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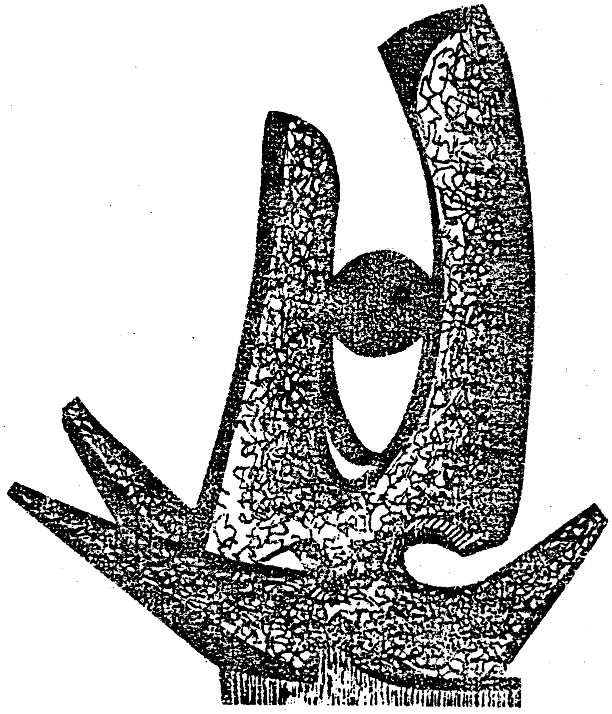

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Limit on Charge Symmetry Breaking in the Optical Model and the Coulomb Energy Anomaly

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ABSTRACT

Cross sections for elastic scattering of neutrons from ^{40}Ca have been measured at 30.3 and 40.0 MeV and analyzed to obtain optical model potentials. The optical potentials for neutron and proton scattering are found to be very similar after a correction for Coulomb effects, indicating that a static charge symmetry breaking Hartree potential is too small to explain the Coulomb energy anomaly for bound states.

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21.10.Dr; 25.40Cm

At first glance it seems that it should be simple to calculate the difference in the masses of two mirror nuclei such as ^{3}H and ^{3}He or ^{41}Ca and ^{41}Sc. That simple approaches fail, by more than 500 keV in the case of the ^{41}Ca-^{41}Sc pair, was first pointed out by Nolen and Schiffer1) and this difference became known as the Coulomb-energy or Nolen-Schiffer anomaly. In spite of an intense theoretical effort since this discovery2), and the calculation of many small (and mostly cancelling) corrections, the problem remains. In a survey of the situation, Negele3) concluded that the only apparent solution was to introduce a small charge symmetry breaking (CSB) potential in the nucleon-nucleon interaction, such that the strong interaction between two neutrons (V^{nn}) is more attractive than that between two protons (V^{pp}). As a result, the extra neutron in ^{41}Ca is bound more tightly than the proton in ^{41}Sc, reducing the discrepancy. In a schematic Hartree model, Negele showed that a difference of about 20 MeV-fm^{3} in the volume integrals of V^{pp} and V^{nn} is sufficient to remove the anomaly. A difference of this size is not predicted by the usual theoretical models2,4) but is consistent with experimental determinations of the scattering lengths and effective ranges for the nn and pp systems4).

Of course, a charge symmetry breaking potential such as that proposed by Negele3) will affect not only the potential felt by bound nucleons, but also the optical model potential describing nucleon scattering. In this letter we describe a measurement of elastic scattering from ^{40}Ca at 30.3 and 40.0 MeV. With these results, neutron scattering data are available over a sufficiently large energy range to permit a rather precise comparison with the available proton scattering data. We have obtained optical model potentials for the neutron data and have compared the real parts of these potentials with those for protons. After a correction for Coulomb effects, the neutron and proton potentials are nearly the same, apparently ruling out a CSB Hartree potential of the sort originally discussed by Negele3).

The experiments were performed using the Michigan State University beam swinger time-of-flight system, as adapted for neutron scattering5). Neutrons produced by the ^{7}Li(p,n)^{7}Be reaction were scattered from encapsulated cylindrical targets of natural metallic calcium6) and were detected with an overall resolution of 0.75 to 1.4 MeV by a liquid scintillation detector placed 5-9 meters from the scatterer. Backgrounds from the thin aluminum container and from air scattering were measured at every angle. The absolute normalization (accurate to ±3%) was determined by a direct measurement of the source neutron flux at 0^o. The results are shown in Fig. 1. Data of similar quality

have been obtained for ^{32}S, ^{28}Si and ^{12}C and will be reported elsewhere.

Since we wish to compare our results with those from proton scattering, we describe here only the results from optical model searches made with the average geometrical parameters obtained in an earlier analysis of proton data7). The searches were carried out with the code GIBELUMP, as modified to fold the prediction with multiple scattering, attenuation and angle averaging effects prior to comparison with the experimental data8). Only after the final fits had been obtained were the results used to deconvolute the data to obtain the cross sections shown in Fig. 1. The resulting optical potentials are shown in Table I and Fig. 2. Also shown in Fig. 2 are potentials describing lower energy neutron scattering taken from Rapaport et al.10) and proton potentials from the analyses of van Oers7). The same geometrical parameters7) were used for all these analyses.

Before comparisons of the neutron and proton potentials can be made, it is necessary to correct the proton scattering results for a trivial effect of the Coulomb force. Namely, that the protons are slowed down an amount ΔE_c by the Coulomb repulsion, and because the (local) optical potential is energy dependent as is shown in Fig. 2, they feel a stronger nuclear attraction than neutrons of the same bombarding energy[11]. The necessary correction is made most simply by comparing neutron data taken at a bombarding energy E_n with proton data at $E_p = E_n + \Delta E_c$. We evaluate ΔE_c 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 angles. This should equalize the average wavelengths of neutrons and protons in the regions dominating the scattering. We obtain $\Delta E_c = 7.0 \pm 0.6$ MeV; as expected this is somewhat less than the average Coulomb energy (7.7 MeV) of a proton in the electric field of ^{40}Ca.

We proceeded by least squares fitting the proton potentials of Fig. 2 (equally weighted) to a straight line. The greatest uncertainty in this procedure arises from the anomaly in the proton potentials for energies between 17 and 25 MeV. This anomaly may reflect the opening of the neutron channel above the (p,n) threshold at 15.5 MeV; it is consistent with this observation that there is no equivalent anomaly in neutron scattering where the (n,p) threshold is 0.3 MeV. In any case one might expect compound nucleus scattering to be important near threshold. We therefore limited the fitted region for protons to $E_p > 25$ MeV. For comparison <u>all</u> the neutron data were fitted to a line with the slope obtained for the protons. The results in terms of volume integrals are

$$\begin{aligned} -J_p/A &= (501 - 3.0\ E_p)\ \text{MeV-fm}^3 \\ -J'_p/A &= (480 - 3.0\ E_n)\ \text{MeV-fm}^3 \qquad (1) \\ -J_n/A &= (473 - 3.0\ E_n)\ \text{MeV-fm}^3 \quad . \end{aligned}$$

Here J'_p is the volume integral after the shift (7.0 MeV) described above; this correction for Coulomb effects accounts for most of the observed difference between proton and neutron scattering.

To relate these results to the CSB potential of Negele[3] we use a simple folding model. Denoting the volume integrals of the two body pp, pn and nn interactions by J^{pp}, J^{pn} and J^{nn} we have for a nucleus with Z protons and N neutrons

$$\begin{aligned} J'_p &= ZJ^{pp} + NJ^{pn} \\ J_n &= ZJ^{pn} + NJ^{nn} \end{aligned} \qquad (2)$$

where we have assumed that the proton energies have been shifted as described above. Defining the CSB interaction as $J^{CSB} = J^{nn} - J^{pp}$, and noting that N=Z, we obtain[12]

$$J^{CSB} = \frac{2(J_n - J'_p)}{A} \quad . \qquad (3)$$

For the volume integrals of Eq. 1, we obtain from Eq. 3

$$J^{CSB} = 14 \pm 10\ \text{MeV-fm}^3 \qquad (4)$$

where the uncertainty has been evaluated from the scatter about the fitted lines in Figs. 2 and 3 and the uncertainty in ΔE_c. The use of optical potentials from other (less extensive analyses of the proton and neutron data yields consistent results. The present result is roughly consistent with $J^{CSB}=0$, but the data somewhat favor $J^{CSB}>0$, or V^{nn} <u>less</u> attractive than V^{pp}, and J^{CSB} is three standard deviations from the value of -19.4 MeV-fm^3 proposed by Negele[3)].

While the present analysis reflects rather directly the central issue for the Coulomb energy problem: the difference in the single particle potential seen by protons and neutrons, several simplifying assumptions have been made. However, test calculations at 40 MeV showed that taking into account the differences, due to core polarization, in the rms radii of protons and neutrons[13)] did not significantly affect the extracted volume integrals. Furthermore, a correction for effects following from core polarization, would presumably make J^{CSB} still more positive since $|V^{pn}| > |V^{pp}|$, protons are concentrated on the surface and absorptive processes reduce the contribution of the nuclear interior.

The present result then appears inconsistent with a CSB two nucleon interaction being the source of the Coulomb energy anomaly, at least for the static Hartree CSB potential used in the original estimates[3)]. If the CSB potential is more complex, for example, if it has an important spin dependent part, then such conclusions are not immediate. But, in any case, the requirement that both scattering and bound state data be fitted simultaneously will severely constrain any theory of CSB interactions[4,14)].

In summary, we have measured cross sections for neutron elastic scattering from ^{40}Ca at 30.3 and 40.0 MeV, permitting

a precise comparison with proton scattering from the same nucleus over a wide energy range. The real parts of the optical model potentials obtained for neutron and proton scattering are very similar after correction for Coulomb effects, apparently ruling out the explanation of the Coulomb energy anomaly in terms of a simple (static Hartree) charge symmetry breaking interaction; unless the CSB interaction is more complex, it seems that the Coulomb energy anomaly must arise from nuclear structure effects or other less exotic properties of the two body interaction[15)].

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11. We implicitly assume that the Coulomb part of the optical potential is local. It is not known what change in V_R is caused by this assumption (universal in optical model phenomenology) but an estimate based on the size of the exchange matrix element for the ground state of mass-41 (Refs. 1,3) indicates that it is less than +0.3 MeV and hence negligible in the present context.
12. The Coulomb force pushes the protons slightly outward with respect to the neutrons, so that the neutron and proton densities are no longer precisely equal as we have implicitly assumed. Because of these core polarization effects, eq. 3 follows exactly only if the interactions involved are of short range and independent of density.
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FIGURE CAPTIONS

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

Fig. 2. Values of the real potential for nucleon scattering ((●) present results; (o), Ref. 10; (×) Ref. 7). The geometry is that of Table I. The lines are least squares fits assuming the same slope for neutrons as obtained for protons; see the text for details.

Fig. 3. Differences of the volume integrals per nucleon for proton and neutron scattering. The points are the differences between the fitted line for protons (Fig. 2) and the measured values for neutrons; the dashed line is the average of these differences; the shaded area is the average with its associated uncertainty after correcting for Coulomb effects; and the dot-dash line, the value of the difference implied by the CSB interaction of Ref. 3.

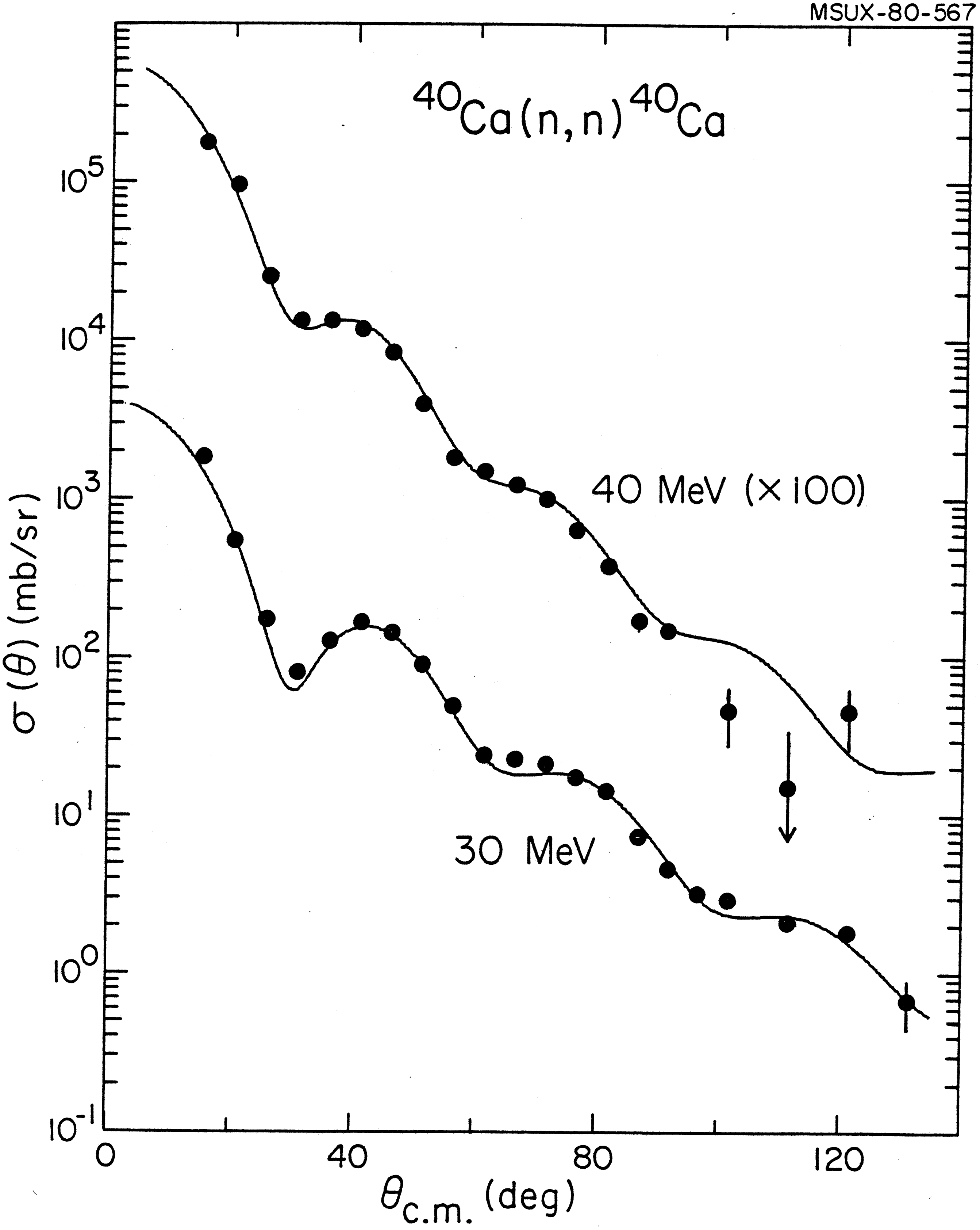
Table I. Optical model parameters for elastic neutron scattering[a].

	V_R (MeV)	W_V (MeV)	W_{SF} (MeV)	χ^2/N	J_n/A[b] (MeV-fm^3)
30.3 MeV	47.32	0.142	7.749	3.6	395.3
40.0 MeV	40.73	3.731	3.738	5.4	340.3

(a) Notation is that of Ref. 9. For all searches the geometrical parameters were kept constant at r_R=1.152, a_R=0.692, r_I=1.309, a_I=0.549, r_{SO}=1.01 and a_{SO}=0.75, all in fm. In addition V_{SO}=6.2 MeV. See Ref. 7.

(b) $J_n/A = (\int V_R(r)\,dV)/A$.

Fig. 1


MSUX-80-567
^{40}Ca(n,n)^{40}Ca
40 MeV (×100)
30 MeV
σ (θ) (mb/sr)
$\theta_{c.m.}$ (deg)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0
40
80
120

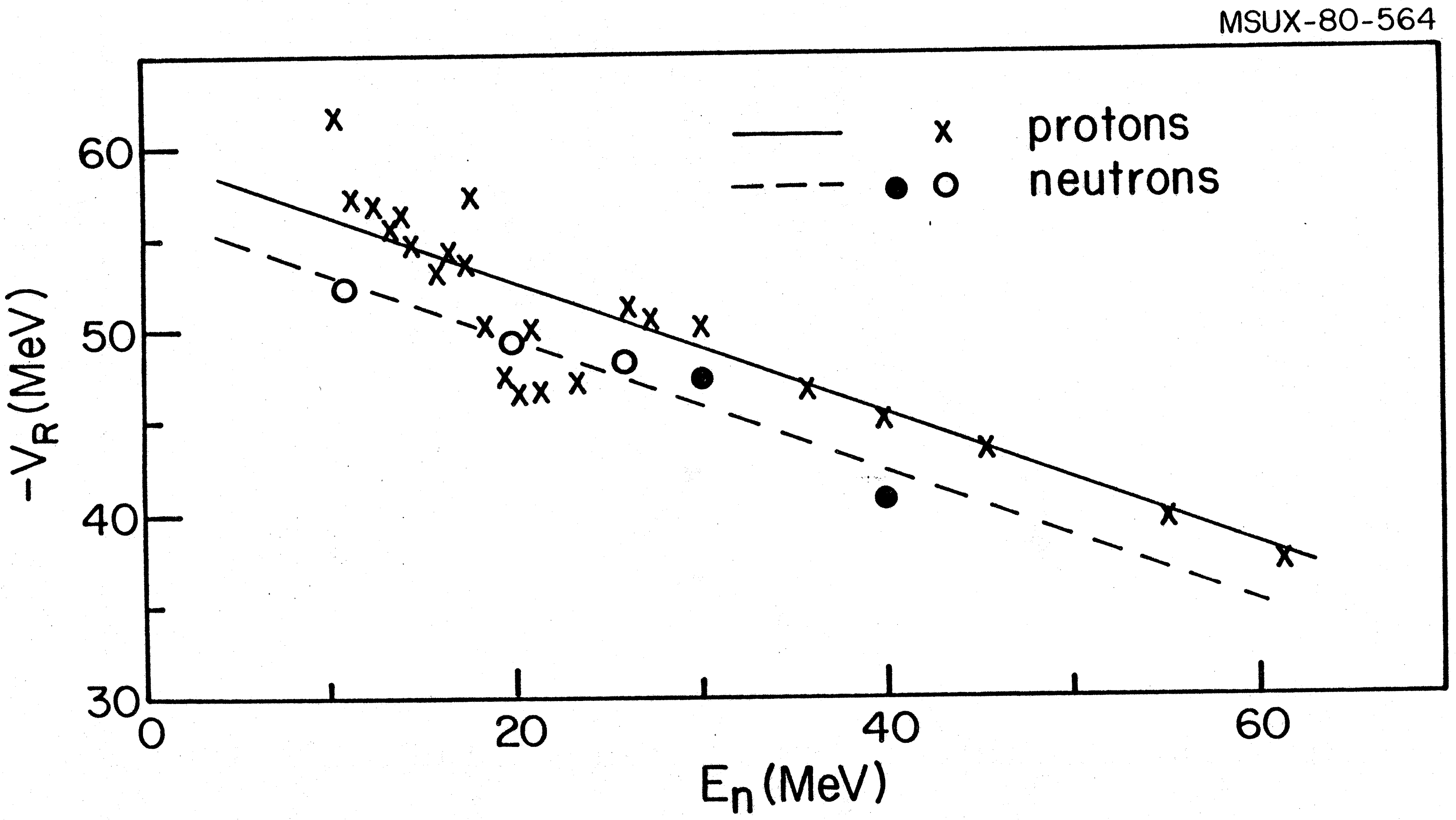
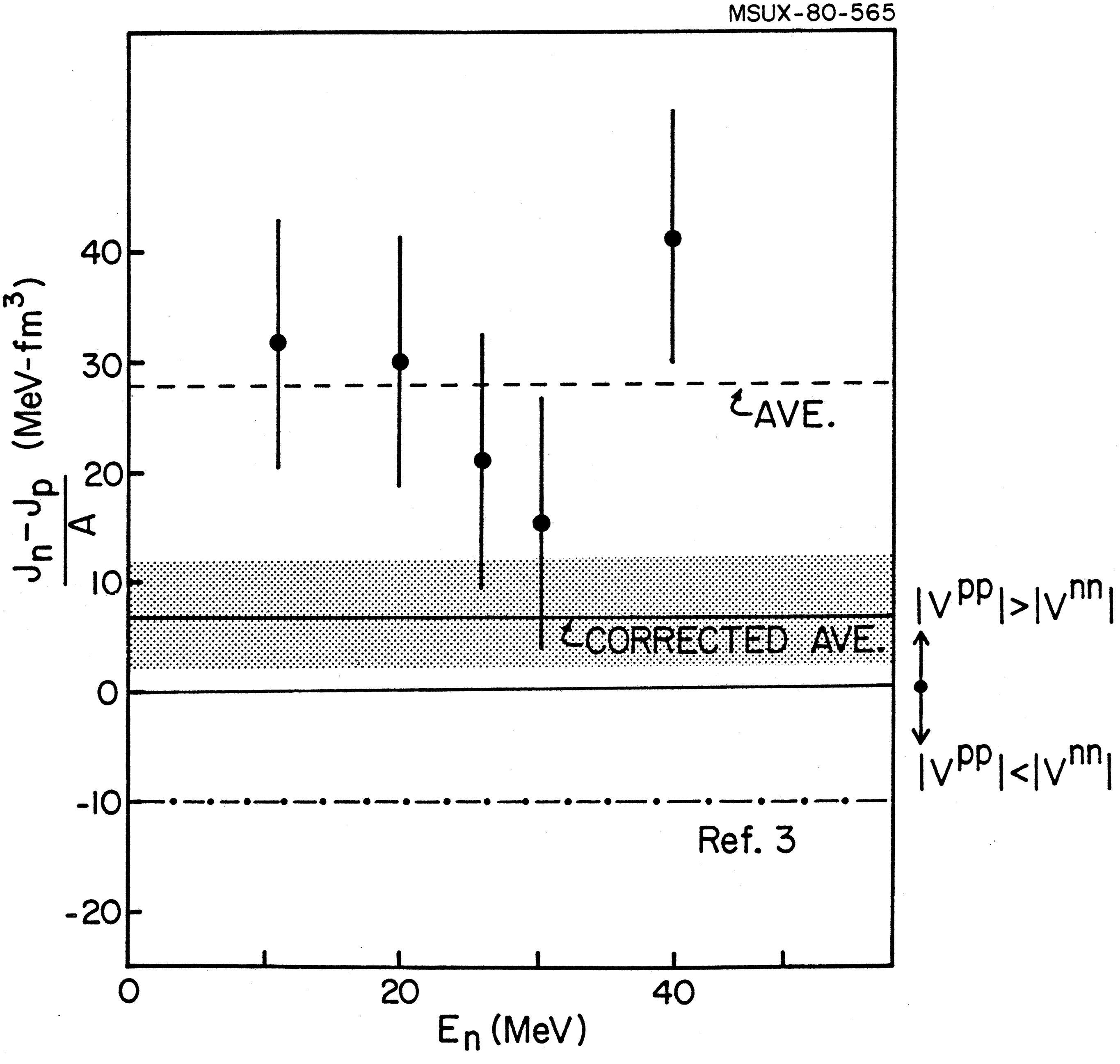


Fig. 2

Fig. 3


MSUX-80-565
$\frac{J_n - J_p}{A}$ (MeV-fm^3)
40
30
20
10
0
-10
-20
AVE.
CORRECTED AVE.
Ref. 3
$|V^{pp}| > |V^{nn}|$
$|V^{pp}| < |V^{nn}|$
0
20
40
E_n (MeV)