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where a and b refer to the two transitions considered and where, again, the small energy-dependent factors have been neglected.
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J-DEPENDENCE STUDIES IN (α,p) REACTIONS AT 30 MeV

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Proton angular distributions have been measured for the reactions ^{58}Ni$(\alpha,p)^{61}$Cu, ^{60}Ni$(\alpha,p)^{63}$Cu, and ^{28}Si$(\alpha,p)^{31}$P at $E_\alpha=30$ MeV. Strong J dependence is observed for the $l=1$ transfer distributions to the ground and first excited states of ^{61}Cu and ^{63}Cu, whereas essentially no J dependence is observed for the $l=2$ transfer distributions to the first and second excited states of ^{31}P. Distorted-wave Born-approximation calculations are also discussed.

In recent years numerous direct reactions have been shown to be J dependent,[1] i.e., the relative shapes of the angular distributions of the emerging particles for a given l transfer are dependent upon the total angular momenta of the final states involved in the reactions. This previous work has shown that the (α,p) reaction (along with its inverse) exhibits the most pronounced J dependence. The marked J dependence observed in the (α,p) work strongly suggests that this reaction could be employed as a useful spectroscopic tool in nuclear-structure studies. Some qualitative success in interpreting J dependence in (α,p) reactions with distorted-wave Born-approximation (DWBA) calculations support this argument. There has been no extensive systematic study to establish the range in atomic number, incident energy, and excitation energy over which J dependence might serve as a reliable technique for extracting spectroscopic information. Such a program of study has been initiated at the Naval Research Laboratory (NRL), and the present Letter reports on the three reactions ^{58}Ni$(\alpha,p)^{61}$Cu, ^{60}Ni$(\alpha,p)^{63}$Cu, and ^{28}Si$(\alpha,p)^{31}$P at an incident alpha energy of 30 MeV. States of well-established spins and parities were chosen for study. J dependence has not been studied previously at as high an incident energy in (α,p) reactions. The marked difference between the results on Ni and Si indicates some possible limitation on the range of applicability of J dependence as a spectroscopic tool.

The 30-MeV alpha beam was produced by the NRL sector-focusing cyclotron, and beam currents ranged from 0.2 to 0.8 μA. The isotopically enriched Ni targets and the natural SiO targets were self-supporting foils with a nominal areal density of 0.5 mg/cm^2. The protons were detected with a counter telescope consisting of a 1-mm Si passing counter and a 4-mm Si stopping counter. Digital particle identification was made using the NRL on-line computer facility. The observed energy resolution was generally about 150 keV full width at half-maximum, and this was quite adequate for resolving the proton groups of interest.

On the left of Fig. 1 are shown the measured proton angular distributions for the ground and first excited states of ^{61}Cu and ^{63}Cu from the reactions ^{58}Ni$(\alpha,p)^{61}$Cu and ^{60}Ni$(\alpha,p)^{63}$Cu. These distributions for $l=1$ transfer exhibit a very marked J dependence at $E_\alpha=30$ MeV. Comparison of these results with those of Lee et al.[2] for the same states at $E_\alpha=18$ MeV indicates that the effect is enhanced at 30 MeV over what is observed at the lower energy. The data of Fig. 1 also reveal that the pairs of distributions with the same J^π are nearly identical.

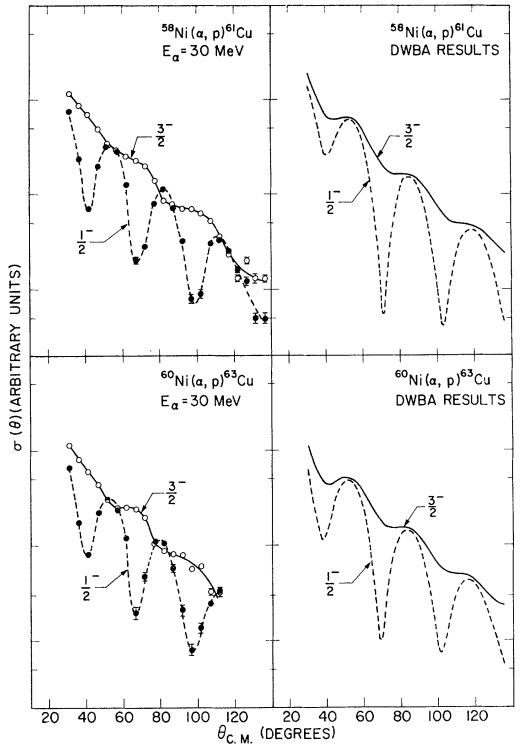

FIG. 1. Proton angular distributions for $l=1$ transfer to the ground ($J^\pi = \frac{3}{2}^-$) and first excited states of ^{61}Cu and ^{63}Cu. The excitation energies of the first excited states in ^{61}Cu and ^{63}Cu are 0.48 and 0.67 MeV, respectively. The curves through the experimental points on the left of the figure are drawn to aid the eye. The c.m. cross section at $\theta_{c.m.} = 31°$ is approximately 115 μb/sr for the ^{58}Ni, $\frac{3}{2}^-$ distribution. Absolute cross-section measurements have not as yet been made for the ^{60}Ni reaction. The calculated distributions are shown on the right.

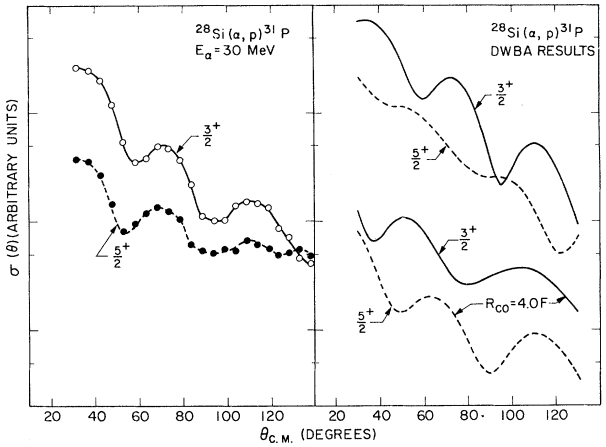

FIG. 2. Proton angular distributions for $l=2$ transfer to the first ($J^\pi = \frac{3}{2}^+$) and second excited states of ^{31}P. The excitation energies of the first and second excited states of ^{31}P are 1.27 and 2.23 MeV, respectively. The curves through the experimental points on the left of the figure are drawn to aid the eye. The c.m. cross section at $\theta_{c.m.} = 31°$ is approximately 230 μb/sr for the $\frac{3}{2}^+$ distribution. The calculated distributions are shown on the right.

Yamazaki, Kondo, and Yamabe[3] measured the proton angular distributions at $E_\alpha = 22.2$ MeV for the first and second excited states of ^{31}P from the reaction ^{28}Si$(\alpha,p)^{31}$P. These distributions for $l=2$ transfer were quite reasonably interpreted by Lee et al.[2] as further evidence for strong J dependence in (α,p) reactions. The $\frac{3}{2}^+$ first excited state distribution oscillated strongly with angle, whereas the $\frac{5}{2}^+$ distribution was rather featureless. On the basis of what was found at lower energies for all three reactions, plus the NRL results on ^{58}Ni and ^{60}Ni at 30 MeV, one might expect that the $l=2$, ^{28}Si$(\alpha,p)^{31}$P angular distributions would also show a strong J dependence at $E_\alpha = 30$ MeV. Instead, the result shown in Fig. 2 was observed. There is no obvious J dependence, and the disappearance of the effect has occurred by virtue of the $\frac{5}{2}^+$ distribution oscillating rather strongly and nearly in phase with the $\frac{3}{2}^+$ distribution.

An attempt has been made to explain the observed angular distributions by local, zero-range, DWBA calculations using the code JULIE.[4] The mechanism of the (α,p) reaction is assumed to be the stripping of a triton from the incident alpha particle. For the form factor, the wave function of a triton cluster bound in a Woods-Saxon well is used, with the well depth adjusted to make the binding energy equal to the separation energy of the triton and the initial nucleus. The usual form[5] of the optical model potential was used with the spin-orbit term having the same Woods-Saxon shape as the real part of the potential. The optical-model parameters are given in Table I. The proton parameters for both Ni and Si as well as the alpha parameters for Ni were taken directly from the literature.[5,6] A parameter set for a deep, real well ($V = 159.6$ MeV) was selected for the alpha channel of Ni from the various optical-model potentials given in Ref. 6 because recent work[7] has indicated that the deeper optical-model potentials give better results in DWBA calculations on alpha-induced reactions than the more shallow ones. An analysis by Satchler[8] of the scattering of 28-MeV alpha particles from Si is available. In this analysis a search was only made for optical potentials with $V \approx 50$ MeV. In order to obtain an optical-model potential with a deeper real well, elastic-scat-

Table I. Optical-model parameters for DWBA calculations.

Target nucleus	Particle	V (MeV)	W (MeV)	r_0 (F)	a (F)	r_c (F)	V_{so} (MeV)	W_D (MeV)	r_0' (F)	a' (F)
^{28}Si	alpha[a]	187.3	13.8	1.657	0.466	1.4	•••	•••	•••	•••
	proton[b]	51.1	5.44	1.098	0.711	1.2	5.80	1.79	1.442	0.500
^{58,60}Ni	alpha[c]	159.6	17.7	1.484	0.504	1.3	•••	•••	•••	•••
	proton[b]	53.5	3.0	1.12	0.75	1.2	6.40	5.91	1.33	0.58

[a]See text.
[b]See Ref. 5.
[c]See Ref. 6.

tering "data" were generated from Satchler's parameter set. A search was than made to fit these generated "data" starting at $V = 180$ MeV using the search code ABACUS-2.[9] The parameters resulting from this search are those shown in Table I.

The results of the DWBA calculations are shown on the right side of each figure. The pairs of calculated distributions were separately and arbitrarily normalized to simply show the relative shapes in a clear manner. The relative intensities of the experimental distributions are as found experimentally.

The calculations for the ^{58}Ni and ^{60}Ni (α,p) reactions are in fairly good qualitative agreement with the experimental data. The calculations do not involve a lower radial cutoff. The deep minima for the $\frac{1}{2}^-$ distributions occur within a few degrees of the experimental minima, and the decrease in cross section with angle for both the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ distributions is in good agreement with experiment. As far as relative shapes are concerned, the only major discrepancy between theory and experiment is that the calculations predict the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ distributions to be in phase, whereas experimentally they are out of phase.

The ^{28}Si$(\alpha,p)^{31}$P calculations are shown on the right of Fig. 2. It was found that the shapes of the distributions were fairly sensitive to the lower cutoff radius employed. The upper pair of distributions are for zero cutoff, and the lower ones are for a 4.0-F cutoff radius. For the zero-cutoff case there is still a moderate amount of J dependence predicted, in contrast to the experimental results. It is interesting to note, however, that the calculated $\frac{3}{2}^+$ distribution characterizes the experimental distribution quite well. For the lower pair, the calculated $\frac{5}{2}^+$ distribution characterizes the corresponding experimental one reasonably well. The 4.0-F choice came closest to predicting no J dependence. Perhaps the most reasonable statement that can be made for the ^{28}Si(α,p) calculations is that it does not seem to be beyond the ability of the theory to predict the disappearance of J dependence.

The difficulties noted in these preliminary calculations indicate the desirability of making nonlocal, finite-range computations with a microscopic-model form factor. These more sophisticated calculations may reduce or eliminate the problems discussed. Better optical-model parameters derived from additional elastic-scattering measurements may also be necessary.

The small amount of data that exist on the J dependence of (α,p) reactions makes it difficult to draw general conclusions about the reliability of this technique to extract spectroscopic information. However, the strong energy dependence of this effect in the reaction ^{28}Si$(\alpha,p)^{31}$P as evidenced by the disappearance of J dependence in going from 22 to 30 MeV has several important implications. Such anomalous behavior may be characteristic of the lighter nuclei. It this is so, then one needs to exercise extreme caution in drawing conclusions from J-dependence studies in the lighter nuclei. On the other hand, the Ni results at the very least suggest that the effect is apparently well behaved in the heavier nuclei. We expect to test these postulates in future experiments.

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PHOTOPRODUCTION OF π^0 WITH PLANE POLARIZED 3-GeV PHOTONS*

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The cross section for photoproduction of π^0 mesons was measured at a photon energy of 3 GeV and squared four-momentum transfer (t) of -0.1 to -1.2 $(\mathrm{GeV}/c)^2$ using plane-polarized photons. The asymmetry was found to be consistent with +1.0 for t values above -0.4 and below -1.1. For $-0.4 \leq t \leq -1.0$ there is a dip in the asymmetry and at $t = -0.6$ it drops to 0.55 ± 0.15. This result precludes a simple Regge model with ω^0 and B; a theoretical description requires Regge cuts or an ω' exchange.

The methods of obtaining polarized photons by electrons impinging on a suitably oriented crystal are described in the literature.[1,2] We used a diamond crystal mounted on a goniometer in the doughnut of the Cambridge Electron Accelerator. When struck by a circulating beam of 6-GeV electrons, a suitable crystal orientation produces a "spike" of photons at 3 GeV above the normal bremsstrahlung spectrum; a photon polarization $(N_\perp - N_\parallel)/(N_\perp + N_\parallel)$ of ± 0.6 is obtained in the spike region.

The reaction

$$\gamma + p \rightarrow \pi^0 + p, \quad \pi^0 \rightarrow \gamma + \gamma \qquad (1)$$

is measured by detecting the protons (angle and momentum) in a magnetic spectrometer[3] and each of the two γ rays in two lead-glass hodoscopes (energy and angle).[4] Since the kinematics are overdetermined we can check that the event corresponds to Reaction (1). Between π^0 runs we measured the photon spectrum from the crystal by means of a 30 (15×2)-counter electron-positron pair spectrometer; the coincidence rates are converted to visually displayed spectra with an on-line computer. Runs were also taken with an amorphous electron target to give an unpolarized photon beam. The experimental layout is shown in Fig. 1.

The coherent crystal bremsstrahlung spectrum depends critically on the angle between bombarding electrons and the crystal axis. Since there may be an indeterminate angular spread in the electron beam we assumed such a smear in angle plus a central angle to give computed spectra to fit the measured spectra. The theory then gave us computed photon polarizations as a function of photon energy. From these spectra and the quantameter reading[5] $d\sigma_\perp/dt$ and $d\sigma_\parallel/dt$ could be computed. We checked this procedure by seeing that $d\sigma/dt = \frac{1}{2}(d\sigma_\parallel/dt + d\sigma_\perp/dt)$, where $d\sigma/dt$ was measured from the runs with unpolarized photons. From these cross sections the asymmetry parameter α is calculated:

$$\alpha = (d\sigma_\perp - d\sigma_\parallel)/(d\sigma_\perp + d\sigma_\parallel).$$

The results for our runs are shown in Fig. 2. This parameter is an average over cross sections taken at a photon energy of 3.0 ± 0.2 GeV. The errors shown are statistical; systematic errors in efficiency cancel in this ratio. A systematic error in α due to inaccurate measurement of the photon spectrum from run to run should be less than ± 0.1 in α.

We made a further check of our polarization calculations by measuring the coherent photoproduction of ρ^0 from lead:

$$\gamma + \text{Pb nucleus} \rightarrow \rho^0 + \text{Pb nucleus}, \quad \rho^0 \rightarrow \pi^+ + \pi^-.$$

A charged-particle telescope was placed at 14° with respect to the photon beam and the spectrometer was set for a π^- coming off at 14° on the other side. This setup is then sensitive to