J DEPENDENCE OF THE ANGULAR DISTRIBUTIONS FROM (p,d) REACTIONS AT 28 MeV *

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Lee and Schiffer[1] have recently found a marked dependence of the angular distributions in the (d,p) reaction on the spin of the final state following capture of an $l=1$ neutron by a spin-zero target. Using 8- to 12-MeV deuterons and targets ranging from Ca to Ni, they found that $\sigma(\theta)$ for $J=\frac{1}{2}$ final states exhibited a very deep minimum at some angle beyond 90°. The cross sections in the angular region of interest were 2 to 5% of the forward-angle maxima. In an investigation of the (p,d) reaction at 28 MeV bombarding energy on elements ranging from Ti through Ni, we have found a strong dependence of the shape of the forward-angle maxima on the J of the final state following pickup of an $l=3$ neutron from a spin-zero target. Since the presently observed effect occurs where the cross sections are large, it will also be useful as a spectroscopic tool for states whose cross sections are too small to permit observation of the Lee-Schiffer effect.

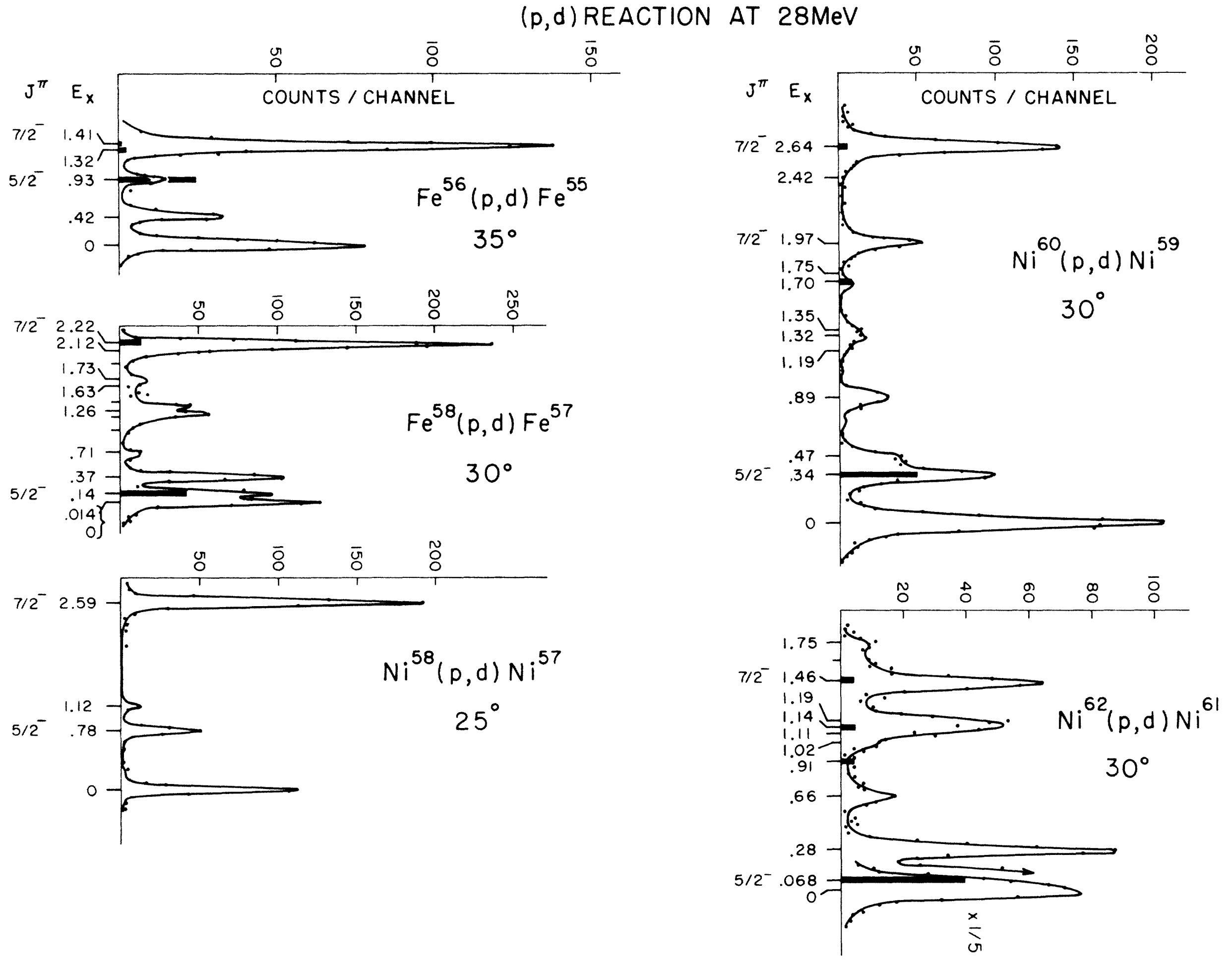

FIG. 1. Deuteron spectra from the (p,d) reaction at 28 MeV. The known excitation energies for each residual nucleus are shown. J^π is given only for states discussed in the text.

Present indications are that the two effects have different origins, the latter (at large angles) being due to spin-orbit coupling in the entrance and/or exit channels, while the former (at forward angles) is due to a spin-orbit effect on the wave function of the picked-up neutron.

The spectra of deuterons from isotopic targets of ^{56}Fe, ^{58}Fe, ^{58}Ni, ^{60}Ni, and ^{62}Ni are shown in Fig. 1. These spectra were obtained with the 28-MeV proton beam of the University of Colorado cyclotron. An E-ΔE telescope of solid state detectors and a multiplying circuit were used to identify and measure the deuteron energies. The energy levels for ^{57}Ni are those obtained in the present measurements; for the other nuclei, the previously known levels are listed.[2,3] Spin assignments are shown only for those states showing $l=3$ distributions in (d,p) measurements,[3-5] in the (p,d) reaction at 17.0 and 18.5 MeV,[6] and in the current investigation. The relative cross sections[3,4] in the (d,p) reaction are shown by the horizontal bars; spin $\frac{5}{2}$ is assigned to the strongest (as well as lowest) state. (The 136-keV state of ^{57}Fe and the 68-keV state of ^{61}Ni have previously been assigned[2] spin $\frac{5}{2}^-$.) In the (p,d) reaction, the strongest yield is expected for pickup of a neutron from the presumably filled $1f_{7/2}$ shell; these states will have a relatively feeble yield compared with that for the major $1f_{5/2}$ state in the (d,p) reaction. Thus states weakly excited in the (d,p) reaction and strongly excited in the (p,d) are assigned[6] spin $\frac{7}{2}^-$.

The angular distributions for the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states are shown in Fig. 2(a). The distributions for the $\frac{7}{2}^-$ states are similar to those we have observed for states of known spin $\frac{7}{2}^-$ in ^{47,48}Ti and ^{51}Cr. [The experimental energy of the $\frac{7}{2}^-$ peak in ^{55}Fe is 1.38 MeV; Whitten[7] has found in (p,d) measurements at 17.5 MeV that the 1.41 and 1.32 states have $l=3$ distributions with a cross section ratio of ~3.5 to 1.] From Fig. 1 it is evident that the energy resolution (~120 keV) of the present measurements was inadequate to resolve some of these states, particularly in

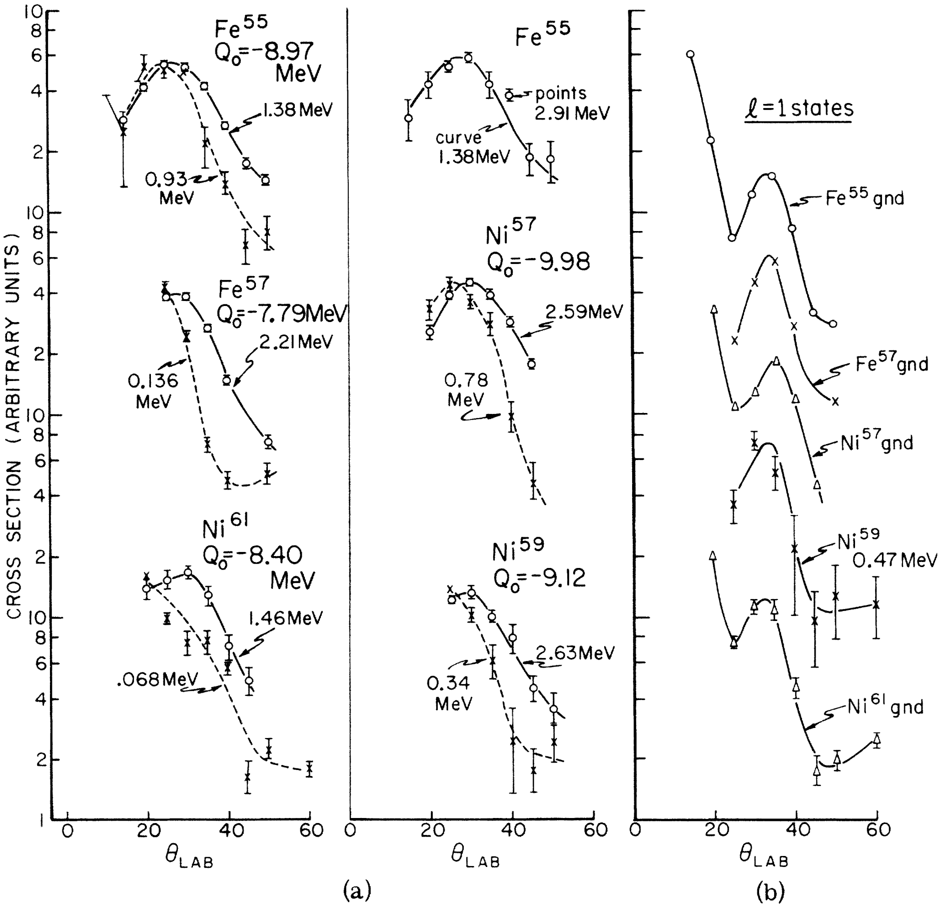

FIG. 2. (a) Relative angular distributions for $l=3$ pickup to $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states for the various residual nuclei. (b) Relative angular distributions for $l=1$ pickup. (The curves shown are lines connecting the experimental points.)

the case of the 68 keV state of ^{61}Ni. Some assurance that our decomposition of the experimental data is reasonably good is given by the angular distributions for the other members of the doublets. The latter should have $l=1$ distributions[3,4,6] and are shown in Fig. 2(b) together with other $l=1$ distributions for comparison.

The differences in $\sigma(\theta)$ for $J=\frac{5}{2}$ and $J=\frac{7}{2}$ are very marked. The peaks for the $\frac{5}{2}^-$ states are at a smaller angle in each case and the fall-off with increasing angle is steeper and deeper. This effect is not due to the difference in Q value for the pairs of states, as can be seen by the essential identity of $\sigma(\theta)$ (relative) for the 1.38- and 2.91-MeV states of ^{55}Fe in Fig. 2(a). The $l=3$ distributions for higher states show a slight increase of peak angle with excitation energy, but the rate of shift is too small to account for the observed shift for the $\frac{5}{2}^-$ states.

The J dependence of $\sigma(\theta)$ can be investigated with a distorted-wave calculation where a spin-orbit term $V_1\vec{l}\cdot\vec{s}$ is added to the optical potentials and also to the potential which describes the wave function of the picked-up neutron. The forward-angle behavior of $\sigma(\theta)$ was found to be insensitive to the optical potential parameters which were taken from elastic scattering data.[8] The neutron wave function is customarily described by adjusting the potential well in order to give the actual neutron separation energy. This method fails in our case since the separation energies for $J=\frac{5}{2}$ and $\frac{7}{2}$ are very similar. However, the effect is easily explained if we take the neutron well from the simple *jj* shell model and ignore the incorrect asymptotic form of the neutron wave function.

Figure 3 shows the results of a distorted-wave calculation of ^{56}Fe$(p,d)^{55}$Fe reaction leading to the 1.38-MeV ($\frac{7}{2}^-$) and 0.93-MeV ($\frac{5}{2}^-$) states of ^{55}Fe. The calculations assume 6 MeV splitting between the shell model $f_{7/2}$ and $f_{5/2}$ levels. The smaller peak angle and larger fall-off for $J=\frac{5}{2}$ can be understood in the smaller binding (or equivalently larger "effective" radius) of the $f_{5/2}$ neutron. The effect on the relative strengths is also striking, the peak cross section for $J=\frac{5}{2}$ being almost a factor of two greater than the peak for $J=\frac{7}{2}$. If the shell-model wave functions are reliable for extracting relative magnitudes, some doubt is then cast on the extraction of spectroscopic information for different orbitals presently given in the literature.

Calculations using shell-model wave functions for ^{56}Fe$(p,d)^{55}$Fe at 17.5 MeV or for ^{54}Fe$(d,p)^{55}$Fe at 12 MeV indicate a smaller effect on the $l=3$ cross sections at forward angles than in the present case. However, the existing data are not of sufficient accuracy to check the small but observable shift predicted by these calculations.

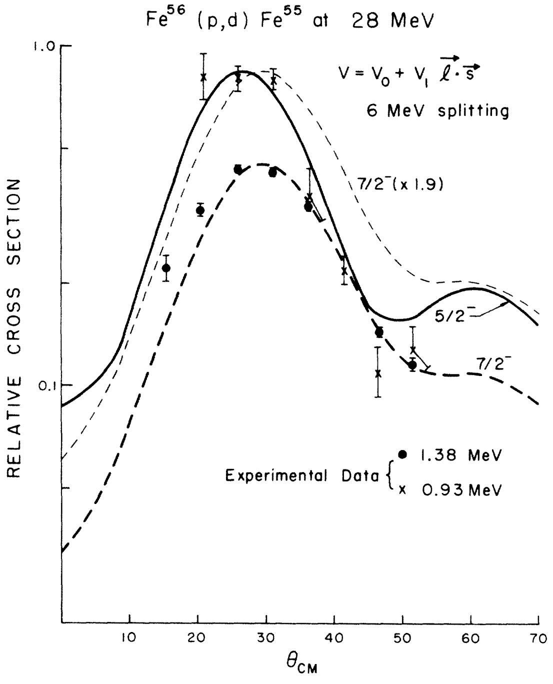

FIG. 3. Comparison of experiment and distorted-wave calculations. The heavy curves shown the relative cross sections for $f_{5/2}$ and $f_{7/2}$ pickup, while the light curve for $\frac{7}{2}^-$ has been normalized (×1.9) to the same maximum value as for $\frac{5}{2}$ to exhibit more clearly the difference in $\sigma(\theta)$ for the two cases. The corresponding experimental points have been normalized to the theoretical curves.

The $l=1$ distributions shown in Fig. 2b are all similar. Several distributions for $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states[1] have been compared, but no unambiguous difference was found, although there is a slight indication that the 25° minimum may be relatively deeper for $\frac{1}{2}^-$ than for $\frac{3}{2}^-$. More detailed angular distributions will be required to establish the difference that it is now safe to conclude must exist. If the j dependence of the angular distributions arises from the neutron spin-orbit interaction, one would expect a smaller effect for $l=1$ than for $l=3$ at forward angles. By the same argument, larger effects are to be expected for pick-up of neutrons from higher l states.

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PARTICLES WITH A CHARGE OF $\frac{1}{3}e$

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The SU(3) group, as used to describe the strong interactions of mesons and baryons in the manner of Gell-Mann[1] and Ne'eman,[2] admits representations of dimension 3. If the elements of this representation are associated with real particles, and if the Gell-Mann Nishijima strangeness scheme is not modified,[3] the elements of the "3" representation correspond to three particles, an isotopic spin doublet with charges of $-\frac{1}{3}e$ and $+\frac{2}{3}e$, and a singlet with a charge of $-\frac{1}{3}e$. Elements of the antiparticle representation "3*" have opposite charges. Gell-Mann, who has emphasized the importance of investigating the existence of such particles, has named them quarks.[4]

At least one of the charge-$\frac{1}{3}e$ quarks must either be stable, or decay very slowly by β decay into the charge-$\frac{2}{3}e$ quark. It seems likely that, if quarks exist at all, they are coupled but weakly to regular particles or that they have large masses. Otherwise they would probably have been noted, particularly in bubble chamber pictures of high-energy interactions. Interactions producing quarks would show two tracks, with bubble densities of $\frac{1}{9}$ and $\frac{4}{9}$ minimum, which would probably be noted in scanning. This lack of production suggests the conclusion: If quarks have masses not much larger than that of the nucleon, their coupling to regular mesons and baryons must be weak. Such generalizations must be made with care, however. The production of Ω^- hyperons in such interactions does not seem to be large and the Ω almost certainly does interact strongly with matter.

Our search for quarks was then divided into two parts following different assumptions as to the interaction of quarks. In each case we lose no generality by limiting our search to quarks of charge $\frac{1}{3}e$. The first method assumes a weak coupling of quarks to regular particles. In particular the assumption is made that the quark-nucleon total cross section is not larger than a few millibarns. For production processes we make the minimal assumption that the only coupling of importance is the electromagnetic coupling which we know is $\frac{1}{3}e$ and $\frac{2}{3}e$.

The very large accelerations of charged particles involved in the strong interactions results in the radiation of photons in nominally strong interaction processes and also results in the production of pairs by virtual photons. The probability of emitting a real photon in an interaction is of the order of $(e^2/\hbar c)$; the probability of emitting a pair will be of the order of $(e^2/\hbar c)(e_q{}^2/\hbar c)$ where e_q is the charge of the particles. These numbers must be modified to allow for phase space factors and for the radiative damping so important at high energies where a very large number of reaction channels are open. We do