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(p,n) SYSTEMATICS AND THE COSMOLOGICAL CONNECTION*

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(p,n) Systematics and the Cosmological Connection

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ABSTRACT:

Inclusive measurements of (p,n) reactions at intermediate energies of 50-1000 MeV have yielded new information in recent years on the energy and target mass dependence for direct interactions in (p,n) reactions. Furthermore, central collision processes can add appreciably to the inelastic cross-section at intermediate energy producing intermediate mass fragments (IMF) in substantial yields at energies above 200 MeV. These systematics are of much value for interpreting cosmic-ray exposure times, alteration of elemental abundances, and cosmological processes.

INTRODUCTION

The spallation reactions are described by a simple two-step mechanism, an initial fast nuclear cascade followed by an evaporation spectrum that is Maxwellian.[1] The fast cascade is described as a one-pion exchange between two nucleons as given in the equation:

$$p_1 + n_2 \rightarrow n_1 + n_2\Pi^+ \rightarrow n_1 + p_2 \ldots \qquad (1)$$

where the intermediate state (NNΠ) can be resonant or non-resonant. The resonant state delta (Δ) has been rigorously investigated over the last 30 years or so. The non-resonant state can be described as a fast s-wave ($\Delta\ell=0$) interaction similar to that modelled by the pre-equilibrium description by Blann. These models predict the energy and angular dependencies of (p,xn) reactions which are typical of most spallation reactions. The exception is the contribution to the inelastic cross sections due to fragmentation processes which have unique energy and angular dependencies.

Spallation and fragmentation reactions become important in astrophysical settings in predicting the radiation effects of cosmic rays on

interstellar matter, exposure times, alteration of elemental abundances and cosmological processes of dibaryon neutron resonances in neutron stars.

PERIPHERAL COLLISIONS

The majority of spallation reactions are reasonably described by a cascade of several fast nucleons followed by evaporation of a large number of particles whose energy spectra are Maxwellian. The initial state interaction is obscured due to averaging and statistical processes; in particular, the angular and momentum dependence of simple inclusive processes is lost. The extent to which and manner in which the energy, angular, and momentum transfer dependence of a reaction cross section reflects various aspects of the kinematics, nuclear structure, or reaction mechanism, depends specifically on the initial interaction and intermediate state propagator (resonance state). The energy dependence of (p,n) and other spallation reactions are of much value in interpreting the intermediate energy reactions.

The (p,n) reactions are of much interest because of energy and momentum restrictions of the initial (p,n) charge exchange. The energy dependence of (p,n) reactions below 1 GeV on a variety of targets has been observed to vary inversely with bombarding energy[1-5] and similar to that of the free particle p-n scattering cross section.[3,5] For proton-nucleus interactions, the reaction appears to be an initial quasifree (QF) p-n charge exchange resulting in an excited nucleus, which subsequently decays via evaporation of neutrons and gamma rays. The p-n reactions are therefore described by pre-equilibrium and cascade processes that are resonant and non-resonant scattering with intermediate state propagators such as Δ (isovector) and N' (isoscaler) resonances.

Phenomenologically the (p,n) reactions can be parameterized in a manner similar to that of Pearlstein[6] who has investigated the systematics of neutron emission from intermediate energy proton bombardment. The cross section varies as the target mass, $A^{4/3}$, and the double differential cross section (energy and angle) was fit to the function:

$$\frac{d^2\sigma\ (p,xn)}{dEd\Omega} = \sum_{n=1}^{4} A_n(\theta)\ E \exp\left[\frac{-E}{t_n(\theta)}\right] \ldots \qquad (2)$$

The parameter set for E_p=590 MeV is given in Ref. 6 (Table II) where a three-term Legendre expansion in the angular dependence of temperature and amplitude was used. The total cross section was fit to:

$$\sigma(p,xn) = \alpha A^{\beta} \ldots \qquad (3)$$

where $\alpha = 0.021$ and $\beta = 4/3$ with an uncertainty of 5% over the entire mass range. Similarly the energy dependence was parameterized as given in Ref. 6 (Eq. 8) varying inversely with proton energy, $1/E_p$. The 1/E dependence has long been observed experimentally (See Ref. 1) at intermediate energies.

Inclusive measurements of (p,xn) reactions at E_p = 60-800 MeV have shown that the simple two-step process at energies greater than 200 MeV is a constant except for the simple 1/E kinematic energy dependence. This effect

can be observed in the mass distributions for as many as 14 neutrons out in the $^{209}Bi(p,xn)$ reaction, where the curves are constant at all energies greater than 200 MeV (See Fig. 1). The energy and linear momentum transfer inferred from these constant mass curves can be related by the separation energy and most probable momentum transfer determined from the maximum in the mass curve:

$$\langle E_{sep} \rangle = \langle P_{mp} \rangle^2 / 2M_N \ldots \quad (4)$$

or $\langle P_{mp} \rangle = 320$ MeV/c. This value agrees with other proton-nucleus studies at intermediate energies, which have been examining the linear momentum transfer of intermediate cascade processes. Based on a simple momentum transfer model using the uncertainty principle, one finds:

$$\langle P_{mp} \rangle \times r_p = \langle \ell \rangle h \ldots \quad (5)$$

where $\langle P_{mp} \rangle = 320$ MeV/c and $r_p = r_o$ and $\langle \ell \rangle$ the critical orbital angular momentum transferred. In all cases, $\langle \ell \rangle = 2$, which corresponds to a $\Delta\ell = 2$ transition for the peripheral interaction on the surface of all nuclei, i.e., an S to D or P to F state transition, that is, a tensor interaction. Once the resonance state has reached the critical orbital angular momentum ($\Delta\ell$) transfer, the only way to transfer more momentum is through rotation of the system as a whole (I = J+R), that is excitation of rotational degrees of freedom. The rotational momentum transfer is not limited to a critical value and can transfer the maximum linear momentum carried by the projectile to the surface of the target.

CENTRAL COLLISIONS

The effects of central nuclear collisions on the distribution of light mass elements (A = 6-16) were investigated in terms of the energy and target mass dependence of the reaction. The central collision is characterized by a large multiplicity of very light mass fragments (i.e., p,n and α) with a single light mass residue (A = 6-16). Global fits of the experimental production cross sections are parameterized with the variables E_{cm}, A_{target} and $A_{fragment}$, where the center of mass energy ranges from 20 MeV to several GeV. The results of this analysis can be used to calculate galactic cosmic-ray irradiation effects in meteorites and interactions with the interstellar medium.

Kuroda[7] has reviewed the origin of isotopic anomalies observed in meteorites and has noted that the production of deficient elements Li, Be, and B (and other anomalies) appears to be due to the x-process in nucleosyntheses. Furthermore, Kuroda[7] notes that "the exact nature of the x-process is not fully understood." The x-process, it appears, is a combination of spallation or peripheral fragmentation reactions and central collisions with both evaporative and non-evaporative intermediate mass (A = 6-16) fragments (IMF). In the stellar atmosphere, the very deficient light elements are readily destroyed by protons. Hayakawa[8] was the first to point out that cosmic rays of GeV energies can produce these light elements from interactions with meteoritic stellar on interstellar materials. Proton (and α-particles) interactions with C,N,O have been shown[9,10] to contribute

substantially to light element production in the stellar environment; however, galactic cosmic rays (GCR) interacting with meteoritic, stellar or interstellar matter produce copius quantities of light elements as noted by Reeves and others,[11-15] Shapiro,[16] and by Viola and others.[17,18] Three processes contribute to the production of isotopes in the reaction of relativistic heavy-ions with a target;[19] target fragmentation or spallation, projectile fragmentation, and near central collisions.

The spallation or fragmentation cross sections of various nuclides can be routinely calculated using an internuclear cascade code (INC) and is equally good for both light-ion and RHI interactions. However, the production of IMF from medium to heavy targets cannot be predicted using the INC particulary at low energies. The third process due to near central collisions in RHI reactions has been widely investigated[20-27] experimentally at Berkeley. The light mass products with intermediate energy resulting from near central collisions are characterized by their high multiplicity and by the almost complete dissociation of the target and projectile. Central interactions have been studied using activation techniques by Cumming and co-workers[29-30] and others.[19,31,32] Poskanzer, Butler, and Hyde[33] were among the first to measure IMF production at relativistic energies (5.5 GeV protons on uranium) using detector telescopes to identify individual isotopes and elements from hydrogen to argon. The early studies indicated that evaporation processes may account in part for the production of IMF, but that other unknown processes may also be contributing at relativistic energies.

Recent studies at IUCF[34] and TRIUMF[35] have been investigating IMF production with intermediate energy proton reactions on targets of Aℓ, Si, and Ag respectively. These counter studies have obtained high quality IMF differential cross section data and energy spectra. Green, Korteling, and Jackson[35] have studied the reaction Ag(p,IMF)X at energies of 210-480 MeV. They found that the fragment spectra were little affected (except in overall magnitude) with changes in the incident proton energy. Furthermore, a major fraction of the IMF yield (>75% for Li and >98% for oxygen) was non-evaporative and could be described in terms of an isotropic emission process in the rest frame of the moving source. They found that the total isobaric cross sections could be fit to a power law of the form A_f^{-n} in the fragment mass with n = 3.71. In the study of Kwiatkowski, et al.,[34] the reaction Aℓ(p,IMF)X was studied at E_p = 180 MeV and compared with INC calculations. High yields of light fragments and forward peaking of the angular distributions suggest that the fragments are emitted from a hot moving source. The data at 180 MeV exhibits many similarities with data at 2.1 and 4.9 GeV proton bombardment of ^{27}Aℓ.[36] The INC comparison at 180 MeV describes peripheral, quasifree processes relatively well, but is unable to account for the light fragment yields or their angular distributions. In particular, no significant yield for A = 7 was predicted although substantial yields were observed. It was noted that these data are of considerable interest relating to studies of cosmic-ray origins and propagation.[37-39]

Activation measurements[37] of the Si(p,^{7}Be)X and KCℓ(p,^{7}Be) reactions have been made at IUCF at proton energies of 60-200 MeV. These data are displayed in Fig. 2 along with data on Si by Rayuder.[40-42] A global set of data[43-49] for the reaction ^{27}Aℓ(p,^{7}Be)X is shown in Fig. 3 for the energy

range of 30 MeV to several GeV including recent measurements conducted at TRIUMF.[50] In the region of 60 MeV - 1 GeV, the energy dependence of the IMF excitation function for Si follows a power law of the form $\sigma(E) = \sigma_0 E^{0.74}$ with the slope little changed by either $A_{fragment}$ or $A_{projectile}$. The contribution of ^{7}Be to the total mass 7 isobaric yield has been measured in counter experiments[33,35] and found to be approximately 15%. At E_p = 180 MeV on ^{27}Aℓ, the ^{7}Be yield is 1.4 mb,[33] a value in good agreement with the global data set. Using the extensive set of excitation function data[39-50] for the production of ^{7}Be from various targets ranging from ^{12}C to ^{197}Au, the target mass energy dependence was determined. The data are shown in Figs. 4a, b, and c. The cross sectional data[51-54] were fit to a power law of the form $A^{\alpha w-1}$, where $w = (E_0-E_p)$ in MeV. The parameters $\alpha = 2.65 \times 10^{-3}$ MeV^{-1} and E_0 = 931 MeV were found to fit the low energy (65-335 MeV) data very well. Above 1 GeV, the experimental slope approaches zero and at E_p>2 GeV, the slope becomes positive and constant (slope = 1.8). The constant value is in keeping with concepts of limiting fragmentation at relativistic energies. A major component of the particle spectrum at relativistic energies (E_p>1 GeV) appears to be an evaporative component as noted in Ref. 33.

DISCUSSION

Central Collisions:

The formation rate of an IMF from the reaction of A_T elements by a flux of protons with an energy spectrum (ϕE), is given[55] by:

$$\frac{dN_{IMF}}{dt} = \sum_{A_T} N_T \int \sigma (E_p, A_f, A_T) \phi (E_p)\, dE \ldots \qquad (6)$$

where N_{IMF} AND N_T are the number densities of IMF products and any target nucleus, respectively, the time variable is t, and $\sigma(E_p, A_f, A_T)$ is the IMF production cross section parameterized in the above discussion. For cosmic ray protons, the energy spectrum adopted[56] was

$$\phi (E_p) = 12.5\ (E_o + E_p)^{-2.6} \mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{GeV}^{-1} \ldots \qquad (7)$$

where E_o = 0.931 GeV, and E_p is in GeV. This parameterization was found[56,57,58] to fit the demodulated proton flux down to about 500 MeV where solar modulation effects[59] blur the spectrum of the interstellar flux, particularly below 100 MeV/u. The principle modulating region lies within 2-3 A.U. and amounts to a mean energy loss of 210 MeV near earth orbit. Therefore, energy losses resulting from the expansion of solar wind makes it impossible to measure the low energy primary cosmic ray flux and indicates that most of the flux observed below ≈100 MeV originate at higher energies. The solar wind proton flux can be 1-3 orders of magnitude greater than the GCR proton flux after various moderate size solar flare events, however, the duration of such events minimize the solar irradiation effects. On the other hand, the GCR flux with energies of 30-200 MeV/u may be as much as 10-60 times the total high energy flux, particularly near the source.

The relative formation rates for the Si(p,^{7}Be)X reaction were calculated using Eqs. 6 and 7 and the energy dependence cross sections discussed above for E_p = 30 to 80 GeV. This data is shown in Table 1. Previous studies[11-16] used an energy cut-off of E>2 GeV/u due to the fact that little was known about the intermediate energy flux, a lack of knowledge concerning the energy dependence of IMF production and because the relativistic cross sections are approximately constant at the higher energies.

The integral formation rate for E_p = 30 MeV to 2 GeV is 15% of the total integrated rate up to 80 GeV. This is not a large correction to the earlier estimates,[16] however, new experimental information on the intermediate energy flux could alter this interpretation particularly for regions near GCR sources.

The energy dependent non-evaporative IMF components are viewed as near central collision residues. At relativistic energies heavy-ion central collisions amount to about 20% of the total inelastic reaction cross section indicating an impact parameter of ≈0.5 fm compared with 1.2 fm for peripheral fragmentation processes. The central collisions are therefore identified with the short range part of the NN interaction, which is not incorporated in standard versions of the INC. The differences between peripheral and central reactions are not unlike those processes described by isovector (T = 1) and isoscalar (T = 0) transitions.

The isovector transition strength (2T + 1 = 3) is mediated by the long range (1.2 fm) attractive part of the force whereas the isoscalar transition is short ranged and repulsive. The distributions of T = 1 and T = 0 processes compare well with anisotropic peripheral fragmentation and isotropic central collision results. The isotropic central collision multiplicity would therefore include T = 0 final state amplitudes, i.e., α particles, d, and np pairs, in addition to a IMF residue. The T = 0 transitions can therefore be viewed as a motion of the neutrons with or against the protons in the nuclear short range central potential.

The characterization of the non-evaporative IMF production process as a near central nuclear collision for energies E>30 MeV/u may have important consequences for the production of light mass deficient isotopes (Li, Be, B) in type II supernova events. The photodisintegration of Fe-group elements during the endoergic central core implosion of a massive star (M≈30 M) becomes an important contributor to the production of IMF's through reactions such as:

$$^{56}Fe + \gamma \rightarrow {}^{7}Be + 11\ \alpha + 5n - 118.5\ MeV \ldots \qquad (8)$$

The interaction is still the same as in the proton-nucleus collision (pn_A), that is the photon excites the T = 0 isoscalar states (γd_A).

Peripheral Collisions:

Neutron yields and spallation mass curves can be predicted with some confidence for proton interactions with targets at intermediate to high energies. These systematics are of much value for interpreting cosmic-ray exposure times, alteration of elemental abundances (by both primary and secondary particles) and for cosmological processes.

A form of the (p,n) reaction is known to be operative in the formation of neutron stars, viz a vi the weak interaction:

$$e^-(p,n)\nu_e \ldots \tag{9}$$

which is endoergic bv 782 keV. Once equilibrium has been established, it then becomes possible to produce nn collisions, some of which may form dibaryon resonant states given sufficient energy. For example, assuming a $\Delta\ell = 2$ transition for neutrons:

$$n_1 + n_2 \xrightarrow{\Delta\ell = 2} (nn)_{12} \ldots \tag{10}$$

then about 110 MeV is required since the 55 MeV excitation in the center of mass is doubled due to the recoil energy required in the collision. This state has a large width (≈100 MeV) and lives for a very short time (≈6.6×10^{-24} sec). The resonance decays to lower lying excitations via $\Delta J = 1$ and 2 transitions. Thus the transformation of gravitational energy into electromagnetic radiation (or weak interaction radiation ν_e) can be increased from 0.782 MeV to about 55 MeV per neutron, an increase in the energy density of 70 or more. The Maxwellian energy distribution of a neutron star peaks at about 1 MeV; at 55 MeV, the population is approximately 0.5% of the total distribution. To be sure, in addition to dibaryon resonances in the energy range up to ≈100 MeV, there also exist possible quark-cluster states, NNΠ, NΔ, and NN' states at energies up to several hundred MeV in excitation energy.

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TABLE 1

Relative Production Rates for
the Reaction $Si(p,{}^{7}Be)X$

E_p (GeV)	$\phi(E)$ Particle/sec cm^2	σmb 1×10^{-27} cm^2	Relative Rate
0.03	0.42	0.30	0.014
0.10	1.15	0.75	0.097
0.20	1.80	1.05	0.214
0.30	2.16	1.49	0.364
0.40	2.34	1.84	0.486
0.50	2.42	2.18	0.597
0.60	2.43	2.49	0.684
0.70	2.39	2.79	0.754
0.80	2.34	3.09	0817
0.90	2.26	3.37	0.861
1.00	2.19	3.64	0.901
2.00	1.45	6.10	1.000
4.00	0.73	10.20	0.842
10.00	0.22	10.0	0.249
20.00	0.08	10.0	0.090
40.00	0.027	10.0	0.030
80.00	0.009	10.0	0.010

FIGURE OF CAPTIONS

Figure 1: Mass Yield Distribution Ratio's of Polonium Isotopic Products at Different Incident Proton Energies from the Reaction $^{209}Bi(p,xn)^{210-xn}Po$.

Figure 2: Exitation Function for the Reaction $Si(p,^{7}Be)X$ and $KCl(p,^{7}Be)X$ Reactions at Intermediate Energies.

Figure 3: Global Data Set for the Reactions $^{27}Al(p,^{7}Be)X$ at $E_p > 30$ MeV.

Figure 4: Energy and Target Mass Dependence for the Reaction $A_T(p,^{7}Be)X$ at Various Proton Energies.

FIGURE 1

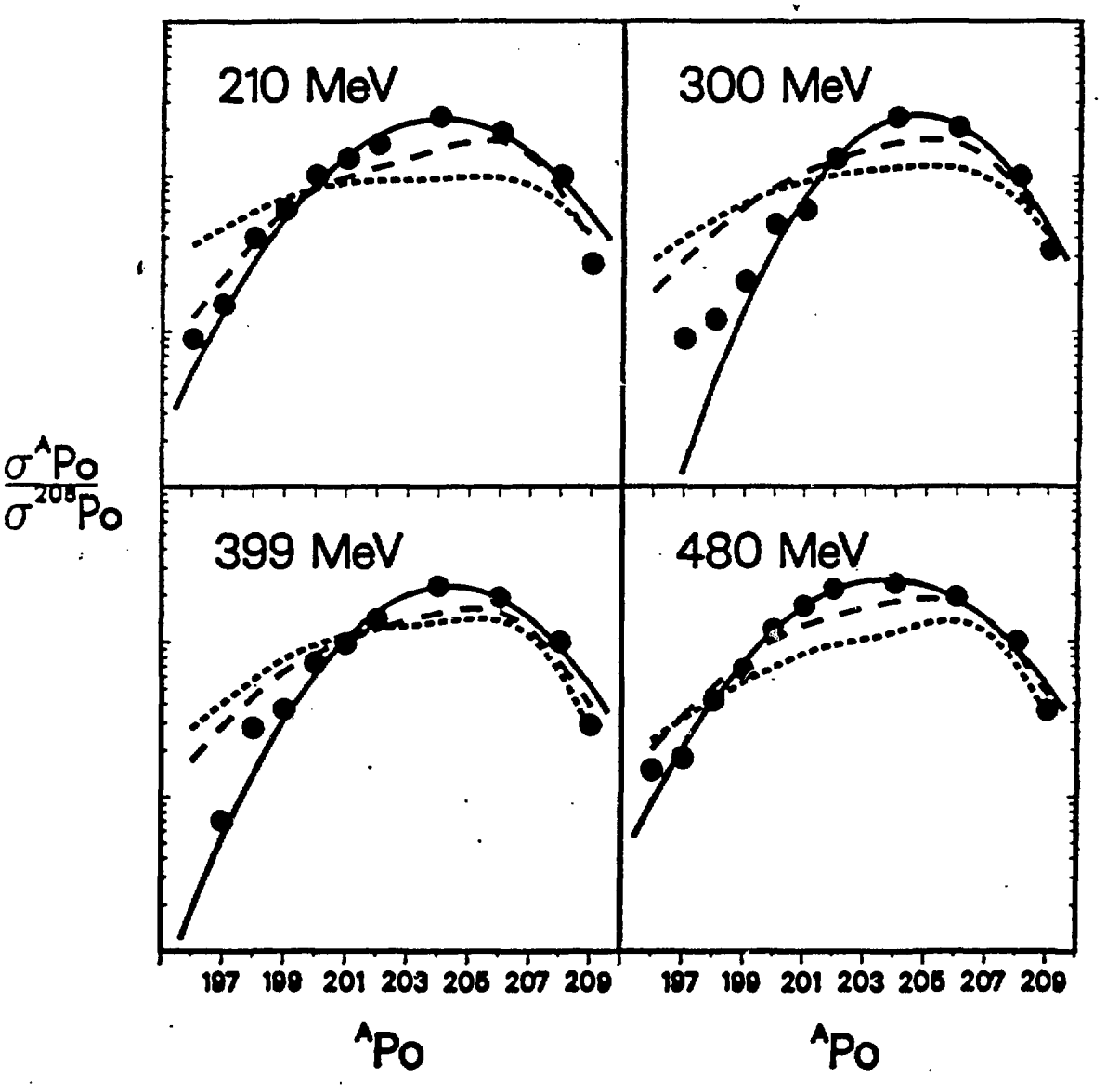
210 MeV
300 MeV
399 MeV
480 MeV
$\frac{\sigma^{A}Po}{\sigma^{208}Po}$
197 199 201 203 205 207 209
197 199 201 203 205 207 209
^{A}Po
^{A}Po

FIGURE 2

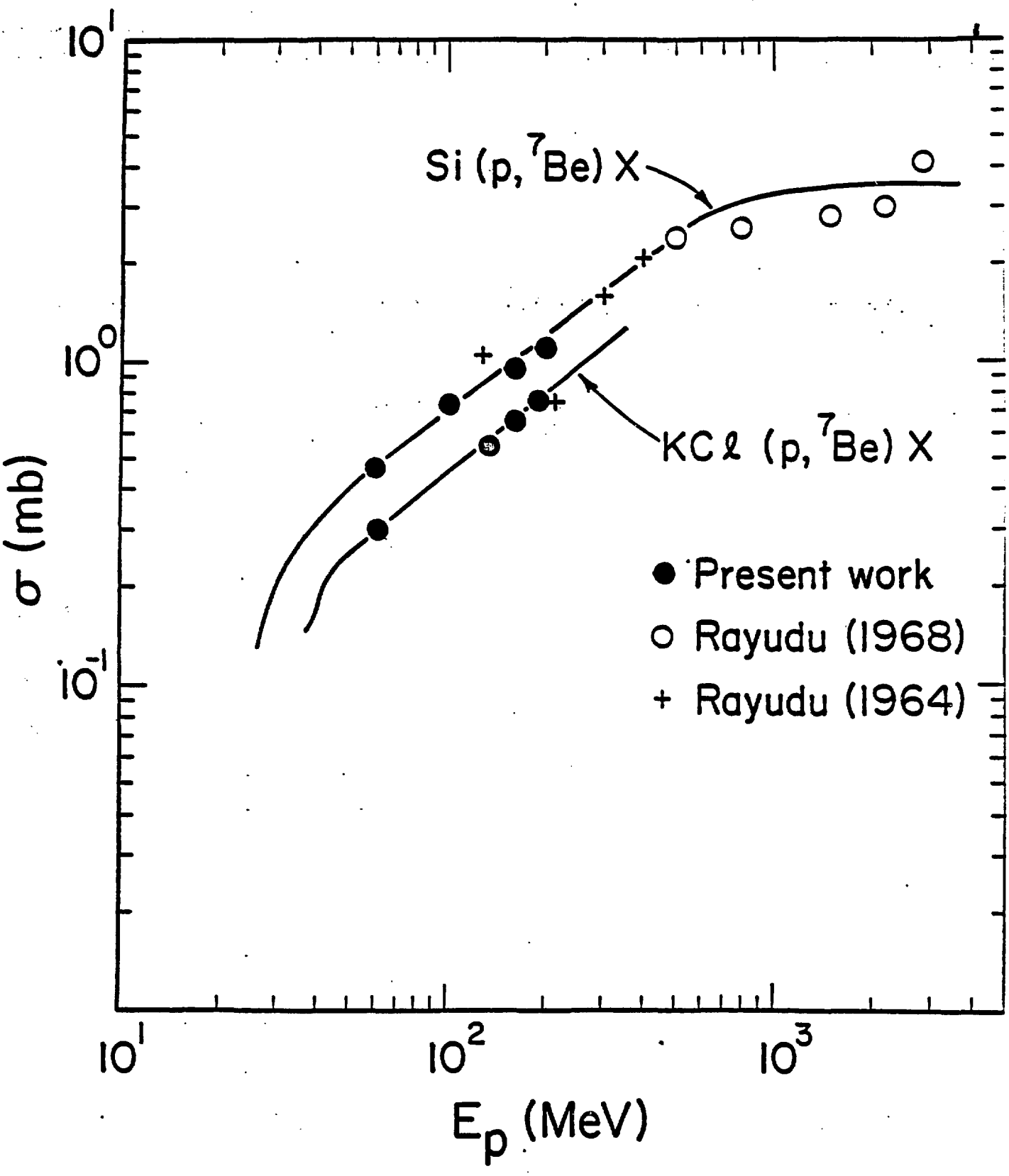
Si (p, 7Be) X
KCℓ (p, 7Be) X
Present work
Rayudu (1968)
Rayudu (1964)
σ (mb)
Ep (MeV)
10^1
10^0
10^-1
10^1
10^2
10^3

FIGURE 3

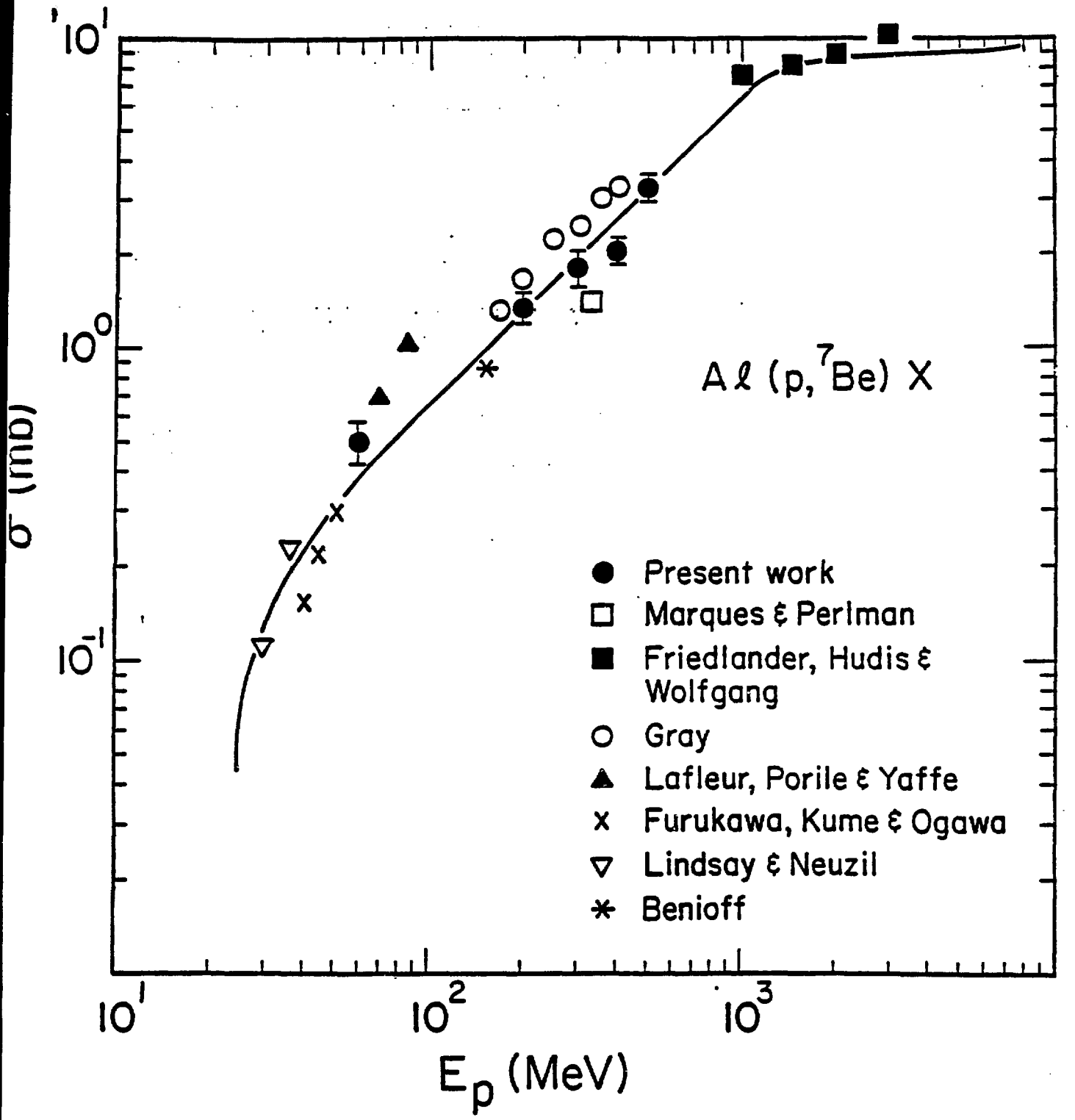
10^1
10^0
10^{-1}
σ (mb)
Aℓ (p, ^{7}Be) X
Present work
Marques & Perlman
Friedlander, Hudis & Wolfgang
Gray
Lafleur, Porile & Yaffe
Furukawa, Kume & Ogawa
Lindsay & Neuzil
Benioff
10^1
10^2
10^3
E_p (MeV)

FIGURE 4

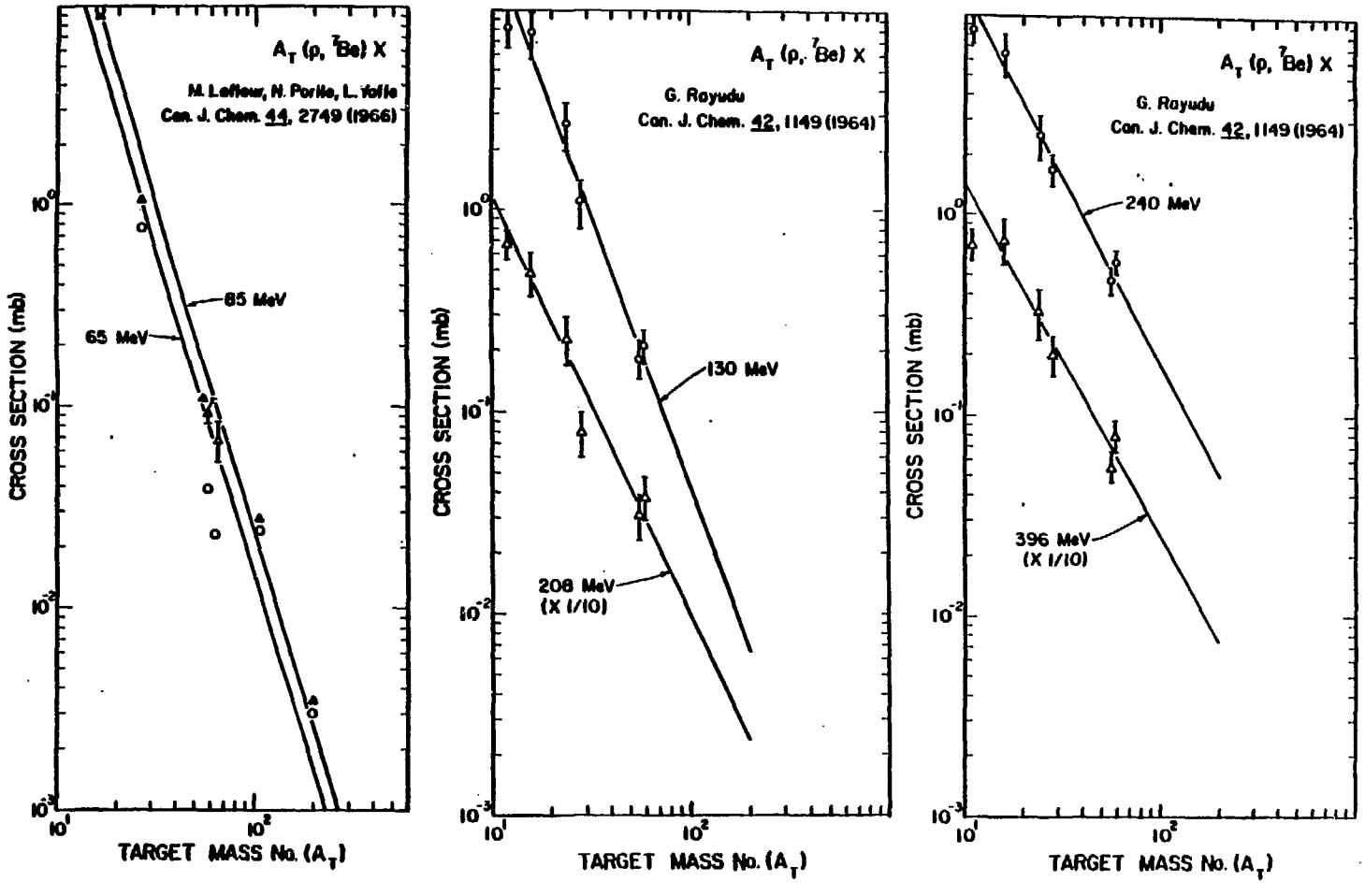

FIGURE 4