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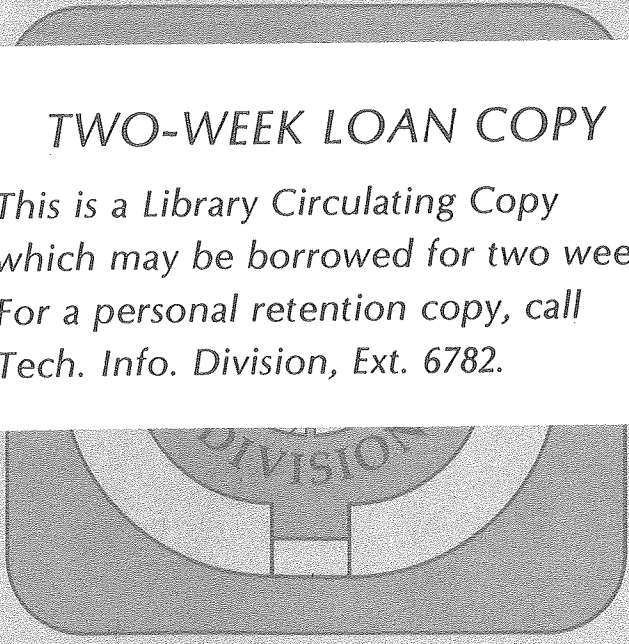
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# Neutron Emission in Relativistic Nuclear Collisions

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## Abstract

Previously reported differences between the measured proton and neutron energy spectra for the reaction  $\sim 400$  MeV/nucleon  $^{20}\text{Ne} + \text{U} \rightarrow \text{p}, \text{n} + \text{x}$  are discussed. A parameter-free cascade-coalescence model of heavy ion collisions is shown to account for these differences. Such measurements are shown to be sensitive to the degree of projectile-target equilibration in relativistic nuclear collisions.

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Charged particle emission in relativistic heavy ion collisions has been extensively studied in the last few years. Measurements of the single particle inclusive spectra of protons, pions and light nuclei have been made using projectiles as heavy as  $^{40}\text{Ar}$ . A wide variety of models have been developed to describe relativistic heavy ion collisions. For a recent review of both experimental and theoretical results see ref. 1.

Measurements of neutron emission have, however, only recently been made.<sup>2</sup> These measurements show that the double differential cross section for  $\sim 400$  MeV/nucleon  $^{20}\text{Ne} + \text{U} \rightarrow \text{n} + \text{x}$  (ref. 2) differs substantially from cross sections for  $\sim 400$  MeV/nucleon  $^{20}\text{Ne} + \text{U} \rightarrow \text{p} + \text{x}$  (ref. 3), and  $^{20}\text{Ne} + \text{Pb} \rightarrow \text{p} + \text{x}$  (ref. 4). The neutron-to-proton ratio,  $R$ , defined by eq. 1, monotonically decreases with increasing fragment energy at all laboratory angles for both sets of proton data. It varies from  $R \approx 4$  at 20 MeV to  $R \approx 0.3$  at 600 MeV at all laboratory angles.

$$R = \frac{d^2\sigma(\text{n})}{d\Omega dE} / \frac{d^2\sigma(\text{p})}{d\Omega dE} \quad (1)$$

The firestreak<sup>5</sup> model predicts that  $R$  should be essentially constant<sup>2</sup> and equal to the neutron-to-proton ratio of the projectile-target system,  $R \approx 1.6$  for  $\text{Ne} + \text{U}$ . Using proton spectra calculated for a  $\text{Pb}$  target raises  $R$  by about 10%. Since the neutron measurements were made at a slightly lower beam energy (see Table 1) it was necessary to calculate the neutron and proton spectra separately at their exact respective beam energies. With this correction the firestreak model predicts<sup>2</sup> that the neutron-to-proton ratio should be

$R \approx 1.7$  at 20 MeV, falling monotonically to  $R \approx 0.9$  at 600 MeV. Thus the firestreak model fails to account for most of the observed fragment energy dependence of the neutron-to-proton ratio  $R$ .

Recently I presented a cascade model of relativistic heavy ion collisions that accounts successfully for charged particle measurements.<sup>6</sup> In this Letter I show that this same model accounts for the fragment energy dependence of  $R$ . My model, which is parameter-free, assumes that the heavy ion collision process proceeds in two steps.<sup>6</sup> First there is a cascade in which the collision is treated as a succession of free nucleon-nucleon elastic scatterings. Then in the final state some of the scattered nucleons coalesce to form light nuclei. This second stage utilizes the coalescence model of Gutbrod et al.<sup>7</sup> One important consequence of my cascade model is that the formation of light nuclei significantly changes the proton and neutron energy spectra.

Light nuclei are known to be copiously produced in relativistic heavy ion collisions.<sup>7</sup> In fact, at forward angles ( $\theta = 30^\circ$ ) and low fragment energies ( $E \leq 80$  MeV/nucleon) more charge is emitted as light nuclei than as free protons.<sup>3</sup> The coalescence model<sup>7</sup> assumes that protons and neutrons coalesce to form light nuclei in the final state if their momenta are sufficiently nearly equal. The coalescence model gives a simple relationship, eq. 2, between the differential cross section for a light isotope  ${}^A_Z$  and the proton and neutron differential cross sections before coalescence took place.

$$\frac{d^2\sigma(Z, A)}{d\Omega dE} = K S^{-(A-1)} \left[ \frac{d^2\sigma(p')}{d\Omega dE} \right]^Z \left[ \frac{d^2\sigma(n')}{d\Omega dE} \right]^{(A-Z)} \quad (2)$$

In eq. 2, the kinetic energies  $E$  are in energy/nucleon and  $S$  is the corresponding momentum/nucleon. The  $K$  is a normalization coefficient. The primes on  $p$  and  $n$  refer to the pre-coalescence values of the proton and neutron cross sections. The coalescence model agrees remarkably well with observed light nucleus energy spectra.<sup>7</sup> Alternatively, it is possible to calculate the pre-coalescence proton and neutron spectra directly from the cross sections for production of protons,<sup>3,4</sup> neutrons,<sup>2</sup> and light nuclei,<sup>3</sup> without introducing parameters. They are given by

$$\frac{d^2\sigma(p')}{d\Omega dE} = \frac{d^2\sigma(p)}{d\Omega dE} + \sum_Z Z \frac{d^2\sigma(Z,A)}{d\Omega dE} \quad (3)$$

$$\frac{d^2\sigma(n')}{d\Omega dE} = \frac{d^2\sigma(n)}{d\Omega dE} + \sum_{(A-Z)} (A-Z) \frac{d^2\sigma(Z,A)}{d\Omega dE} \quad (4)$$

The sums are taken over all possible nuclei, but only H and He isotopes contribute significantly.

It is possible to calculate the neutron-to-proton ratio before coalescence takes place,  $R'$ . Figure 1 compares the neutron-to-proton ratios,  $R'$  and  $R$ , before and after coalescence take place for data at an angle of  $30^\circ$ . The pre-coalescence values of  $R'$  start at  $R' \approx 1.7$  at 20 MeV, and fall slowly to  $R' \approx 0.4$  at 600 MeV. Unlike the observed ratio  $R$  the pre-coalescence value  $R'$  never substantially exceeds the neutron-to-proton ratio of the target nucleus of  $\sim 1.6$ . The difference between the observed ratio  $R$  and the pre-coalescence ratio  $R'$  at low energies is quite simple to understand. Formation of light nuclei removes essentially an equal number of protons and neutrons from a given energy interval. At low energies a much larger

fraction of nucleons coalesce than at high energies. Since there are fewer protons than neutrons before coalescence, a larger fraction of the protons are removed than of the neutrons. These factors account for the observed rise in the neutron-to-proton ratio  $R$  at low energies.

Figure 2 compares the values of the experimental neutron-to-proton ratio  $R'$ , corrected to the time before coalescence, with values calculated from my cascade model. The neutron and proton spectra were calculated separately at their respective beam energies (Table 1). The calculated values are for a U target. Using proton spectra calculated for a Pb target would raise  $R'$  about 10%. The calculated values reproduce reasonably well the fragment energy dependence of  $R'$ . Most of the calculated energy dependence of  $R'$  occurs because the beam energies for the neutron and proton measurements are not exactly the same. If the beam energies were both exactly 400 MeV/nucleon, my cascade predicts that  $R'$  would fall from  $R' = 1.5$  at 20 MeV to  $R' = 1.2$  at 400 MeV. This drop results because the projectile and target are not completely equilibrated. In my cascade calculation the target nucleons dominate the spectrum at low energies and the projectile nucleons dominate at high energies. Therefore,  $R'$  varies from the target neutron-to-proton ratio to that of the projectile in going from low to high fragment energies. The true energy dependence of  $R'$  for 400 MeV/nucleon  $^{20}\text{Ne} + \text{U}$  is predicted to be small because the projectile and target neutron-to-proton ratios are comparable, 1 and 1.59.

Figure 3 shows the experimental neutron spectra corrected to the time before coalescence. The data are calculated from eq. 4 using the neutron cross sections of experiment 1 and the light

nucleus cross sections of experiment 2 (see Table 1). The data are compared with the results of my cascade calculation. The cascade calculation is in reasonably good agreement with the data. The cascade does, however, systematically underestimate the data at low energies.

Refined measurements of  $R^1$  would provide a sensitive test of projectile-target equilibration. Alternatively, comparisons of proton spectra for various isobar projectile pairs, for example  $^3\text{He}$  and  $^3\text{H}$ , would provide a sensitive test of projectile-target equilibration.

The cascade-coalescence model of heavy ion collisions provides a simple parameter-free explanation of apparent anomalies in the neutron-to-proton fragment ratio. In addition, it suggests simple quantitative tests of the degree of equilibration in relativistic heavy ion collisions.

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Table 1. Summary of measurements referred to in this Letter.

<u>Expt. #</u>	<u>Reaction</u>	<u>Energy</u>	<u>Reference</u>
1	$^{20}\text{Ne} + \text{U} \rightarrow \text{n} + \text{x}$	337 MeV/nuc.	2
2	$^{20}\text{Ne} + \text{U} \rightarrow \text{p} + \text{x}$	393 MeV/nuc.	3
3	$^{20}\text{Ne} + \text{Pb} \rightarrow \text{p} + \text{x}$	385 MeV/nuc.	4

## Figure Captions

- Figure 1. Neutron-to-proton ratio at  $30^\circ$  lab angle. Solid symbols are R, open symbols are R'. Triangles use Expt. #2 proton data, squares use Expt. #3 proton data. (See Table 1.)
- Figure 2. Neutron-to-proton ratio R'. Triangles are based on proton data of Expt. #2, squares are based on proton data of Expt. #3. (See Table 1.) The solid line is calculated, for a U target, from the cascade model discussed in the text.
- Figure 3. The square symbols are the experimental neutron cross sections corrected to the time before coalescence. The solid line is calculated from the cascade model discussed in the text.

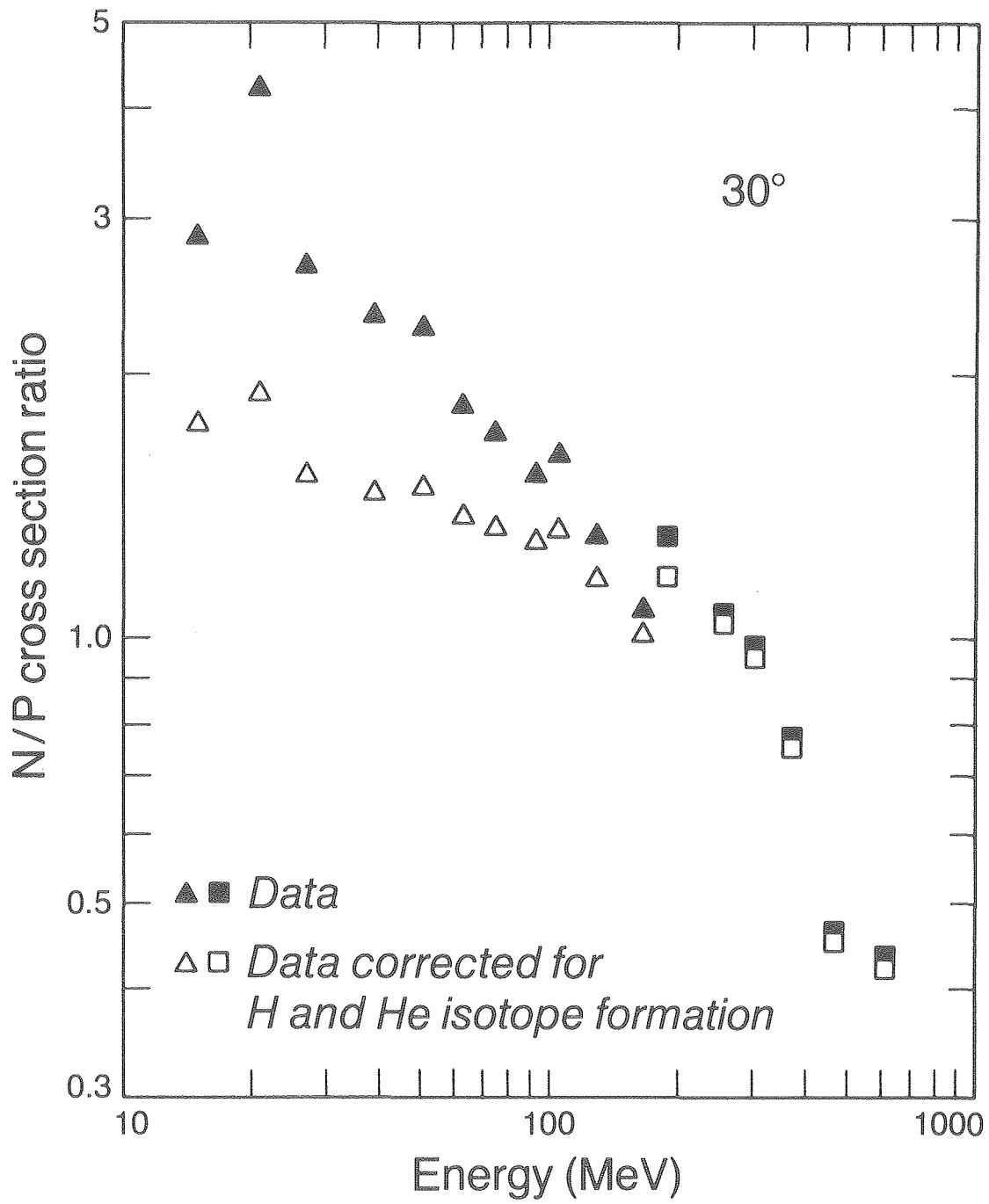


Figure 1

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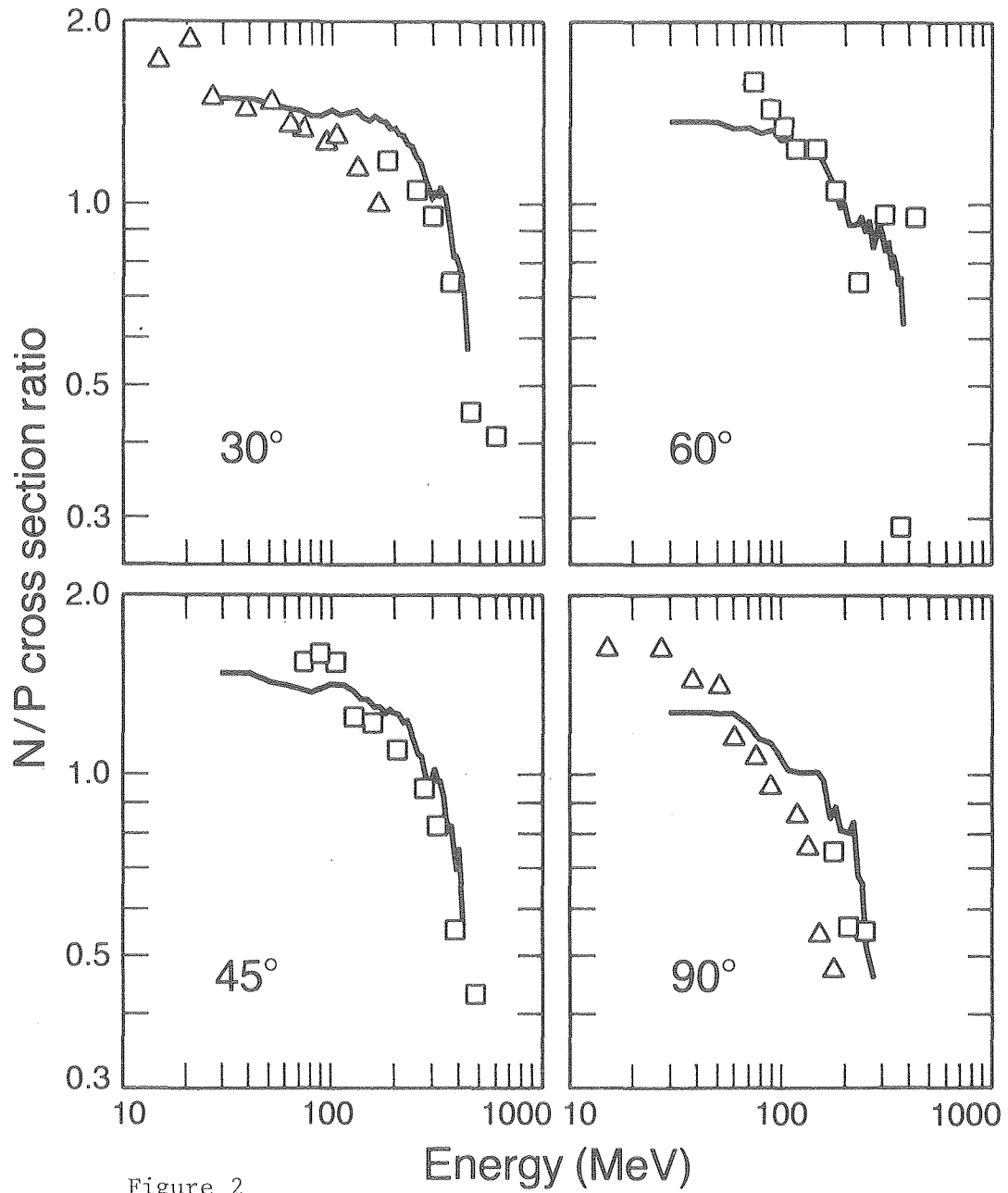


Figure 2

XBL 809-11909

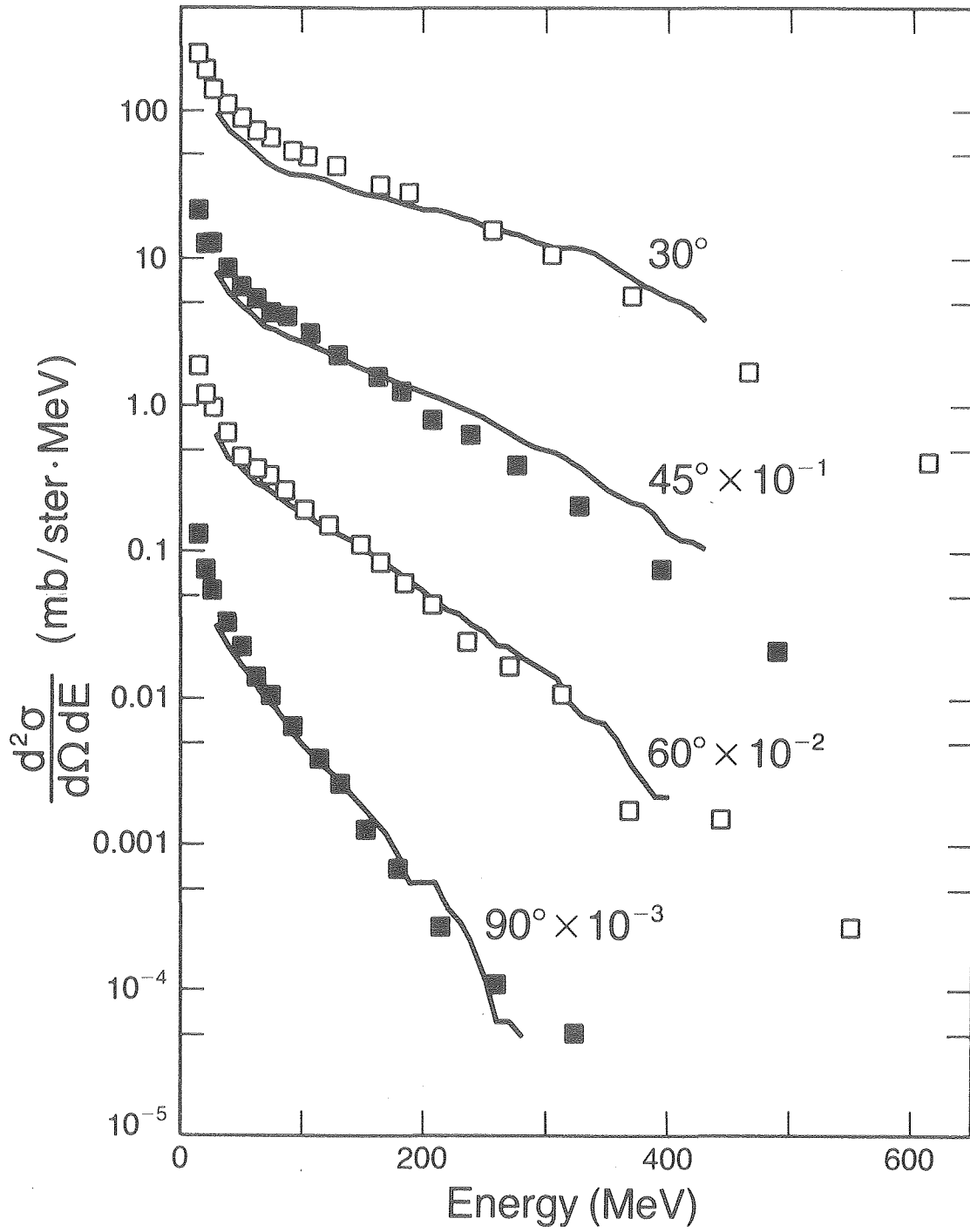


Figure 3

XBL 809-11910