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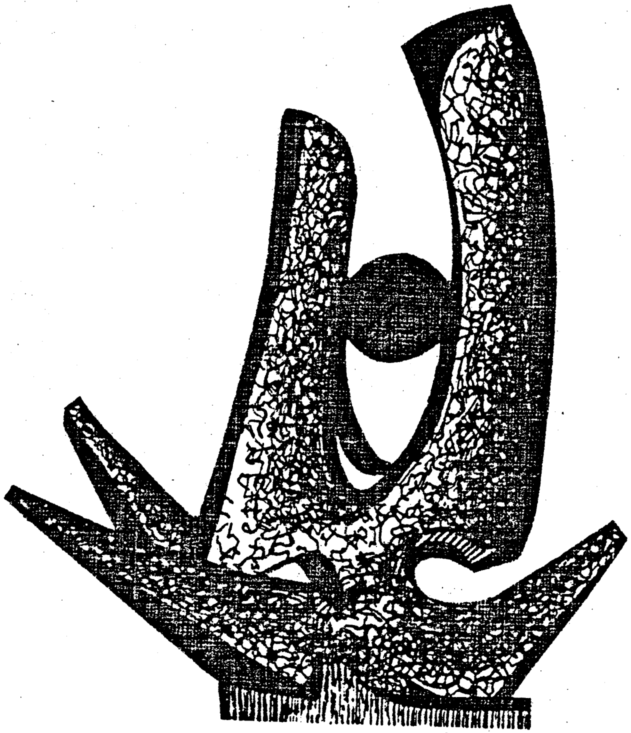

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Imaginary part of the Coulomb correction in nucleon scattering from ^{28}Si*

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Abstract

Cross sections for elastic scattering of neutrons from ^{28}Si have been measured at 30.3 and 40.0 MeV. Phenomenological values of the Coulomb correction term in the nucleon-nucleus optical-model potential are obtained from a comparison of proton and neutron elastic scattering data for ^{28}Si between 14 and 40 MeV. For energies less than about 28 MeV the result is similar to that obtained from an analysis of ^{40}Ca data. For higher energies the imaginary Coulomb correction is substantially larger for ^{28}Si than for ^{40}Ca.

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NUCLEAR REACTIONS ^{28}Si(p,p), (n,n), E=14-40 MeV; deduced optical-model parameters.

Recently ΔW_c, the Coulomb correction term for the absorptive part of the nucleon optical-model potential (OMP), has been determined[1,2] by comparing phenomenological analyses of elastic scattering of neutrons and protons. The Coulomb correction term[3] is generally introduced when scattering of protons and neutrons from the same nucleus are compared, as in the Lane model[3]; it accounts for those differences between the optical potentials for neutrons and protons that are ascribable to purely Coulomb effects. Such differences arise, for example, when the Coulomb field slows down an approaching proton, and the local OMP is energy dependent, or when reactions induced by protons and neutrons have different Q-values. For self-conjugate nuclei the Coulomb correction term is simply the difference betwen proton and neutron potentials for projectiles of the same energies.

Generally, only the real part of the Coulomb correction has been considered, even though an imaginary part was predicted theoretically[2,4,5]. The analyses in Refs. 1 and 2 provided the first phenomenological evidence for this term; both analyses were based on ^{40}Ca data and yielded consistent results. Moreover, in Ref. 1, the energy dependence of ΔW_c has been determined and it has been found to be in agreement with the theoretical prediction of Ref. 4. In this communication further evidence for this term and for its energy dependence are presented, based on an analysis of ^{28}Si data. This is the only self-conjugate nucleus, other than ^{40}Ca, for which both proton and neutron elastic scattering data are available in a large energy range (up to 40 MeV). Additional evidence for ΔW_c in a deformed nucleus is necessary also because these nuclei are influenced less than spherical nuclei by coupled <u>reaction</u> channel effects that can distort[6] the energy behavior of the extracted OMP parameters just at the energies of interest.

It is necessary to consider also possible effects of coupled inelastic channels since the first excited state of ^{28}Si is so strongly populated. We expect that any effects would be approximately the same for proton and neutron scattering at the same energy and thus cancel in the difference; this assumption is made in the remainder of the paper. It was checked by the following computational test. A coupled-channels code was used to generate cross sections for proton and neutron scattering at 30.3 and 40.0 MeV. Coupling to the first excited state was included with a deformation of $\beta = 0.4$. These cross-sections were then fitted over the region of the present experimental data using the spherical OMP. The differences in the imaginary Coulomb correction resulting from the exclusion of channel coupling were thus found to be smaller than the uncertainties shown in Figure 3.

Elastic neutron scattering cross sections were measured using the Michigan State University beam swinger time-of-flight system[7,8]. Neutrons produced by the reaction $^{7}Li(p,n)^{7}Be$ were scattered from cylindrical targets of natural silicon and were detected with an overall resolution of 0.63 to 0.86 MeV by a liquid-scintillation detector placed 7-9 m from the scatterer. The absolute normalization (accurate to ± 3 %) was determined by a direct measurement of the source neutron flux at 0°. Details of the experimental set-up and analysis procedure are reported elsewhere[8]. The results are shown in Figure 1.

In the upper part of Fig. 2 the volume integral per nucleon of the real potential is plotted versus energy. These values have been deduced from the neutron and proton data of Refs. 9-11 and from the present results (see Table 1). The neutron data were analyzed with a standard OMP search on the real and imaginary well depths with the other OMP parameters kept fixed at the following values taken from Ref. 10: r_0=1.17 fm, a_0=0.673 fm, r_w=1.33 fm, a_w=0.575 fm, V_{so}=6.0 fm, r_{so}=1.07 fm, a_{so}=0.78 fm. The real volume integrals obtained are consistant with a linear dependence on energy over most of the range explored; the fits to the proton and neutron data (full and dashed lines, respectively) are separated by an (assumed) energy independent quantity which, in terms of the real potential depth, is $\Delta V_c=(0.37\pm0.09\ Z/A^{1/3})f(r)$ (MeV); f(r) is the Woods-Saxon radial form factor of the OMP. This value of the real Coulomb correction is consistent within errors but slightly smaller than similar determinations of this quantity in other nuclei[7,9].

In the lower part of Fig. 2 are shown the volume integrals per nucleon of the imaginary potential obtained in the same analysis. The errors have been determined as the difference between our volume integrals and literature values obtained with different OMP geometries. Compound nucleus contributions have been ignored because it was found[10] that at 14 MeV they are already less than 10 percent, even for the smallest differential cross sections. However, since compound nucleus contributions increase exponentially with decreasing energy (a factor of 10 every 5 MeV) we have not included the available neutron data at 11 MeV (Ref. 9).

The differences between proton and neutron imaginary volume integrals for ^{28}Si are shown as filled circles in Fig. 3 while the corresponding values from the ^{40}Ca analysis of Rapaport[1] are plotted as open squares. The results from these two nuclei are very similar for projectile energies up to about 28 MeV. The drop in $-J_{\Delta Wc}/A$ for both ^{28}Si and ^{40}Ca around incident an energy of 20 MeV may reflect the opening of the (p,n) channel (both nuclei have a (p,n) Q-value of -15.1 MeV). Above 28 MeV the similarity between the ^{28}Si and ^{40}Ca results ends: the ^{40}Ca values fall rapidly to zero while the ^{28}Si values remain large. An equally weighted linear least squares fit to the ^{28}Si data yields:

$$J_{\Delta Wc}/A=-\{(51\pm8)-(0.66\pm0.17)\cdot E\} \quad (\mathrm{MeV\ fm}^3)$$

which intersects the energy axis at about 77 MeV. Rapaport's fit to the ^{40}Ca data yields:

$$J_{\Delta Wc}/A=-\{(43\pm7)-(1.2\pm0.2)\cdot E\} \quad (\mathrm{MeV\ fm}^3)$$

which is zero for E=36 MeV. These fits are shown as solid and dashed lines, respectively, in Fig.3. The data for both ^{28}Si and ^{40}Ca scatter widely about these linear fits and it's not clear a linear fit is adequate, but it is never-the-less clear that the imaginary Coulomb correction for the two nuclei is very different above 28 MeV.

The assumption of a $Z/A^{1/3}$ variation of the Coulomb correction is reasonable for the real part of the potential but not for the imaginary part. The imaginary Coulomb correction is complicated in that there are several Coulomb effects, some yielding larger absorption for protons and some larger absorption for neutrons. These effects are nuclear structure and energy dependent and do not necessarily behave smoothly with A. Osterfeld and Madsen[12] have made detailed calculations of these effects for ^{40}Ca using the so-called nuclear-structure approach to the optical model. The phenomenological results for $J_{\Delta Wc}$ provide evidence that the energy dependence of one or more of the important contributors to the imaginary Coulomb correction is substantially different for ^{28}Si than it is for ^{40}Ca. Additional information on the competing Coulomb effects in ^{28}Si is necessary to understand the relationship between these two nuclei.

The Coulomb correction has been expressed[13] as

$$\Delta U_c(r,E) = V_c(R_c)\delta U_N(r,E)/\delta E$$

where $V_c(R_c)$ is an average Coulomb interaction potential. A comparison of the energy dependence of the proton potentials in Figure 2 with the respective values of $J_{\Delta Wc}/A$ in Figure 3 demonstrates the failure of such an expression for the imaginary part of the Coulomb correction. While the value of $\mathrm{Imag}(\delta U_N/\delta E)$ changes sign over the energy region considered, the value of $\mathrm{Imag}(\Delta U_c)$ does not change sign. For energies greater than about 30 MeV the imaginary proton potential becomes nearly energy independent while the imaginary Coulomb correction does not vanish. It has been assumed elsewhere[1] that $J_{\Delta Wc}$ (as determined from ^{40}Ca data) remains zero for higher energies ($E>36$ MeV). While it may be true that $J_{\Delta Wc}$ is zero for ^{40}Ca at $E>36$ MeV, the energy independence of the volume integral of the imaginary proton potential is not sufficient evidence to support that conclusion. Higher energy neutron scattering data are required to resolve this issue.

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Fig. 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.

Fig. 2 Values of the volume integrals per nucleon of the real (upper part) and imaginary (lower part) nucleon optical-model potentials for ^{28}Si obtained from analyses of data in Refs. 9-11 with geometries of Ref. 10. The full and dashed lines (upper part) represent linear least squares fits to the data for proton and neutron scattering respectively. The solid line through the imaginary volume integral for protons (lower part) was drawn by eye while the dashed lines represent an error envelope.

Fig. 3 Values of the volume integrals of the imaginary Coulomb correction, $-J_{\Delta Wc}/A = (J_W/A)_n - (J_W/A)_p$ for ^{28}Si (filled circles). These values were obtained by taking the differences between the line through the proton data in Fig.2 and the plotted points for neutrons. The results from reference 1 for ^{40}Ca are plotted as open squares. The solid and dashed lines are unweighted linear least squares fits to the ^{28}Si data and ^{40}Ca data respectively.

Table I. Optical potentials(a) for neutron scattering.

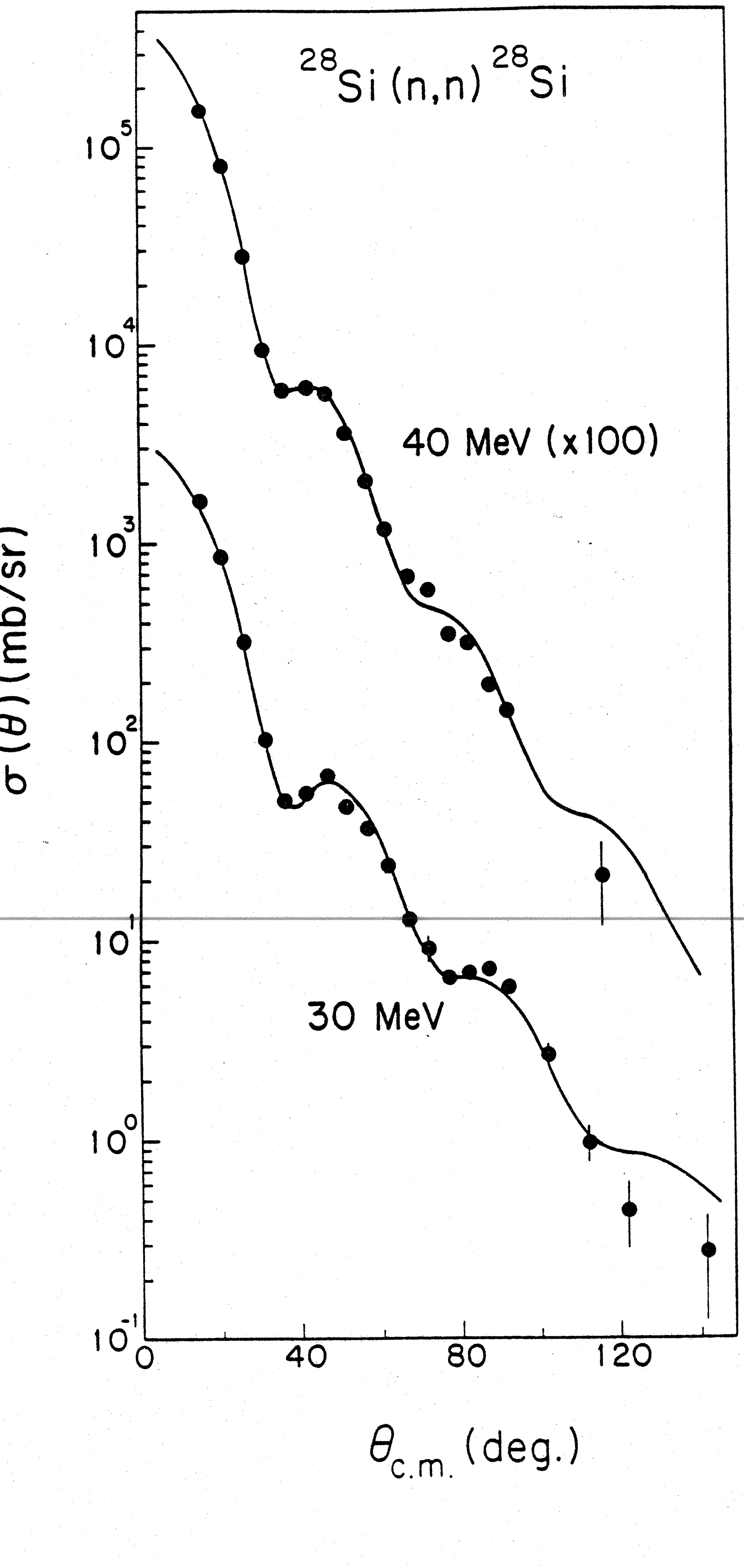
E_n (MeV)	V (MeV)	W_{vol} (MeV)	W_{surf} (MeV)	$(J/A)_{real}$ ($MeV\cdot fm^3$)	$(J/A)_{imag}$ ($Mev\cdot fm^3$)
14.1(b)	47.9	0.96	7.25	435.1	141.6
20.0(c)	48.0	7.90	1.30	435.6	116.5
26.0(c)	44.5	6.12	3.73	404.1	139.4
30.3(d)	44.0	8.88	1.93	399.5	139.6
40.0(d)	39.7	7.10	2.07	360.2	121.1

a) For geometry and spin-orbit potential, see text.

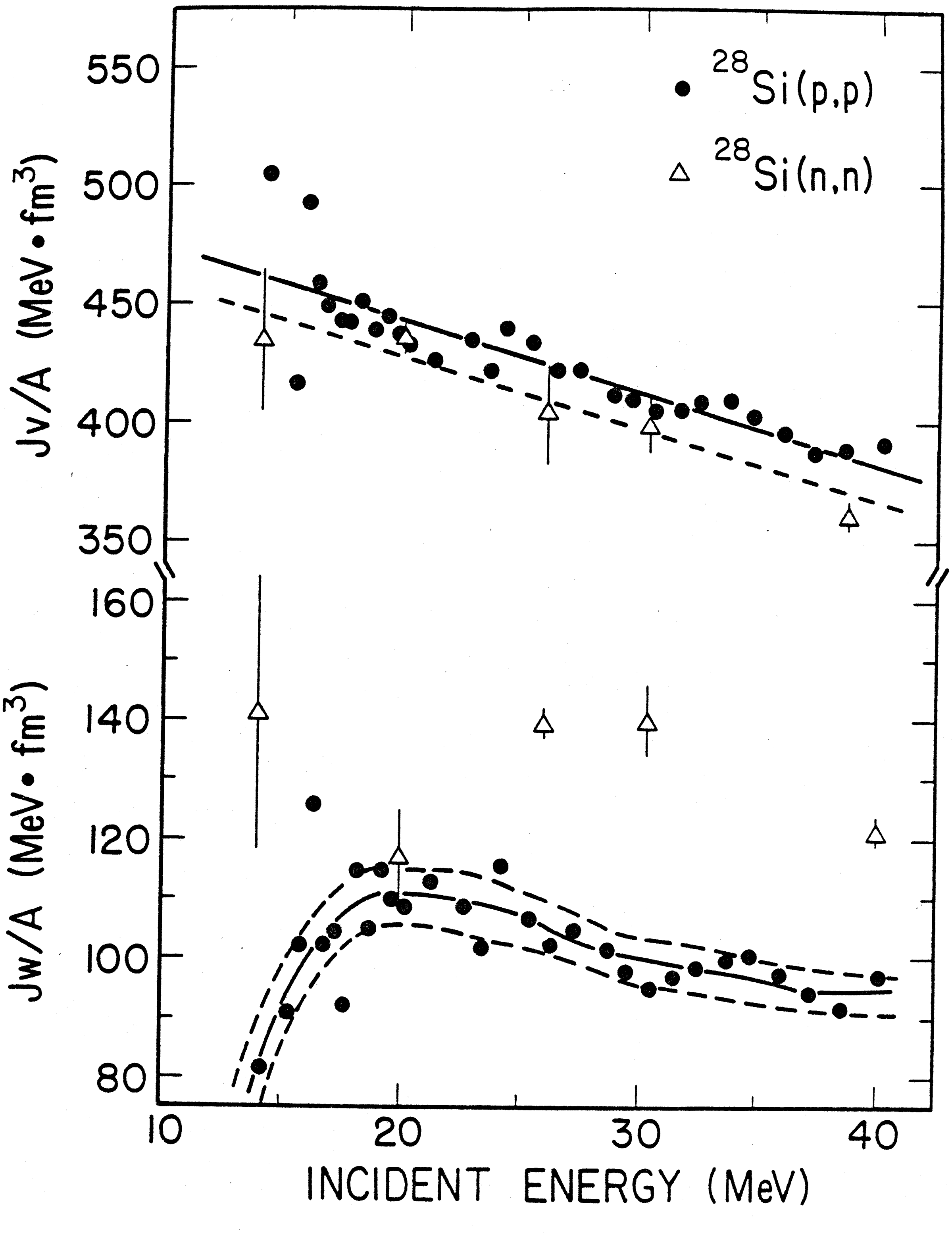
b) Ref. 11

c) Ref. 9

d) Present work.



^{28}Si(n,n)^{28}Si
40 MeV (x100)
30 MeV
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
σ(θ) (mb/sr)
0
40
80
120
$\theta_{c.m.}$ (deg.)



550
500
450
400
350
160
140
120
100
80
Jv/A (MeV • fm^3)
Jw/A (MeV • fm^3)
● ^{28}Si(p,p)
△ ^{28}Si(n,n)
10
20
30
40
INCIDENT ENERGY (MeV)

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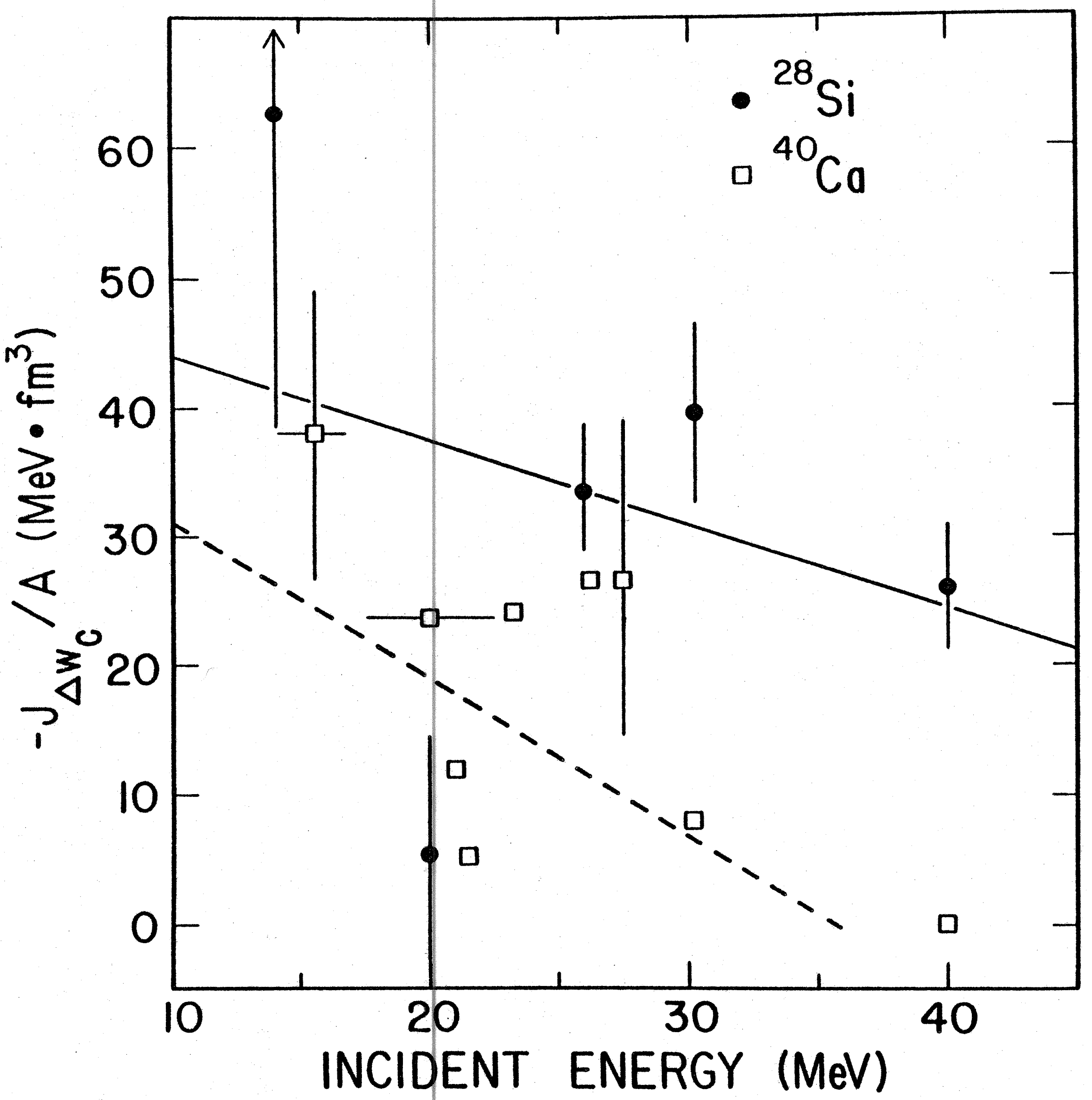
^{28}Si
^{40}Ca
60
50
40
30
20
10
0
$-J_{\Delta w_c}/A$ (MeV • fm^3)
10
20
30
40
INCIDENT ENERGY (MeV)

IUCF 1107