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Measurements and Optical-Model Analyses of Quasielastic (p, n) Reactions*

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Differential cross sections for quasielastic (p,n) scattering from 17–20-MeV bombarding energies have been measured for Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Se, Zr, and Nb in either 7.5 or 15° steps between 3 and 157.5°. A complex isospin-dependent potential, whose strengths and form factors are deduced from the Becchetti and Greenless global neutron and proton optical potentials, gave a good over-all description of the average behavior for the 17–20-MeV quasielastic (p,n) data. In particular, volume real and surface imaginary isospin form factors with strengths of 96 and 48 MeV, respectively, yielded a reasonable fit to both the shape and magnitude of the Fe and Nb quasielastic (p,n) data. On the other hand, using a purely real isospin potential requires a surface interaction of strength 126 MeV for Fe and a volume interaction of strength 107 MeV for Nb. The calculations have been extended to 30- and 50-MeV bombarding energy and have been compared with the measurements of Batty *et al.* At 30 MeV there is good agreement as regards both shape and magnitude; at 50 MeV the shapes are reasonably well described, but the calculated magnitudes are uniformly higher for most of the targets investigated. It is suggested that the 50-MeV data are consistent with a 30% decrease in the isospin strength in going from 30 to 50 MeV.

INTRODUCTION

In a previous paper[1] we reported differential cross sections for quasielastic (p, n) scattering at ~18-MeV bombarding energy. These data (taken every 15° and occasionally only every 30° for some targets) were analyzed by Satchler, Drisko, and Bassel (SDB)[2] to determine the strength and form factor for the isospin interaction. Assuming this interaction to be real, SDB found that an equivalent volume isospin strength of 100 ± 20 MeV adequately describes the magnitude of the quasielastic (p, n) cross sections. This strength is consistent with that determined from optical-model analysis of elastic proton scattering, where the strength of the real potential shows a linear dependence on the symmetry parameter $(N-Z)/A$. In addition, SDB found that at 18.5-MeV bombarding energy the data for the nuclei Ti to Cu clearly favored the surface form for a real isospin interaction, while Nb was better fit with a volume form. The quasielastic cross sections for Sc, Se, Y, Sr, and Zr at 18.5 MeV and Ti, V, and Fe at 17 MeV were measured every 30°, and were not complete enough to choose unambiguously between the two forms. Another consequence of measurements taken every 30° was that the uncertainties on the extracted strength were sufficiently large to preclude a meaningful determination of a possible shell dependence for the isospin strength. The present measurements were undertaken in the hope that more extensive measurements (taken either every 7.5 or 15° and for several bombarding energies between 17 and 20 MeV) would lead to a more definitive determination of the energy and shell dependence for the isospin strength and form factor.

EXPERIMENTAL METHOD

The experimental geometry, targets, and electronics are essentially as described in Ref. 1. The same targets as described in Ref. 1 were used except that Sc and Zr were metal foils instead of colloidal oxide suspensions. To obtain data at 7.5° intervals four additional holes were drilled into the target pit wall, thus yielding holes every 15° between 3 and 135°. The straight-through beam gave data every 15°; the in-between angles were obtained by double-bending the beam such that its angle of incidence at the target was 22.5°, thus yielding data every 15° between 22.5 and 157.5°. Data from the 10 Pilot B detectors were stored simultaneously in 10 512-channel subgroups of a PDP-5 computer analyzer.[3]

EXPERIMENTAL RESULTS

The experimentally measured differential cross sections for quasielastic (p, n) scattering are presented in Figs. 1–3 as a function of bombarding energy. It will be noticed that V, Fe, and Co are the three targets most thoroughly investigated as a function of bombarding energy. In addition, where available, the bent-beam data are plotted with the straight-through data. At some angles, data are missing either because of low intensity at the backward angles making identification difficult or because the neutron peak coincides with

γ rays from collimators, which occurs mainly at the forward angles. The errors are compounded from the statistical counting errors and the uncertainties introduced in drawing a line shape which subtracts out the continuum neutrons. This uncertainty in the background subtraction introduces most of the error in the cross section at the backward angle, where the analog (p, n) cross sections are small, and no appreciable error at the forward angles, where the cross sections are large. However, in no case is the error in the cross sections less than 7%, which represents an estimate of the absolute accuracy of the detector efficiency.

OPTICAL-MODEL CALCULATIONS

For optical-model calculations of quasielastic (p, n) scattering the computer code LOKI 2AEB developed by Schwarcz[4] was used. This code is an exact solution of the isospin coupled equations[5] and has the flexibility of being able to specify differing neutron and proton potential parameters and volume-surface mixtures for both the real and imaginary isospin interaction. Neutron and proton optical parameters were taken from the work of Becchetti and Greenlees,[6] and are applicable for mass numbers greater than 40 and bombarding energies less than 50 MeV. The global proton potentials[6] were:

Real:

$$V_R = 54.0 - 0.32E + 0.4Z/A^{1/3} + 24.0(N-Z)/A,$$

$$r_R = 1.17, \quad a_R = 0.75;$$

Imaginary:

$$W_V = 0.22E - 2.7 \text{ or zero, whichever is greater,}$$

$$W_{SF} = 11.8 - 0.25E + 12.0(N-Z)/A$$

$$\text{or zero, whichever is greater,}$$

$$r_I = 1.32, \quad a_I = 0.51 + 0.7(N-Z)/A;$$

Spin orbit:

$$V_{so} = 6.2, \quad r_{so} = 1.01,$$

$$a_{so} = 0.75, \quad \text{and } E \equiv \text{lab energy}.$$

The corresponding neutron potentials[6] were:

Real:

$$V_R = 56.3 - 0.32E - 24.0(N-Z)/A,$$

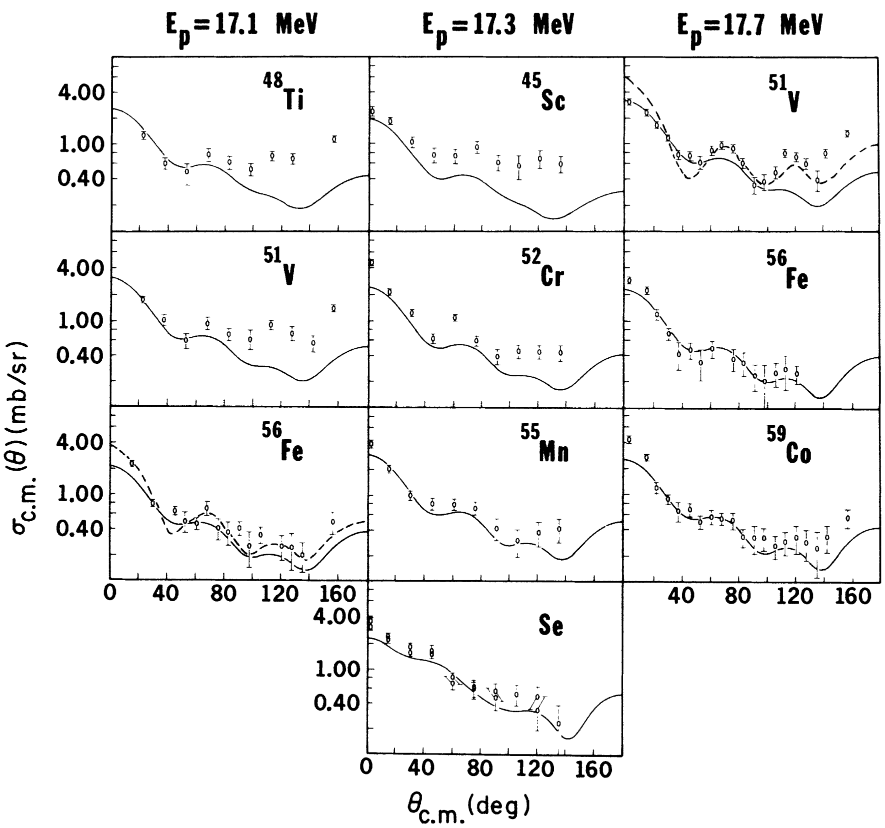

FIG. 1. Measurements and calculations of quasielastic (p,n) angular distributions at 17.1-, 17.3-, and 17.7-MeV bombarding energies. Solid curves are the predictions using the Becchetti and Greenlees complex isospin strengths, while dashed curves are optimum fits obtained by varying these strengths.

$r_R = 1.17, \quad a_R = 0.75;$

Imaginary:

$W_V = 0.22E - 1.56$ or zero, whichever is greater,

$W_{SF} = 13.0 - 0.25E - 12.0(N - Z)/A$

or zero, whichever is greater,

$r_I = r_{I'} = 1.26, \quad a_I = a_{I'} = 0.58;$

Spin orbit:

$V_{so} = 6.2, \quad r_{so} = 1.01, \quad a_{so} = 0.75.$

The dependence of the above real and imaginary proton and neutron potentials upon the symmetry parameter $(N - Z)/A$ (+ for proton and − for neutrons) implies a complex $\vec{t} \cdot \vec{T}$ interaction: The real isospin strength is 96 MeV with a volume form factor identical to that of the real potentials, while the imaginary isospin interaction is of a surface form with strength equal to 48 MeV and with a form factor identical to that of the imaginary surface potentials. In evaluating the real and imaginary strengths for insertion into LOKI 2AEB, the symmetry term $(N - Z)/A$ is neglected, since LOKI 2AEB calculated this dependence via the diagonal matrix elements of $\vec{t} \cdot \vec{T}$. Since the radius and diffuseness parameters for the imaginary neutron and proton potentials were slightly different, an average of these quantities was used. Finally, it should be mentioned that the proton and neutron energies at which the values of the optical parameters were evaluated differ by the Coulomb displacement energy.

The calculations for 17–20-MeV bombarding energy are shown in Figs. 1–3 as solid lines along with the corresponding measurements. It is observed that the optical parameters of Becchetti and Greenlees, and more importantly the complex shell- and energy-independent isospin strengths and form factors deduced therefrom, provide a good over-all description of the average behavior for the 17–20-MeV quasielastic (p, n) angular distributions. The angular-distribution shapes, particularly the location of maxima and minima, are well reproduced by the calculations. Except for Zr and a few cases at the backward angles, the calculated cross-section magnitudes are also in good agreement with the measurements. The over-

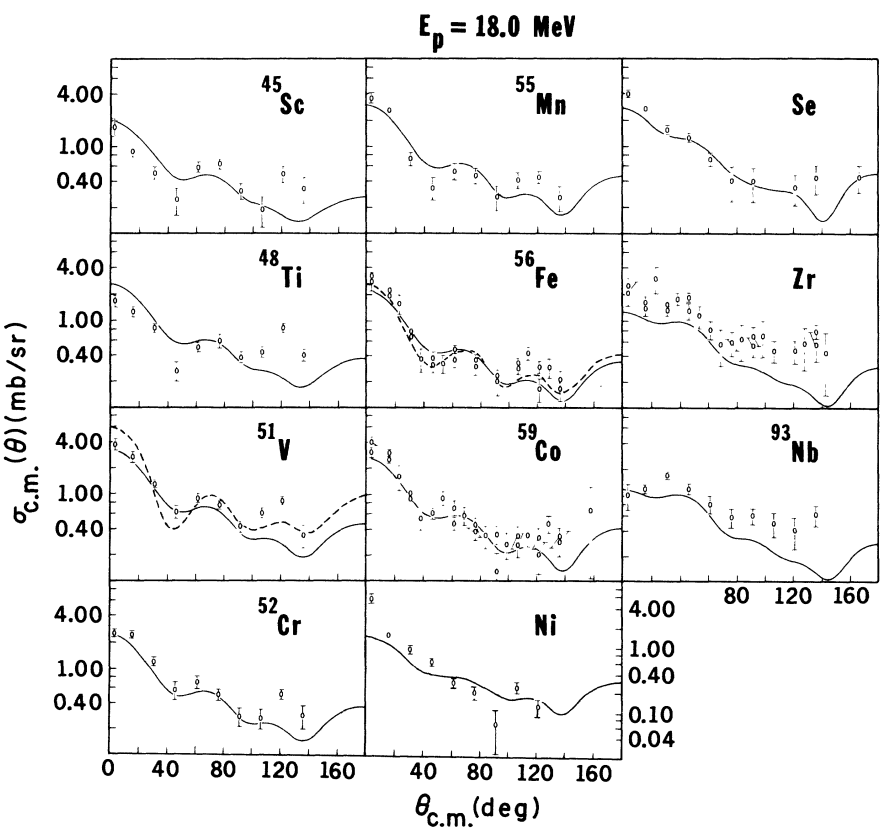

FIG. 2. Measurements and calculations of quasielastic (p, n) angular distributions at 18.0-MeV bombarding energy. See Fig. 1 caption for significance of the solid and dashed curves. Size of the symbols is an indication of the errors for those measurements without error bars.

all agreement is remarkable when one considers that no adjustment in any parameter was made.

Examination of Fig. 2 reveals that the angular distributions for $f_{7/2}$-neutron nuclei ^{45}Sc, ^{48}Ti, ^{51}V, and ^{52}Cr all show the same discrepancy between measurements and calculations in that the calculations are low at the backward angles. For $f_{7/2}$- and $p_{3/2}$-neutron nuclei ^{55}Mn, ^{56}Fe, and ^{59}Co, the calculations are slightly low at the forward maximum. These observations imply that the higher even multipoles do not contribute significantly to the quasielastic transition for odd nuclei, and also suggest that better agreement can be obtained by introducing a shell-dependent isospin interaction. This latter point was verified for ^{55}Mn, ^{56}Fe, and ^{59}Co at 18 MeV, where a search routine yielded a very good fit to the forward maximum (see dashed curve in Fig. 2 for ^{56}Fe), with a minimum χ^2 for equal real volume and imaginary surface isospin strengths of 76 MeV compared with the original strengths of 96 and 48 MeV, respectively. For $f_{7/2}$-neutron nuclei the optimum strengths at ~18 MeV were 65 and 106 MeV, respectively (see dashed curve in Figs. 1 and 2 for ^{51}V). Calculations for ^{56}Fe at 17.1 MeV (dashed curve in Fig. 1) and ^{55}Mn at 17.3 MeV showed that the fits were significantly improved if the equal real volume and imaginary surface isospin strengths of 76 MeV were increased by 10%. These results confirm that better agreement over the Becchetti results can be obtained by introducing a shell dependence and a slight energy dependence for the isospin strengths. Nonetheless, the energy- and shell-independent Becchetti isospin strengths provide a good over-all description of the average behavior for all nuclei between 17 and 20 MeV.

Calculations were done for the most abundant isotope even though measurements were made on targets with naturally occurring abundances. This procedure introduces the greatest error for Ni and smaller errors for Se and Zr. Normalizing to the average neutron excess (which is a very good approximation, especially for the even isotopes)[7] shows that the ^{58}Ni and ^{90}Zr calculations should be increased by 50 and 12%, respectively, while the ^{80}Se calculations should be decreased by 8% to yield the predictions for natural Ni, Zr, and Se shown in Figs. 1, 2, and 3.

Calculations were also performed for Fe and Nb at 18-MeV bombarding energy assuming the isospin interaction to be real. In this case, the symmetry dependence of the imaginary potentials is included in computing the imaginary proton and neu-

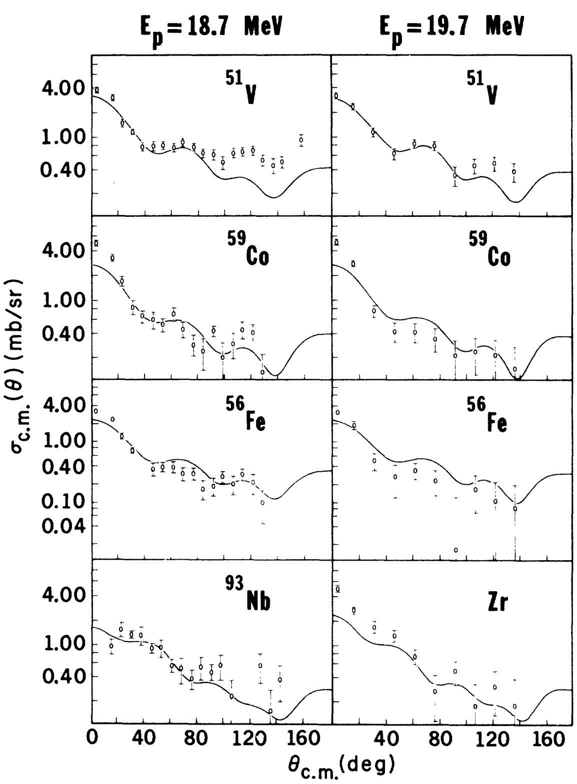

FIG. 3. Measurements and calculations of quasielastic (p,n) angular distributions at 18.7- and 19.7-MeV bombarding energy. See Fig. 1 caption for significance of the solid curves.

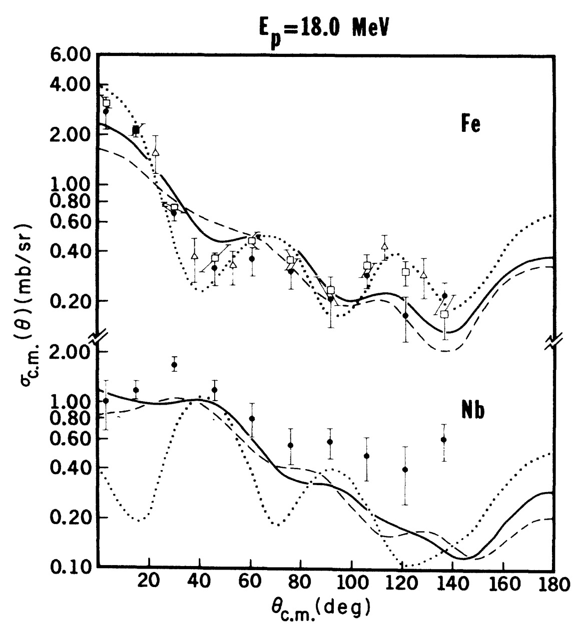

FIG. 4. Measurements and calculations of quasielastic (p,n) angular distributions for Fe and Nb at 18-MeV bombarding energy. Solid lines are predictions using the complex isospin interaction. Dashed and dotted curves are predictions using a real volume and a real surface isospin interaction, respectively. Different symbols for the Fe measurements refer to different experimental runs.

tron strengths for inclusion into LOKI 2AEB. Figure 4 shows the calculated angular distributions for Fe and Nb using a surface real isospin interaction of strength 126 MeV, a volume real isospin interaction of strength 107 MeV, and a complex isospin interaction deduced from the Becchetti parameters. For Nb, the predictions using a complex and a real volume isospin interaction are very similar. For Fe, the complex interaction yields a shape intermediate between the surface and volume predictions, with the best agreement being obtained with a surface real isospin interaction. Figure 4 shows that, in agreement with SDB,[2] a real isospin interaction requires a surface form for Fe and a volume form for Nb. Our volume interaction strength of 107 MeV for Nb ($a = 0.75$ and $r_0 = 1.17$) is to be compared with the value of 100 MeV deduced by SDB for Nb ($a = 0.65$ fm and $r_0 = 1.25$ fm). The close agreement in the strengths is explained by the fact that our smaller radius parameter is partially offset by the use of a larger diffuseness. For Fe our surface interaction strength of 126 MeV ($a = 0.57$ and $r_0 = 1.29$) is to be compared with the value of 75 MeV found by SDB ($a = 0.65$ and $r_0 = 1.25$) and which is obtained from Table I of Ref. 2 using $n = 2$. It is not obvious why our strength for Fe is so much larger, since the smaller diffuseness is to first order offset by the larger r^2 weighting in the volume integral because of the use of a larger radius parameter r_0.

Calculations were also made at 30- and 50-MeV bombarding energy using the complex isospin interaction and compared with the measurements of Batty *et al.*[8] The 30-MeV calculations and measurements are displayed in Fig. 5. It is seen that the isospin strengths and form factors deduced from Becchetti and Greenlees provide a good description of the measurements. In particular, the cross-section magnitudes and the zero-degree dependence of the cross sections with mass number are reasonably well predicted. The change in

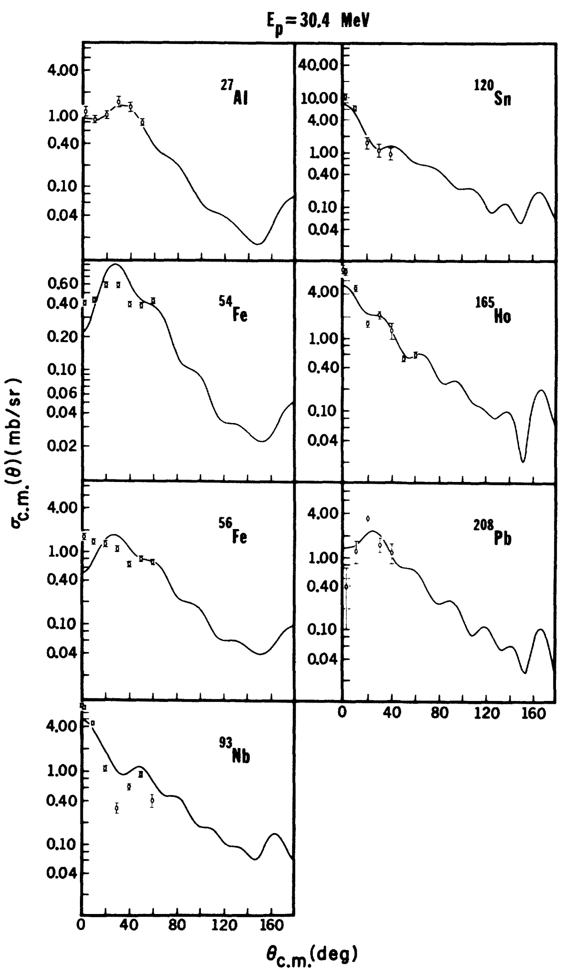

FIG. 5. Measurements and calculations of quasielastic (p,n) angular distributions at 30.4-MeV bombarding energy. Calculations were performed using a complex isospin interaction, while measurements were taken from the work of Batty *et al.*

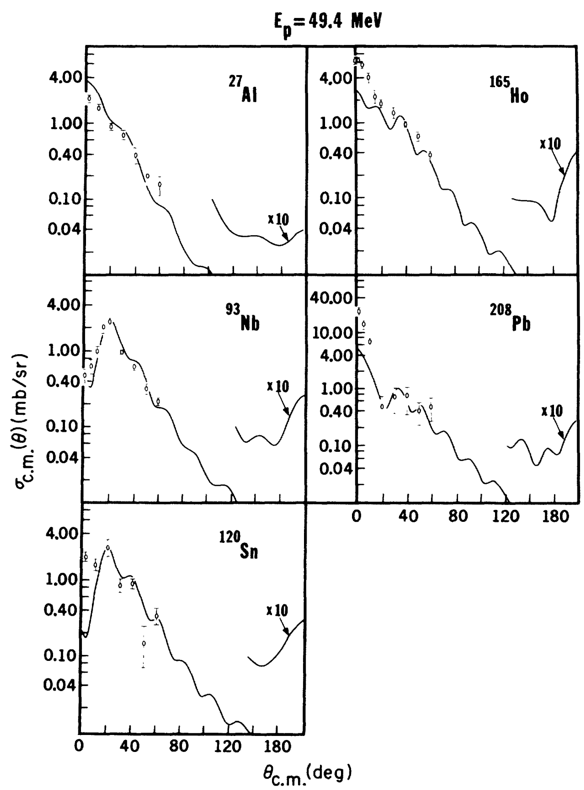

FIG. 6. Measurements and calculations of quasielastic (p,n) angular distributions at 49.4-MeV bombarding energy. Solid lines are the original calculations reduced by a factor of 2, while measurements were taken from the work of Batty *et al.*

shape between ^{54}Fe and ^{56}Fe is not correctly predicted. This is not unexpected, since optical-model calculations only predict average behavior with energy and mass number and not detailed differences between isotopes. The 50-MeV calculations and measurements are displayed in Fig. 6 and again reasonably good agreement is obtained. The solid curves shown are the original calculations reduced by a factor of 2. Since the calculated cross sections vary as the square of the isospin strength,[4] this implies that the strengths must be reduced 30% in order to fit the measured cross-section magnitudes at 50 MeV. Figure 6 shows that the angular distribution shapes, and, in particular, the zero-degree dependence of the cross sections with mass number, are reasonably well predicted. In addition, Figs. 5 and 6 show that the changes in shape between 30 and 50 MeV for Al, Nb, Sn, and Pb are reasonably well predicted with the Becchetti and Greenlees complex isospin interaction.

CONCLUSIONS

Although improved fits can be obtained by introducing a shell- and energy-dependent isospin interaction, the shell- and energy-independent Becchetti complex isospin interaction nonetheless provides a good over-all description of the average shape and magnitude of the 17–20- and the 30-MeV (p, n) quasielastic angular distributions. The good over-all agreement implies the consistency of the Becchetti and Greenlees optical potentials with the average measured charge-exchange cross sections at ~18- and 30-MeV bombarding energies. At 50 MeV the angular-distribution shapes are reasonably well predicted; however, the cross-section magnitudes suggest that the isospin strengths should be decreased by 30%. Evidence that the isospin strength decreases with energy has been presented by Satchler,[9] who concludes that the Thurlow[10] analyses of the 94-MeV quasielastic (p, n) data[11] show that the strength is a factor of 4 lower at 94 MeV compared to that at 18 MeV.

Since the (p, n) quasielastic angular distributions can also be fitted by assuming the isospin interaction to be real, but with varying surface-to-volume mixtures (as has been demonstrated by us, by SDB,[2] and by Schwarcz[4]), the present work does not indicate conclusively that the isospin interaction is complex. However, the assumption of a real isospin-dependent interaction requires a surface form for Fe and a volume form for Nb. The complex isospin-dependent interaction, with volume real and surface imaginary form factors, yields reasonable fits to both Fe and Nb without having to invoke arbitrary surface-to-volume mixtures.

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