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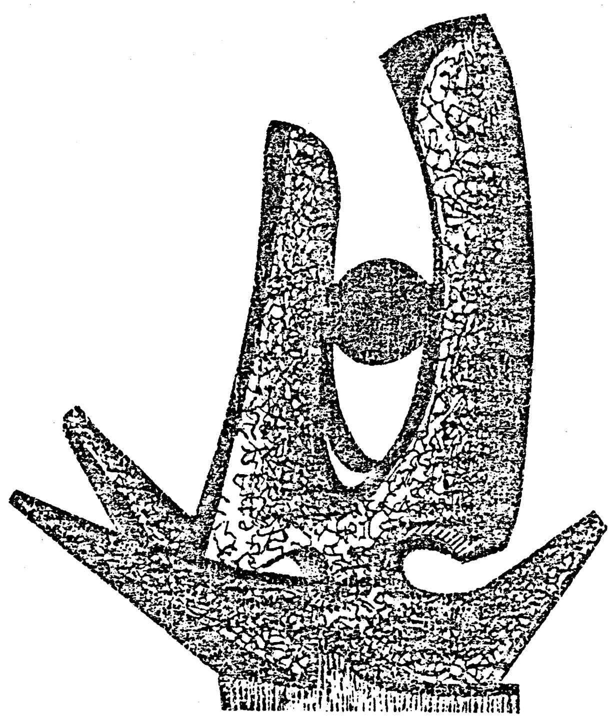

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Neutron Scattering from ^{208}Pb at 30.3 and 40.0 MeV and Isospin Dependence of the Nucleon-Nucleus Optical Model Potential

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ABSTRACT

Cross sections for elastic scattering of neutrons from ^{208}Pb have been measured at 30.3 and 40.0 MeV and analyzed to determine optical model potentials. Comparison of the potentials obtained for neutrons with existing proton potentials yields directly the isovector part of the nucleon-nucleus potential. The potential is energy dependent, is complex, has an imaginary part with both volume and surface components and is smaller than that deduced by other less direct methods. However, it does not reproduce the experimental $^{208}Pb(p,n)^{208}Bi$(IAS) cross sections. This apparent violation of the Lane potential is discussed in detail; it appears that there must be a substantial Coulomb correction for the imaginary potential at these energies, and/or that multistep processes are important for the (p,n) reaction.

At energies below about 100 MeV the interaction between a neutron and a proton is much stronger than that between two protons or two neutrons. Consequently, the average interaction of a proton with an $N>Z$ nucleus (more neutrons than protons) is stronger than that of a neutron. When one describes these interactions by an average potential, the optical model potential (OMP), this difference is reflected in an isovector part U_1 of the potential; a knowledge of U_1 is then fundamental to a description of all nuclear phenomena in which neutrons and protons participate differently (isovector modes). Most previous estimates[1-3] of U_1 involved a comparison of potentials from a range of nuclei with different values of the asymmetry parameter $\epsilon = (N-Z)/A$, or the analysis of (p,n) reactions leading to the isobaric analog state (IAS). Unfortunately both of these approaches are subject to serious uncertainties. In the comparison of different nuclei one must make assumptions about the variation of nuclear geometry with A and ϵ[1] while in the case of the (p,n) reactions there is the unresolved question of the importance of multi-step processes[4] not accounted for by the imaginary part of the OMP.

A more straightforward way of extracting U_1 is by comparison of proton and neutron potentials deduced from analysis of elastic scattering data from the same nucleus. The local OMP is written as a sum of the terms

$$U = -U_N + V_C + V_{s.o.} \qquad (1)$$

where V_C is the Coulomb potential, $V_{s.o.}$ is the spin-orbit term and U_N is the central potential, expressed following the Lane[5] model formalism as

$$U_N = U_0 - \frac{4}{A}(\vec{t}\cdot\vec{T})U_1 \qquad (2)$$

Here $\vec{t}$ and $\vec{T}$ are the isospin of the nucleon projectile and the target nucleus, and U_0 and U_1 are the complex isoscalar and isovector parts of the optical potential. For protons and neutrons we obtain

$$U_p = U_0 + \epsilon U_1$$
$$U_n = U_0 - \epsilon U_1 \qquad (3)$$

and it follows that

$$U_1 = (U_p - U_n)/2\epsilon \, . \qquad (4)$$

While neutron scattering data for ^{208}Pb are available at a number of energies up to 26 MeV[6], the available energy range does not overlap the most precise proton data and furthermore is too small to establish clearly the energy dependence of the potentials. The measurements at 30.3 and 40 MeV described here nearly double the available energy range and provide much the most precise and detailed data available for neutron scattering above 26 MeV from any N/Z nucleus. Analysis of these data provides probably the most reliable available estimate of the isovector part of the neutron and proton potentials. The extended energy range allows one for the first time to determine directly the energy dependence of the isovector potential and the detailed shape of its imaginary part. The potential obtained appears to be inconsistent with the Lane Model of the OMP, leading to the conclusion that some Coulomb related effects are omitted from the usual prescription for the imaginary isovector potential or that multistep processes not described by the Lane Model are important in the (p,n) reaction.

The measurements were performed using the MSU beam swinger time-of-flight system[7,8] as modified for neutron scattering. Neutrons produced by the $^7Li(p,n)^7Be$(g.s.+0.429 MeV) reaction are scattered from a 200 gram cylindrical target of isotopically enriched ^{208}Pb (98.69%)[9] and detected in a liquid scintillation counter with an overall energy resolution of about 1.1 MeV FWHM, sufficient to resolve the first excited state of ^{208}Pb at 2.6 MeV. Relative uncertainties are typically 2-4% but reach 8% at a few angles. Observation of the $^{7}Li(p,n)$ flux at 0° yields the absolute normalization independent of the least well known quantities and accurate to within ±3%. Corrections are made for dead time, source anisotropy and background attentuation due to the sample.

The OMP has the usual form[10] with

$$U_N = Vf(X_R) + i[Wf(X_I) - 4WDg(X_I)] \quad (5)$$

where $f(X_i)$ is a Woods-Saxon form factor, $g(X_i)$ is the derivative of a Woods-Saxon, $X_i = (r-r_i)/a_i$ and V, W and WD all have isoscalar and isovector parts as prescribed by the Lane formalism. The potentials are deduced from searches carried out with the code GIBELUMP as modified to fold the OM prediction with multiple scattering, attentuation and angle averaging effects prior to comparison with the experimental data[8,11]. This technique avoids the ambiguities involved with deconvolution of experimental data; only a straightforward convolution of the theoretical prediction is required. The center-of-mass cross-sections (Fig. 1) are deduced by deconvolution only after a satisfactory fit to the data is obtained[8] and the OM parameters have been fixed. The spin-orbit part of the potential was fixed at the values of Ref. 12 since no polarization data were available for use in the neutron potential determination. Some of the proton scattering data[11] were reanalyzed ignoring the polarization data and using the same fixed spin-orbit potential. The volume integrals did not change significantly. A check was also made for the effect of possible radius differences for the proton and neutron distributions in ^{208}Pb and only a negligible effect was found.

The resulting real, volume imaginary and surface imaginary potential strengths are shown in Fig. 2 along with the results at lower energies[6] and from the proton data.[10] All results are from analyses done with the "average" geometrical parameters of ref. 10. In the energy range considered a linear energy dependence describes the potentials reasonably well.

Before applying Eq. 4 to extract the real part of U_1 one must account for the fact that a proton slows down in the repulsive Coulomb field of the nucleus. Because the real (local) OMP is energy dependent the proton feels a stronger potential than a neutron of the same bombarding energy, even for $U_1=0$. We have corrected for this effect by shifting the proton bombarding energies so that the slowed proton and the neutron have the same average velocity. The energy shift is evaluated[13] by determining, in a computational experiment, the difference between neutron and proton energies which forces the diffraction maxima and minima to fall at the same (average) angles. This procedure should equalize the average wavelengths of the neutrons and protons in the regions dominating the scattering. We obtain a shift of -18.8 ± 0.5 MeV, corresponding, for the observed energy dependence of the real part of the proton potential, to a decrease in the magnitude of the real potential by 6.06 MeV or a Coulomb correction[13] of $0.44Z/A^{1/3}$. This value is in agreement with that determined by Rapaport et al.[14] given the observed differences is the dependence of V_p on energy.

Similar procedures are not expected to be valid for the imaginary potential. It is more reasonable[15] to adjust the bombarding energies so as to compare at equal level densities in the $^{208}Pb + p$ and $^{208}Pb+n$ systems; since both are odd-even systems and since the neutron and proton binding energies are nearly the same the densities will be about equal at equal bombarding energies. Hence no energy shift has been made for the imaginary potentials. However, there are known effects[16] which might cause differences in the imaginary part of the neutron and proton potentials, even for N=Z nuclei - the most obvious of these is the difference in the Q values for the (n,p) and (p,n) reactions. Since there are no calculations for ^{208}Pb and since the various effects tend to cancel at these energies in ^{40}Ca,[16] we have ignored them. But they need not cancel in ^{208}Pb and may render the imaginary part of U_1 more or less unreliable.

From Eq. 4 we obtain,

$$V_1 = (16.5 \pm 1.0) - (0.183 \pm 0.008)E \qquad E > 10 \text{ Mev}$$
$$W_1 = (-2.8 \pm 1.0) - (0.035 \pm 0.010)E \qquad E > 20 \text{ Mev} \qquad (6)$$
$$WD_1 = (13.1 \pm 0.8) - (0.035 \pm 0.010)E \qquad E > 20 \text{ MeV}$$

corresponding to volume integrals of

$$(J_1/A)\text{real} = 126. - 1.40\ E\ (\text{MeV fm}^3) \qquad E > 10 \text{ MeV}$$
$$(J_1/A)\text{imag} = 104. - 0.67\ E\ (\text{MeV fm}^3) \qquad E > 20 \text{ MeV}$$

All parts of U_1 are energy dependent and both the surface and volume part of the imaginary potential are important. While the present value of $(J_1/A)_{real}$ is smaller than that determined by other methods,[1,2,12] it is in good agreement with theoretical estimates[3]. The present results for V_1 are probably not very accurate below 10 MeV because the implied proton energy is so small that a simple shift such as that which we have used probably does not account reliably for the Coulomb effects; moreover, the real part of the proton data differs significantly from the linear extrapolation near zero energy.

In the Lane Model the cross sections for nucleon elastic scattering and charge exchange are related through the isovector potential. As a check on the present U_1 we calculated the cross sections for the ^{208}Pb(p,n)^{208}Bi(IAS) reaction in the DWBA, using a Lane consistent form factor prescription[17] for the coupling potential $U_{pn} = -2\sqrt{\frac{\varepsilon}{A}}\, U_1$. The result of this apriori

calculation (see Fig. 3) seriously underestimates both the magnitude and structure of the experimental cross section. In the context of the Lane Model, this must be attributed to an incorrect Coulomb correction; since the discussion above leads to the conclusion that this is most uncertain for the imaginary potential we have attempted to fit the data by adjusting the strength of the surface (WD_1) and volume (W_1) parts of the isovector potential. A calculation with a purely surface peaked potential (W_1=0, $\frac{J}{A}(WD_1)$)= 170 MeV fm^3 fits the general trend of the data but has too much structure (the apriori calculation was dominated by W_1). Also shown in Fig. 3 is a calculation in which W_1 and WD_1 are adjusted to fit the data. The volume integral of this fitted potential is ≈ 160 MeV fm^3 ($\frac{J}{A}(W_1)$=95; $\frac{J}{A}(WD_1)$ = 65) twice as large as for the apriori Hoffmann[17] prescription. This corresponds to a substantial Coulomb correction concentrated mainly in the surface region. A possible alternative explanation is that two step processes may be important in the (p,n) channel and are not adequately described by the imaginary OMP for the elastic scattering channels.

There is an apparent contradiction of our result with the analysis of Patterson, Doering and Galonsky (PDG)[2] which reproduces the ^{208}Pb(p,n) cross section as well as the elastic data. However, this is achieved by using an unrealistically small[3,14] real Coulomb correction of 0.27 $Z/A^{1/3}$ as compared to the usual value of 0.4 $Z/A^{1/3}$ and to our value of 0.44 $Z/A^{1/3}$. For ^{208}Pb this results in an increase of 2.35 MeV in the real part of the isovector potential, sufficient to reproduce the (p,n) cross section. However, one expects that the PDG[2] procedure would lead to a poor description of the N=Z data because the Coulomb correction is underestimated; this is found to be the case for ^{40}Ca.

In summary, we have measured cross sections for elastic scattering of neutrons from ^{208}Pb at 30.3 and 40 MeV and have extracted the real and

and imaginary isovector parts of the optical model potential by comparing the neutron potentials we obtain with those describing proton scattering. The isovector potential obtained is energy dependent, is complex, its imaginary part contains both volume and surface terms and it is substantially smaller than potentials obtained by less direct methods. In the Lane Model this isovector potential underestimates the $^{208}Pb(p,n)^{208}Bi(IAS)$ cross section, indicating that a substantial imaginary Coulomb correction is needed for ^{208}Pb in this energy region and/or that a Lane Model description is inadequate, possibly due to contributions of multistep processes.

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FIGURE CAPTIONS

Figure 1. Differential cross sections for elastic scattering of 30.3 and 40.0 MeV neutrons. Relative uncertainties are shown where they are greater than the size of the points; in addition there is a ± 3% normalization uncertainty.

Figure 2. Values of the real, imaginary volume and imaginary surface potentials for nucleon scattering. The proton data are from ref. 10, the low energy neutron data are from ref. 6 and the filled circles are the present neutron data. The solid lines are equally weighted linear least squares fits and the dashed line is the proton potential shifted to lower energy by 18.8 MeV. (see text).

Figure 3. Cross sections for the ^{208}Pb(p,n)^{208}Bi reaction at 45 MeV (ref. 18). The curves are the results of DWBA calculations, all with the same real isovector potential. The dashed (---) curve is an apriori calculation based on the potentials of Fig. 2 and the Hoffmann prescription;[17] The dot-dash (-·-·-) curve is for a surface peaked imaginary isovector potential (W_1=0); the solid (——) curve contains both surface and volume imaginary potentials chosen to fit the data.

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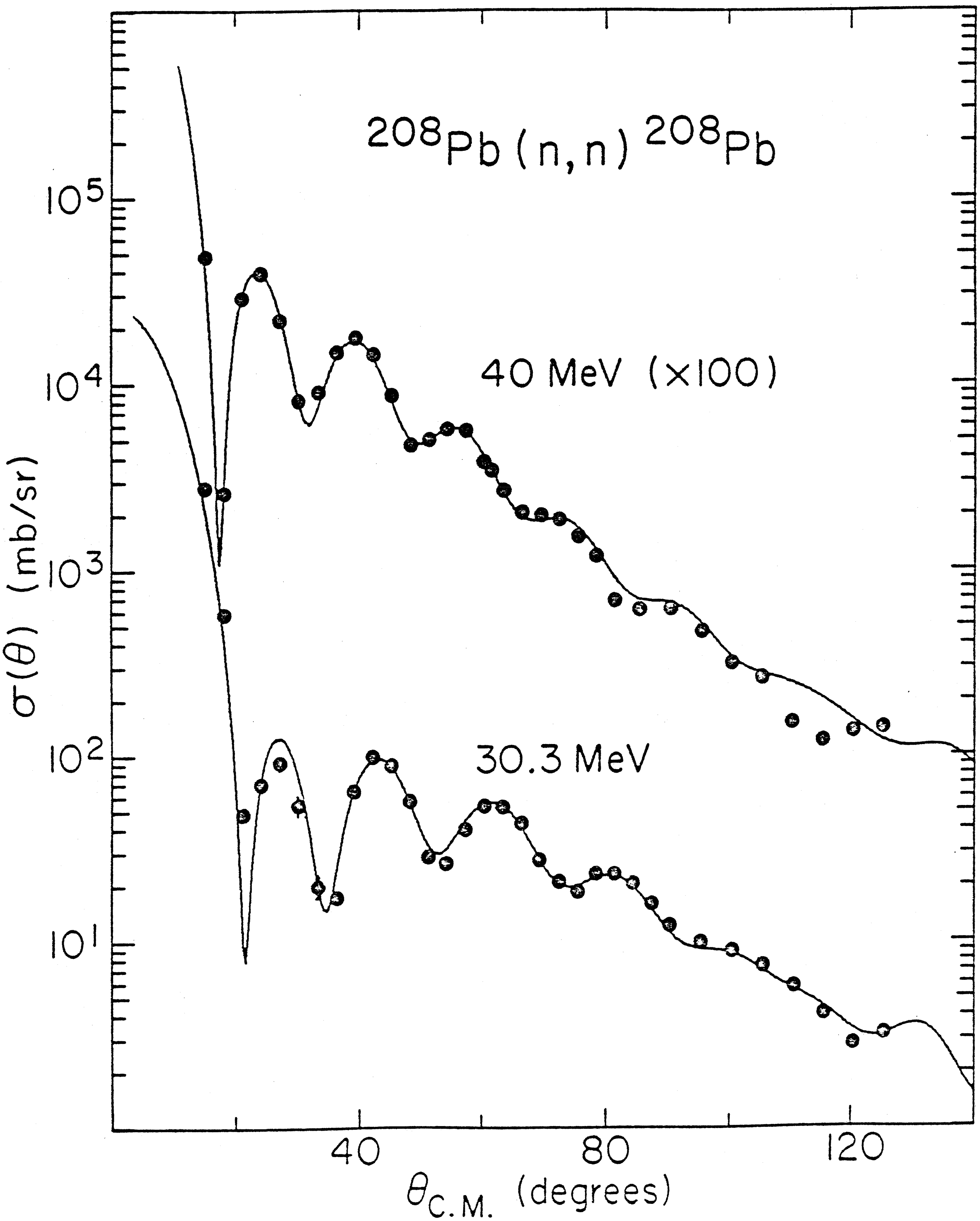

$^{208}Pb(n,n)^{208}Pb$
40 MeV (×100)
30.3 MeV
10^5
10^4
10^3
10^2
10^1
$\sigma(\theta)$ (mb/sr)
40
80
120
$\theta_{C.M.}$ (degrees)

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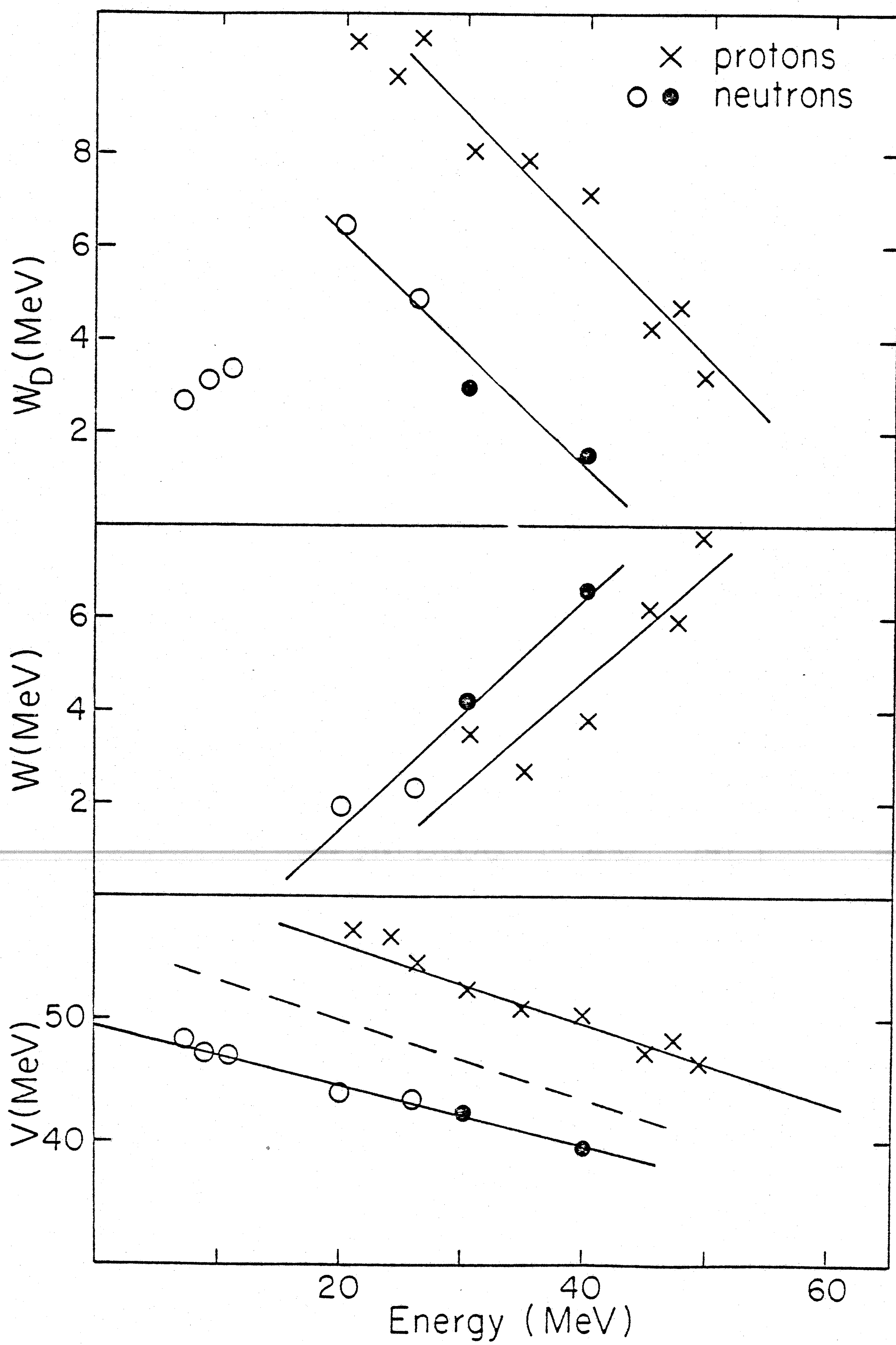
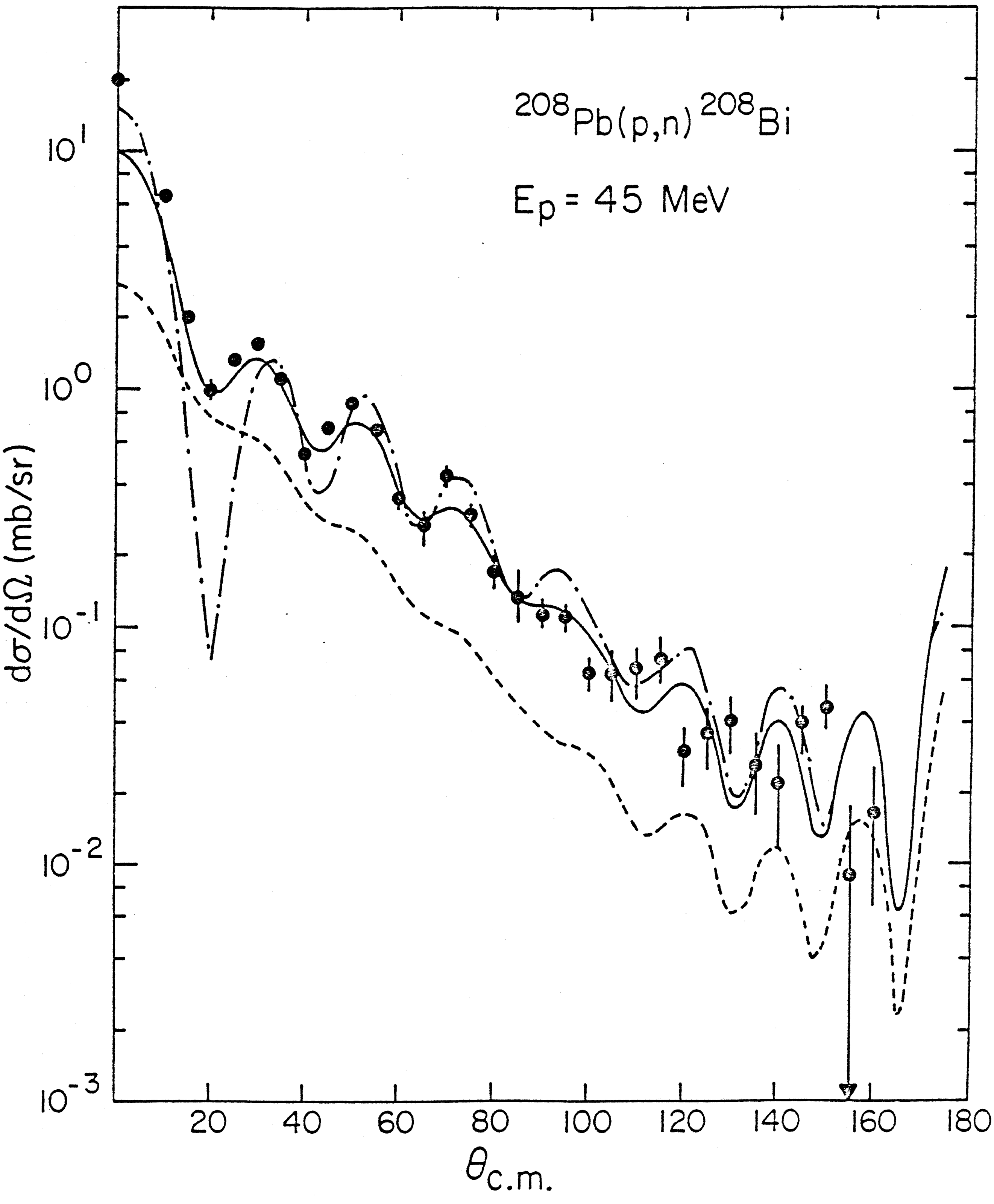


× protons
○ ● neutrons
W_D(MeV)
8
6
4
2
W(MeV)
6
4
2
V(MeV)
50
40
20
40
60
Energy (MeV)



$^{208}Pb(p,n)^{208}Bi$
$E_p = 45$ MeV
$d\sigma/d\Omega$ (mb/sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
40
60
80
100
120
140
160
180
$\theta_{c.m.}$