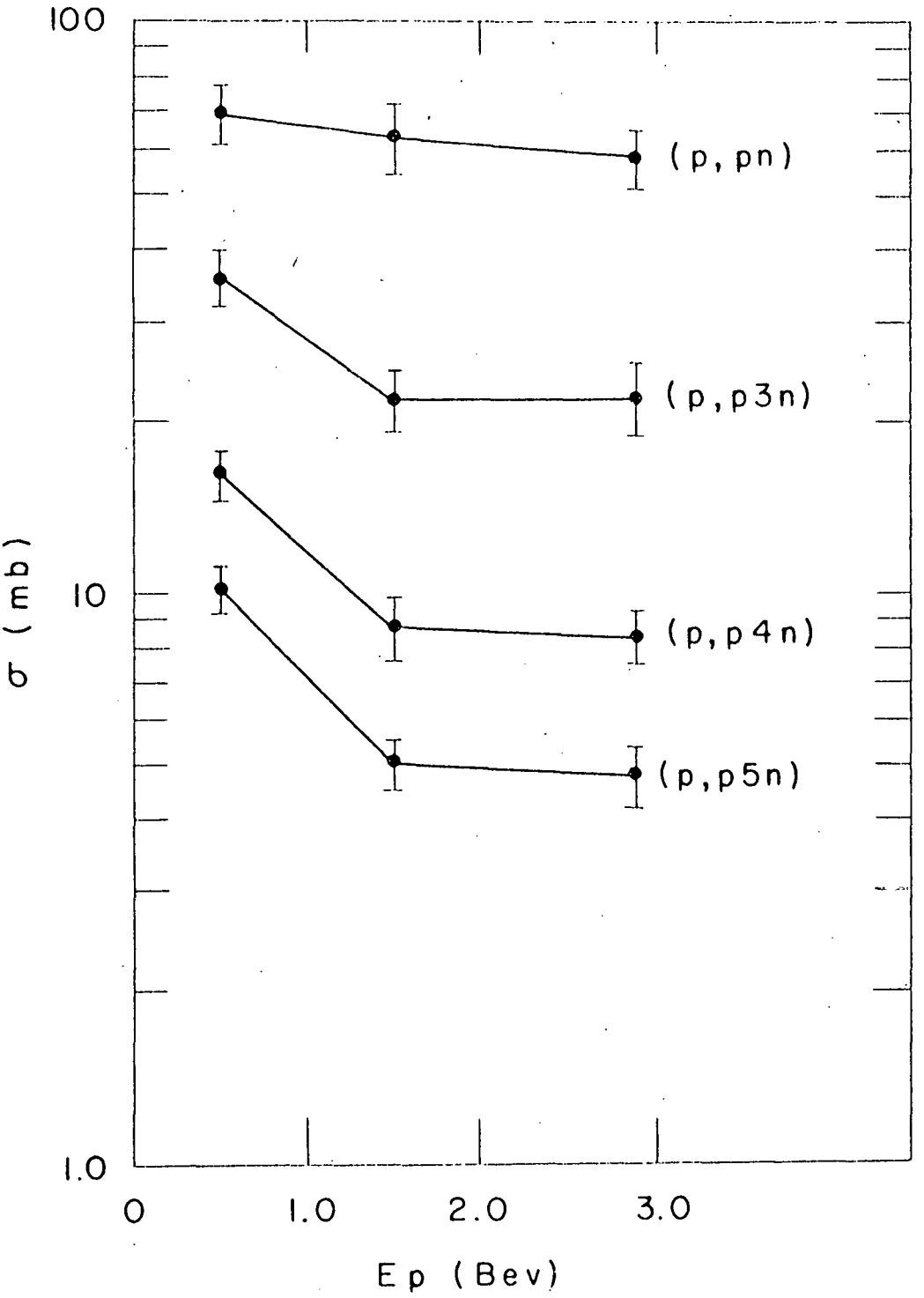
Fig. 4. Comparison between experimental and calculated cross-sections for $Ga^{71}(p,pxn)$ reactions at 0.46, 0.96, and 1.84 Bev. The shaded area refers to the values predicted by the calculation and their associated uncertainties.

Fig. 5. Comparison between experimental and calculated cross-sections for $Ga^{69}(p,pxn)$ reactions at 0.46, 0.96, and 1.84 Bev.

Fig. 6. Comparison between experimental and calculated cross-sections for $Ga^{69}(p,xn)$ reactions at 0.5 and 1.5 Bev.

Fig. 7. Comparison between experimental and calculated excitation functions for $Ga^{69}(p,3p)$ and $Ga^{71}(p,p\alpha)$ reactions.

Fig. 8. Ratio of (p,pxn) to (p,pn) reaction cross-sections at high energies. --- I^{127} + 2 Bev protons[16]; —— Ga^{71} + 1.5 Bev protons; -·-·-Ga^{69} + 1.5 Bev protons.


100
10
1.0
σ (mb)
(p, pn)
(p, p3n)
(p, p4n)
(p, p5n)
0
1.0
2.0
3.0
Ep (Bev)

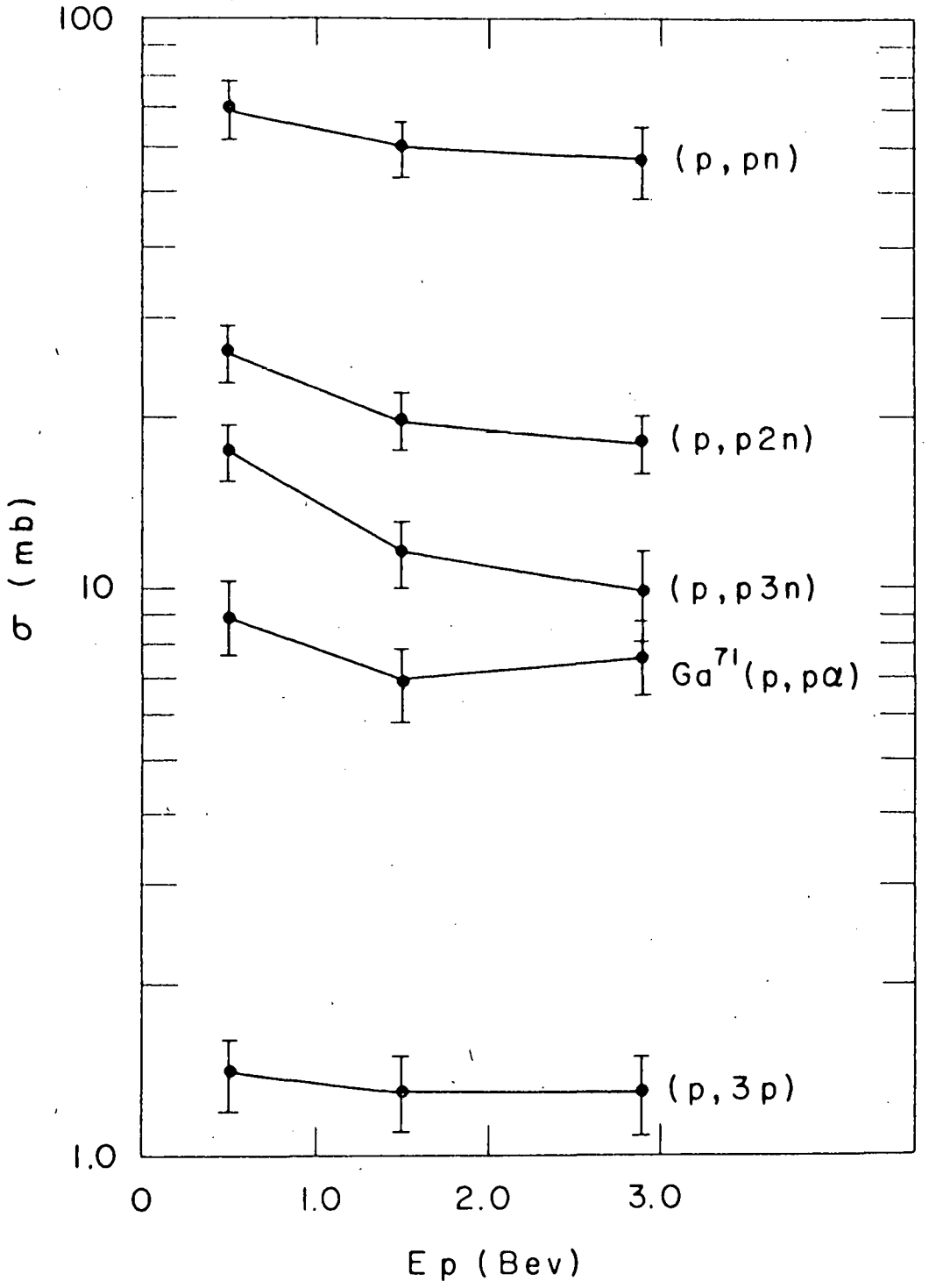


FIG. 2.

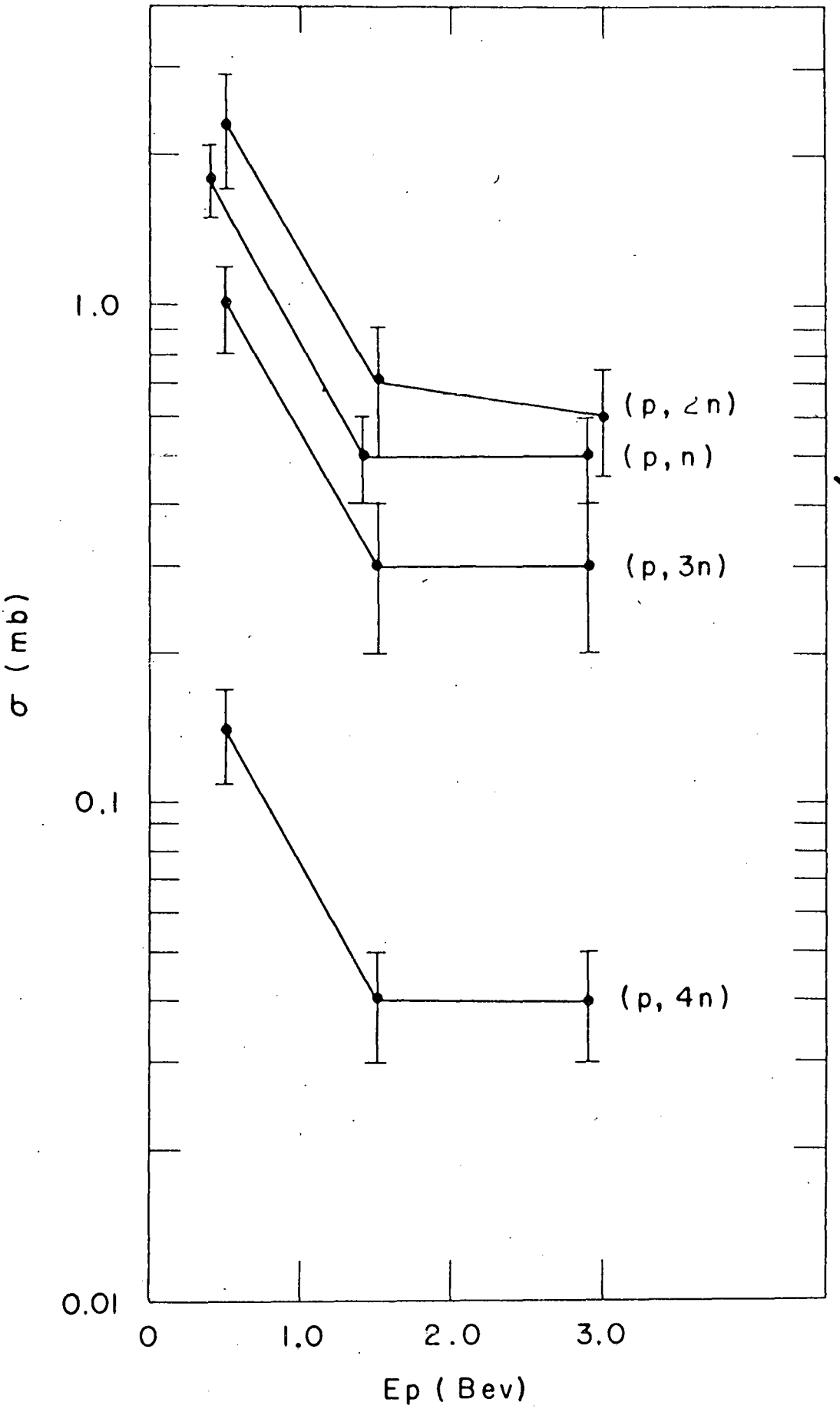


FIG. 3
N.T Porile

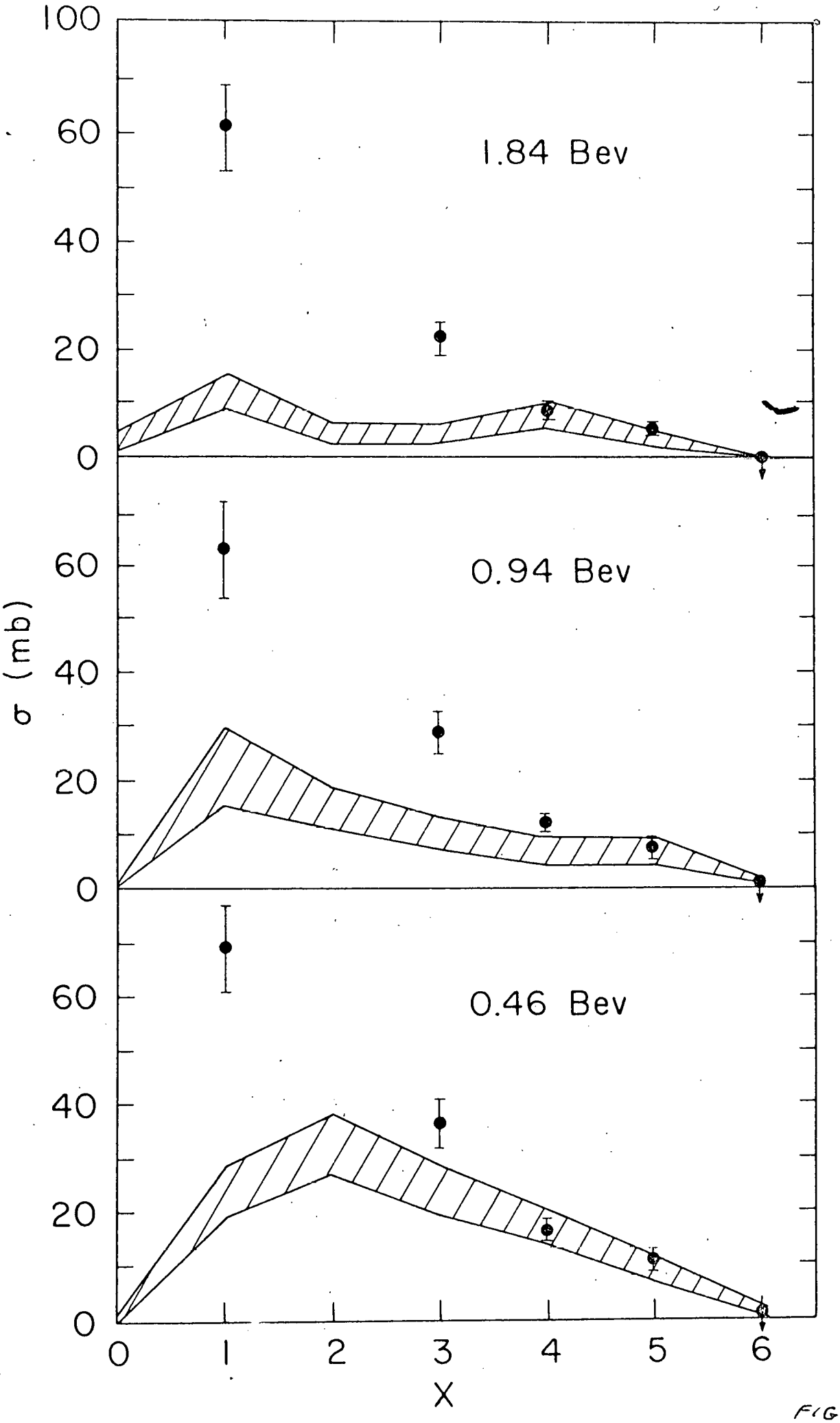

100
60
40
20
0
1.84 Bev
60
40
20
0
0.94 Bev
60
40
20
0
0.46 Bev
σ (mb)
0
1
2
3
4
5
6
X

FIG 4

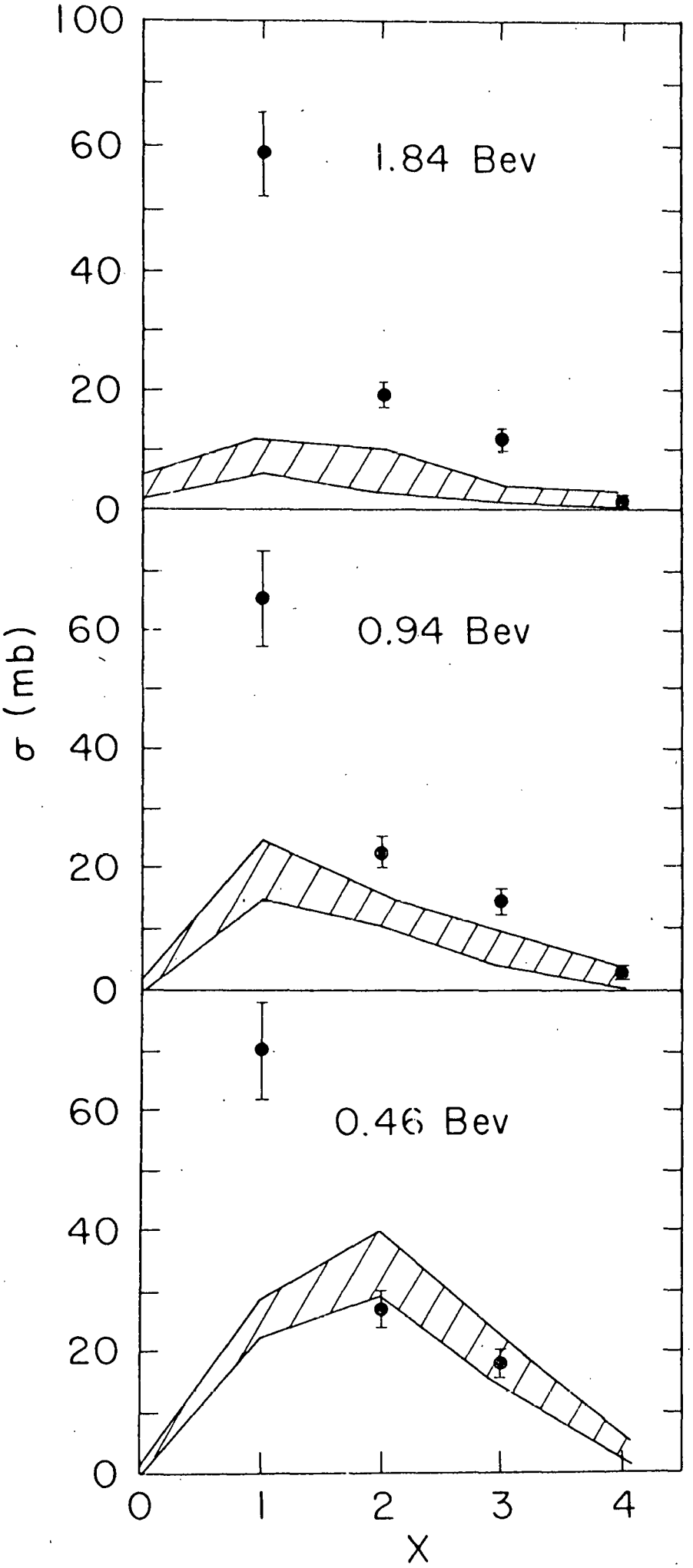
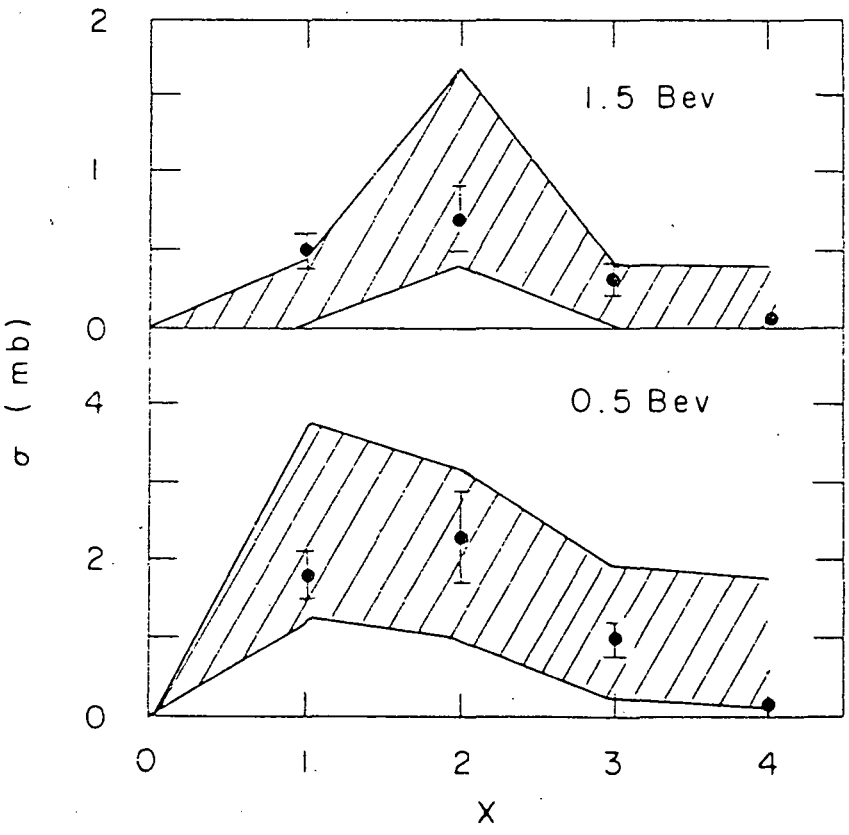
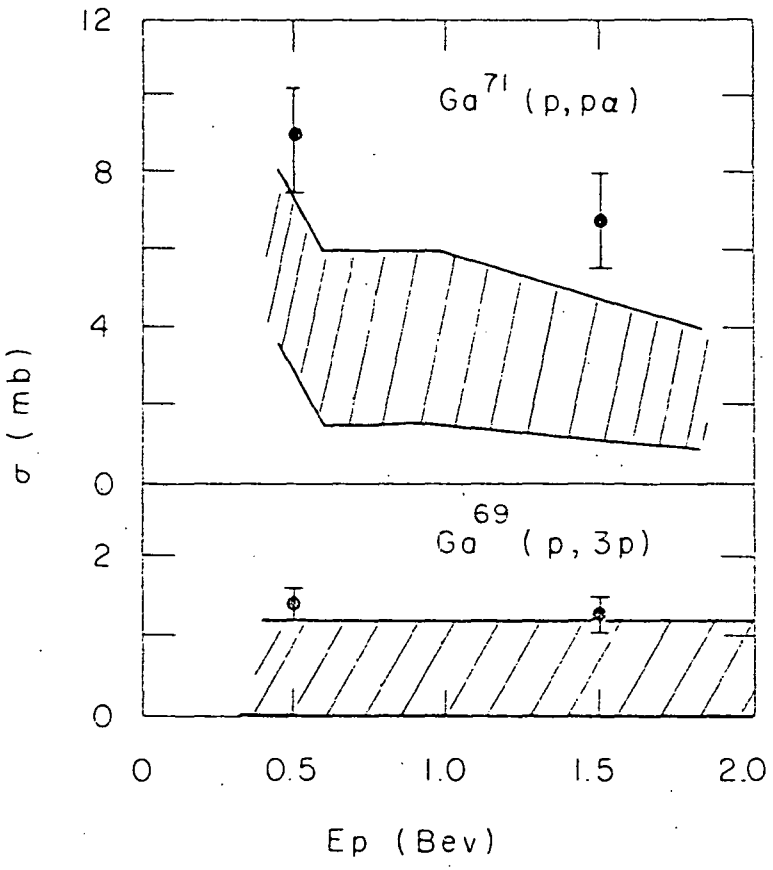
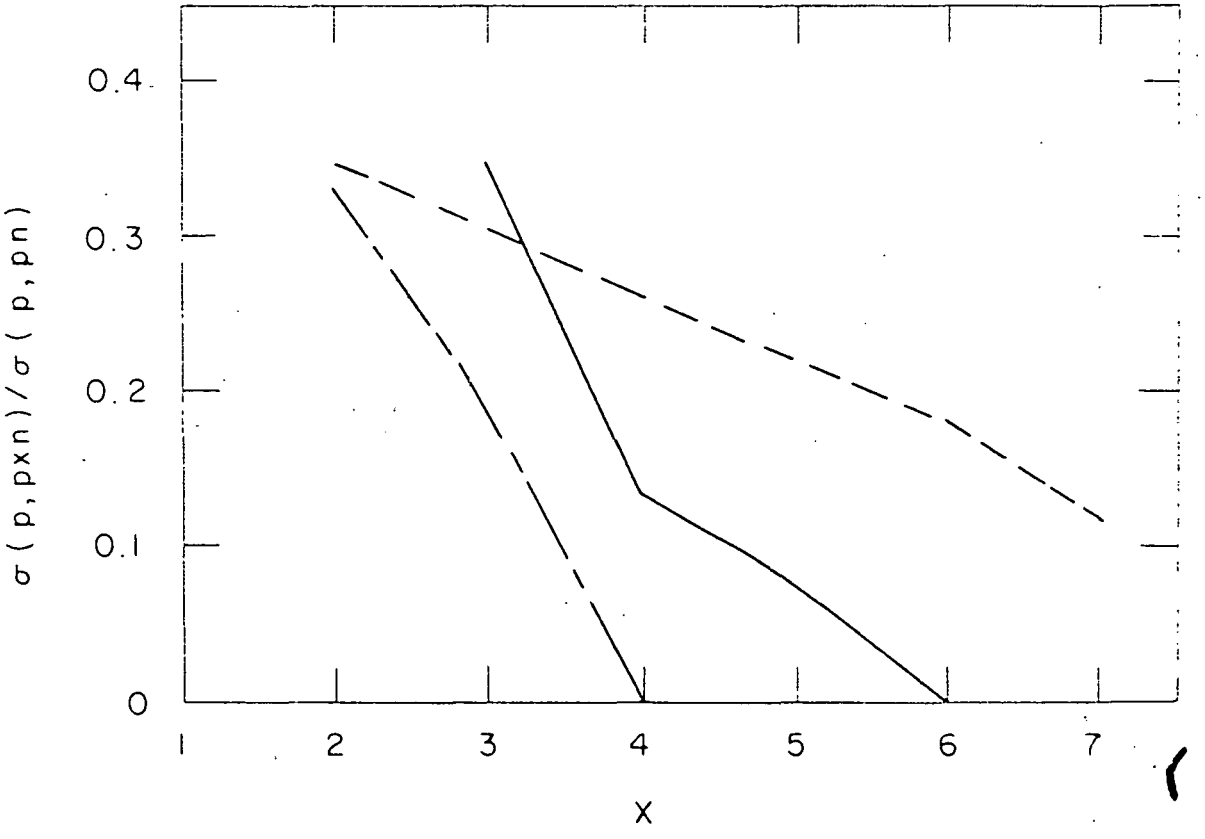

100
60
40
20
0
1.84 Bev
60
40
20
0
0.94 Bev
σ (mb)
60
40
20
0
0.46 Bev
0
1
2
3
4
X

FIG 5


1.5 Bev
0.5 Bev
σ (mb)
X
0
1
2
3
4
0
1
2
0
2
4


12
8
4
0
2
0
σ (mb)
Ga 71 (p, pα)
Ga 69 (p, 3p)
0
0.5
1.0
1.5
2.0
Ep (Bev)


0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
X
σ (p, pxn) / σ (p, pn)