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Comparison of Measured Neutron Spectra with Predictions of an Intranuclear-Cascade Model*

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Neutron spectra resulting from bombardment of targets of ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb with 45 MeV protons have been measured at many angles between 0° and 160°. Intranuclear-cascade, Monte-Carlo calculations predict too many high-energy neutrons in the forward direction and too few neutrons, particularly high-energy neutrons, at angles greater than $\sim 45^\circ$. Beyond 90° the underprediction is by factors of 10 to 100. For angle-integrated spectra, however, there is reasonable agreement between theory and experiment.

NUCLEAR REACTIONS ^{48}Ca, ^{90}Zr, ^{120}Sn, ^{208}Pb (p,nx); E = 45 MeV; measured $\sigma(E_n,\theta)$ and $\int d\Omega\sigma(E_n,\theta)$; enriched targets. Intranuclear-cascade model.

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1. Introduction

For proton spectra initiated by 62- and 39-MeV protons, a detailed comparison has recently been made between experiment and intra-nuclear cascade models[1]. In that comparison it was seen that the models predicted relatively too many high-energy protons at small angles and too few protons of all energies at large angles. In this Comment we compare the predictions of the ORNL model[2] with neutron spectra produced by 45-MeV protons incident on thin targets of ^{48}Ca (1 mg/cm^2), ^{90}Zr (10 mg/cm^2), ^{120}Sn (10 mg/cm^2), and ^{208}Pb (10-30 mg/cm^2)[3,4]. Experimental details may be found in references 3 and 4. The spectra were measured at Michigan State University, and the calculations were performed at Oak Ridge National Laboratory. Similar data exist for the same target nuclei but for lower proton bombarding energies, viz. 35 and 25 MeV. A comparison between theory and experiment was made for ^{48}Ca and ^{208}Pb at 35 MeV. As the results were qualitatively similar to those at 45 MeV, only the 45-MeV work is presented here. No cascade calculations were made at 25 MeV, where the range of neutron energy is rather small.

2. Angle-Integrated Spectra

In terms of angle-integrated spectra, Fig. 1 shows the comparison between theory and experiment for each of the four targets. The prediction of the cascade model is given in each case by a histogram having a 5-MeV bin width. The histories of 50,000 incident protons were followed for each target, resulting in statistical errors ranging from 2 % for neutrons in the lowest-energy bin to 5 % in the highest. As the cascade progresses in time, the kinetic energy brought in by the proton is accounted for, but there is no accounting of the mass difference between target and residual nuclei. One consequence of this neglect is, for example, the ejection of neutrons having the same kinetic energy as the incident protons, whereas the maximum neutron energy must trail the incident proton energy by the magnitude of the (p,n) Q value. These magnitudes are (in MeV) 0.51, 6.89, 3.46, and 3.65 for ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb, respectively. An approximate correction for this effect was made by shifting each neutron spectrum by the appropriate Q value.

The measured spectra are represented by the almost-smooth curves, which are, in fact, histograms with 0.1 MeV bin widths. Each of these histograms results from the addition, with proper solid-angle weighting factors, of spectra measured at 32 different angles from 0° to 160° (25 angles from 0° to 150° for ^{48}Ca). The overall estimated error is 20 %[4].

The experimental spectra have structure, but the cascade calculation has no mechanism to reproduce nuclear structure effects. The main structure effect seen is a peak corresponding to a direct charge-exchange transition to the isobaric analogue state of the target, as first observed by Anderson and Wong[5]. This peak is at a neutron energy below the 45-MeV bombarding energy by an amount equal to the Coulomb displacement energy, namely, 7.2 MeV[6], 12.0 MeV[7], 13.4 MeV[6], and 18.8 MeV[8] for ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb, respectively. Bearing in mind that the charge-exchange peaks and other direct-reaction structure observed at the higher energies are outside the domain of the cascade model, we see that there is agreement between theory and experiment to within better

than a factor-of-two. For all four targets there is a tendency for the model to predict too few of the lower-energy neutrons. The overall quality of the fits is comparable to that obtained with preequilibrium models[4].

3. Spectra at Individual Angles

Unlike the preequilibrium models[9], which are statistical models, the cascade models are geometrical in nature and are capable of predicting the angular dependence of spectra. In Fig. 2 we compare measured and predicted spectra at five representative angles for ^{48}Ca. The same comparison is made at six angles in Figs. 3, 4, and 5 for ^{90}Zr, ^{120}Sn, and ^{208}Pb, respectively. As for the angle-integrated spectra of Fig. 1, the computer output of the cascade calculation has been shifted in energy by the relevant (p,n) Q value in each case. For each target the spectrum measured at 0° begins about five MeV higher than at other angles because the 0° spectra were measured with longer flight paths. Although the experimental angular resolution was only 1°, it was necessary to use larger angular bins in the Monte Carlo calculation in order to improve the statistics. The angular ranges used were 0°-4°, 28°-32°, 58°-62°, 85°-95°, 115°-145°, and 145°-175° for comparison with data at 0°, 30°, 60°, 90°, 130°, and 160°, respectively. Even so, at the backward angles many of the energy bins had not a single neutron in them.

For each of the four targets we see that too many high-energy neutrons are predicted at 0°. At 30° the prediction is excellent for ^{48}Ca, but somewhat too high for the other targets. Starting with 60°, however, and for all four targets, the predicted spectra are always too low, particularly at the higher neutron energies - just the opposite of the behaviour at 0°.

To check whether the neglect of evaporation neutrons could be responsible for the very substantial back-angle discrepancy, we performed calculations with the multiple-emission code of M. Blann, ALICE[10], using a Fermi-gas model with level-density parameter $a = A/8$[11]. Preequilibrium emission was assumed to precede evaporation.

The results of these calculations give the overwhelming answer that evaporation is not responsible for the discrepancy. The slope of an evaporation spectrum is much greater than observed here. A specific example - ^{90}Zr at 130° (where the data extend down to 12.5 MeV): Assuming isotropic emission, ALICE predicts 0.13 mb/sr-MeV, whereas the measured value is 0.85 mb/sr-MeV. This discrepancy is dwarfed by what occurs at higher energies. At 19.5 MeV the predicted evaporation is only 1 % of that observed. In fact, the slope (or exponent) of the evaporation spectrum is 4 times that observed. To reproduce the experimental slope would require a reduction in the level-density parameter by a factor of 16! Similar conclusions hold for the other targets. The least discrepancy occurs for ^{48}Ca where the evaporation prediction is 25 % of that observed at the lowest energy, 14 MeV, in the 130° spectrum. But the two spectra diverge with increasing energy. The slope of the evaporation spectrum is 2.6 times that of the experimental spectrum.

4. Conclusions

The intranuclear-cascade model has the same qualitative successes and failures in predicting neutron spectra that it had in predicting proton spectra[1]. In bulk, in the angle-integrated spectra of Fig. 1, the model accounts for the non-equilibrium neutrons. But in detail there are two errors. Reflecting the backward peaking of free p-n scattering, a high-energy quasi-free peak appears in the predicted 0° spectra of Figs. 2-5. At large angles there are many more neutrons observed, particularly at the higher energies, than predicted. These two errors occur for all four targets studied. As already noted[1], proper inclusion of reflection and refraction effects at the boundaries of the stepwise potential used might alleviate both defects.

References

1) H.W. Bertini, G.D. Harp, and F.E. Bertrand, Phys. Rev. C 10, 2472 (1974).

2) Hugo W. Bertini, Phys. Rev. 131, 1801 (1963).

3) R.R. Doering, D.M. Patterson, and Aaron Galonsky, Phys. Rev. C 12, 378 (1975).

4) M. Blann, R.R. Doering, Aaron Galonsky, D.M. Patterson, and F.E. Serr, Nucl. Phys. (1975).

5) J.D. Anderson and C. Wong, Phys. Rev. Letters 7, 250 (1961).

6) J. Rapaport, Nucl. Data B4, 351 (1970).

7) J.D. Carlson, Ph.D.thesis, University of Colorado, 1972 (unpublished).

8) G.M. Crawley, P.S. Miller, A. Galonsky, T. Amos, and R. Doering, Phys. Rev. C 6, 1890 (1972).

9) M. Blann, Ann. Rev. Nuc. Sci. 25, (1975).

10) M. Blann, University of Rochester, Report No. COO-3494-29 (unpublished).

11) D.W. Lang, Nucl. Phys. 26, 91 (1962).

Figure Captions

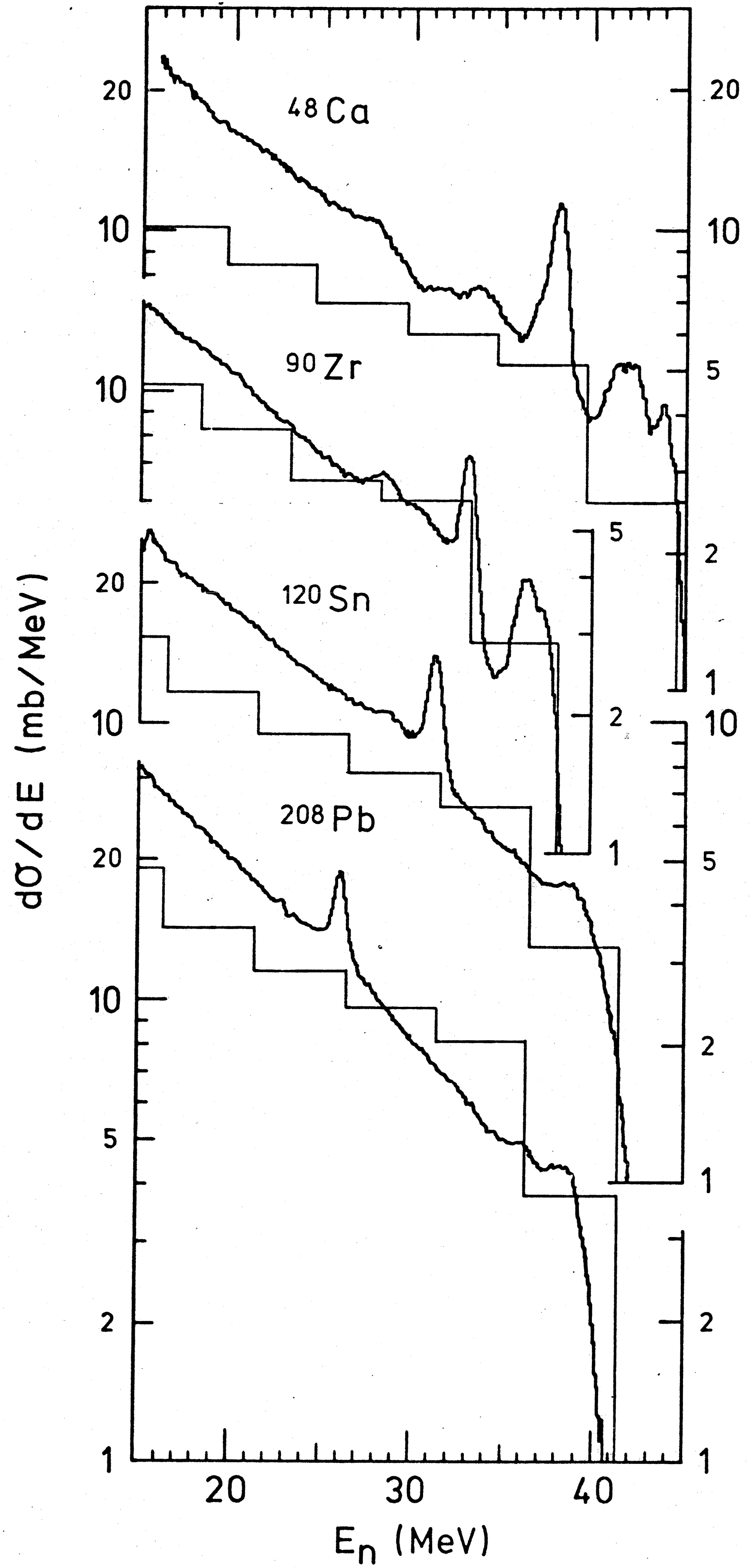
Fig. 1: Angle-integrated neutron spectra. The histograms with the 5-MeV bin widths are the predictions of the intranuclear-cascade model. The other curves are the data.

Fig. 2: Neutron spectra from ^{48}Ca at indicated angles. Theory and experiment are given as in Fig. 1. Downward arrows indicate no events in the Monte Carlo calculation.

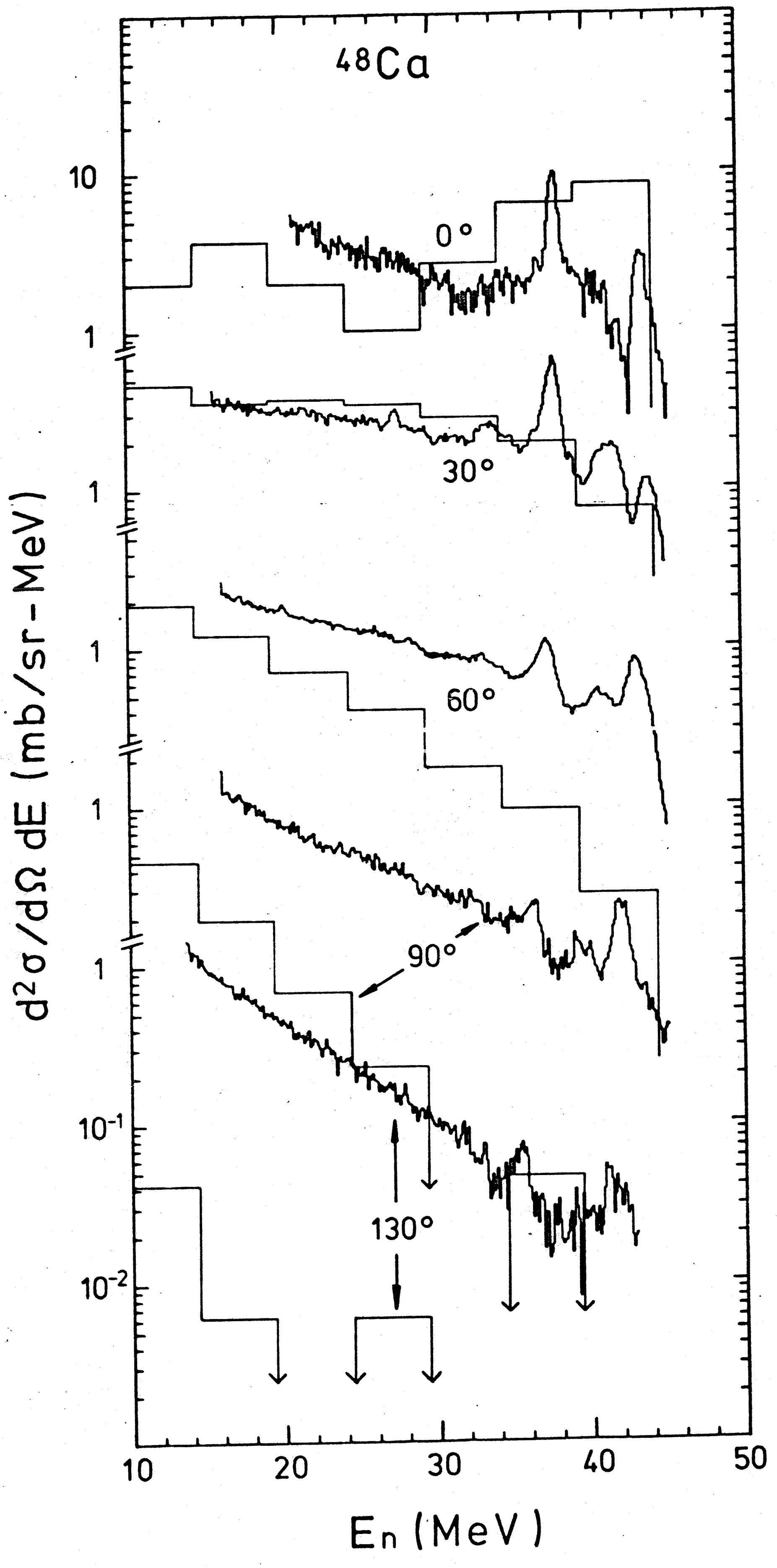
Fig. 3: Same as Fig. 2 but for ^{90}Zr. At 160° there are no predicted events above 10 MeV.

Fig. 4: Same as Fig. 2 but for ^{120}Sn. At 160° there are no predected events above 10 MeV.

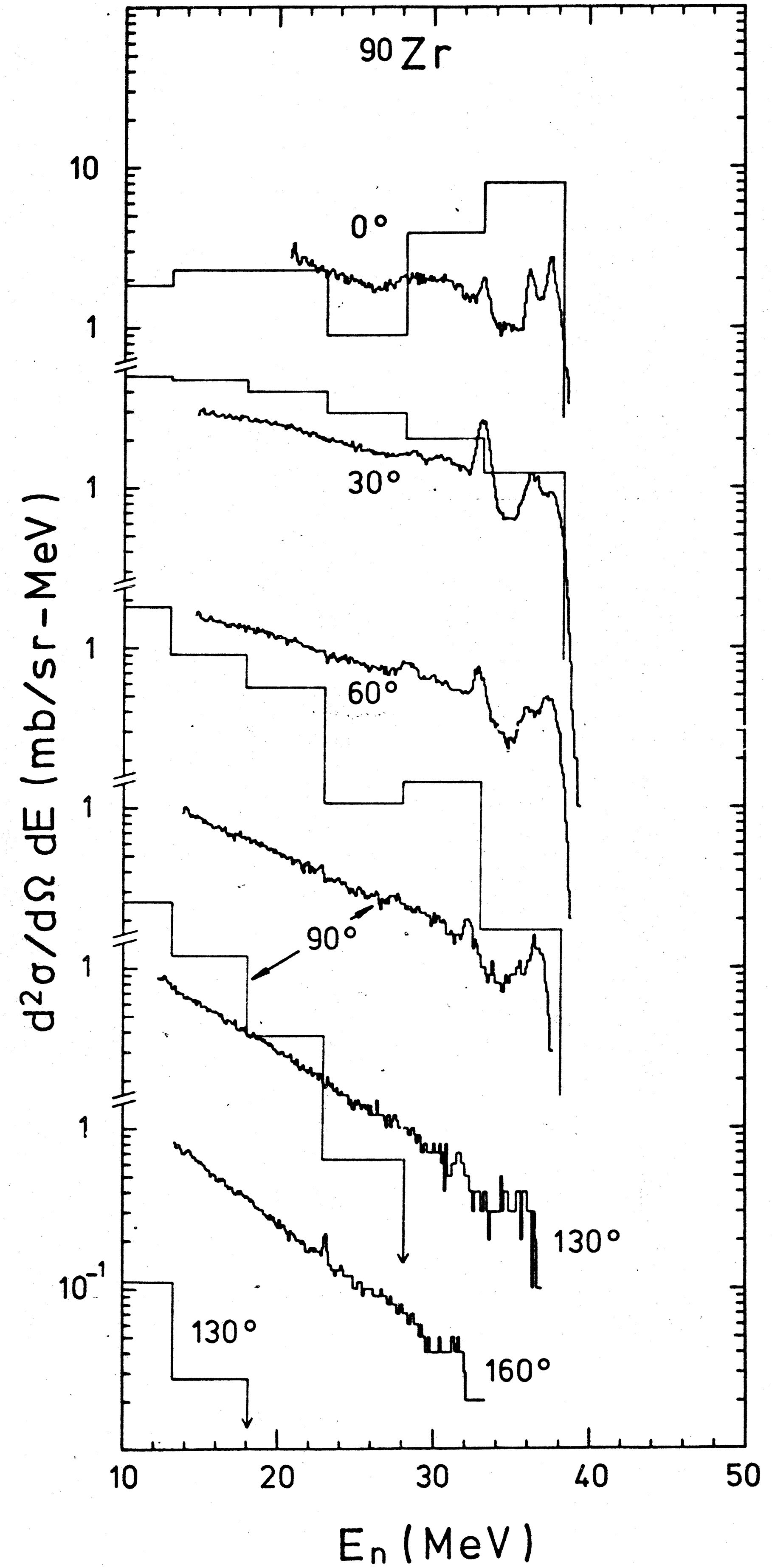
Fig. 5: Same as Fig. 2 but for ^{208}Pb.



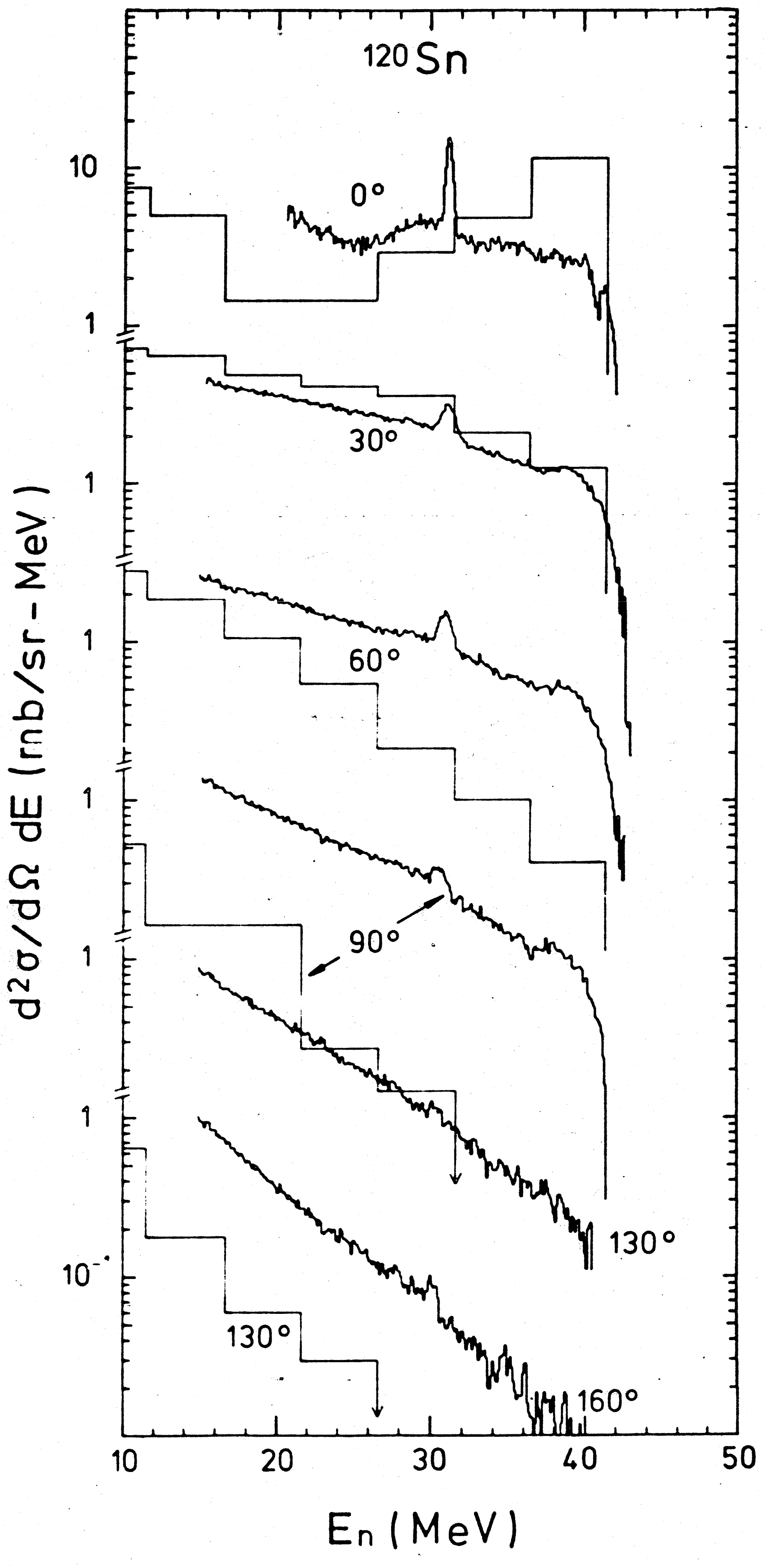
^{48}Ca
^{90}Zr
^{120}Sn
^{208}Pb
dσ/dE (mb/MeV)
E$_n$ (MeV)
20
30
40
1
2
5
10
20



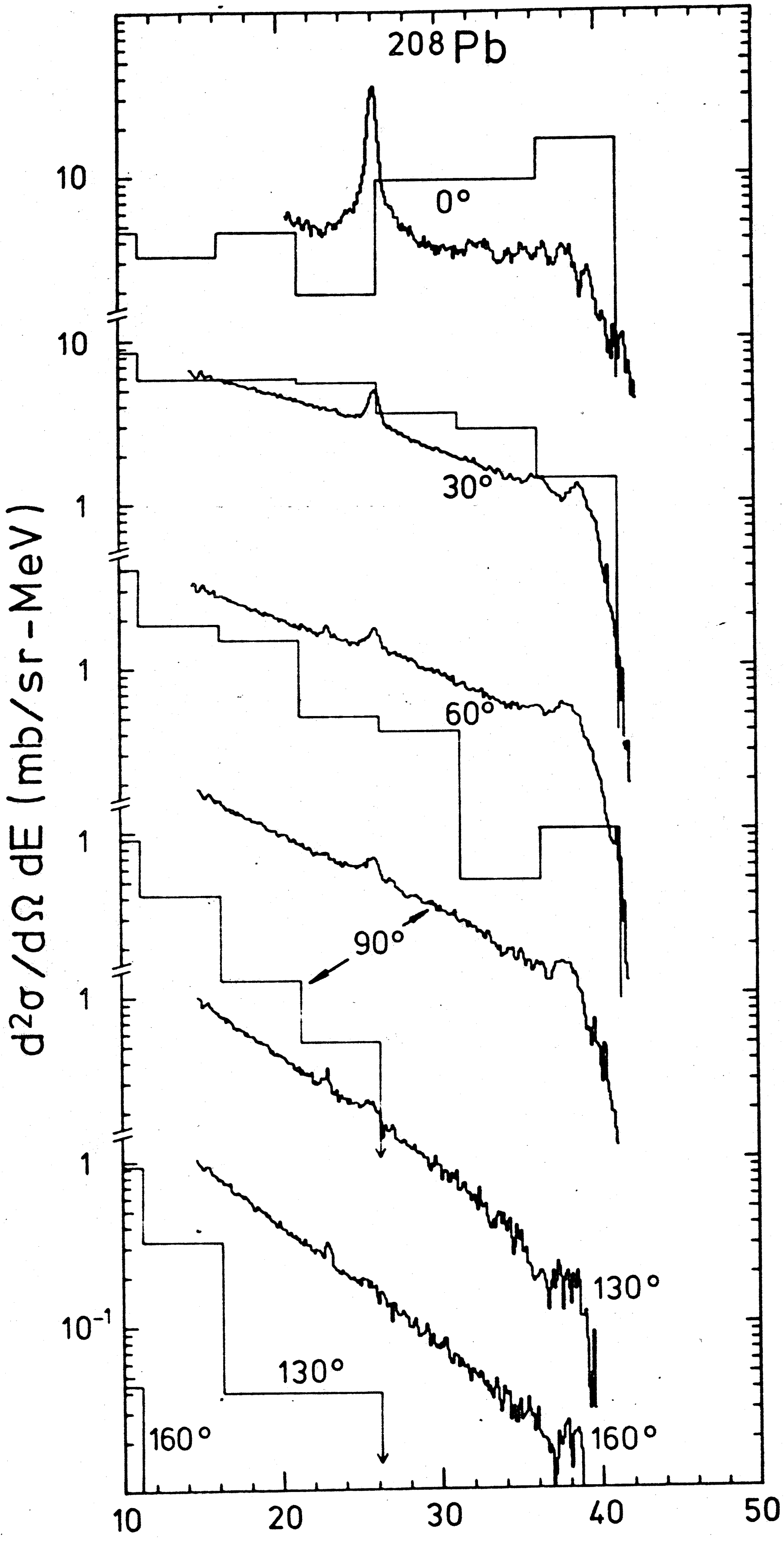
48Ca
0°
30°
60°
90°
130°
10
1
1
1
1
1
10-1
10-2
d2σ/dΩ dE (mb/sr-MeV)
10
20
30
40
50
En (MeV)



⁹⁰Zr
10
1
1
1
1
1
10⁻¹
0°
30°
60°
90°
130°
160°
130°
d²σ/dΩ dE (mb/sr-MeV)
10
20
30
40
50
En (MeV)



^{120}Sn
10
1
1
1
1
1
10^{-1}
0°
30°
60°
90°
130°
130°
160°
10
20
30
40
50
d²σ/dΩ dE (mb/sr - MeV)
En (MeV)



^{208}Pb
0°
30°
60°
90°
130°
130°
160°
160°
10
10
1
1
1
1
1
10^{-1}
10
20
30
40
50
E_n (MeV)
$d^2\sigma/d\Omega\, dE$ (mb/sr-MeV)