$^{40}Ca(p, p\alpha)^{36}Ar$ reaction in a noncoplanar geometry

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The $^{40}Ca(p,p\alpha)^{36}Ar$ reaction has been measured at $E_p = 101.3$ MeV for coplanar quasifree angle pairs ($\theta_p = 70°$, $\theta_\alpha = -45.7°$) and out-of-plane angles $\beta = 0°$, 5°, 10°, 15°, and 20°. Distorted-wave impulse approximation calculations reproduce the shape of the energy sharing distributions and provide spectroscopic factors in agreement with previous work on knockout and transfer reactions.

[NUCLEAR REACTIONS $^{40}Ca(p,p\alpha)^{36}Ar$, $E_{lab}=101.3$ MeV: measured $d^3\sigma/d\Omega_p d\Omega_\alpha dE_p$ for $\theta_p=70°$, $\theta_\alpha=-45.7°$, $\beta_\alpha=0°$, 5°, 10°, 15°, 20°; DWIA analysis.]

The general validity of the distorted wave impulse approximation (DWIA) in the analysis of $(p,p\alpha)$ reactions at bombarding energies of 100 MeV or greater has been shown in previous papers.[1-3] Due to the presence of a three-body final state, such knockout reactions provide a flexible method for understanding the cluster structure of nuclei.[4] The majority of previous works on cluster knockout have concentrated on coplanar energy-sharing measurements at quasifree angle pairs (angle pairs for which zero recoil momentum of the residual nucleus is permitted). Such measurements emphasize the low momentum components of the α-cluster wave function. However, a good measurement of the higher momentum components is essential in order to better define the cluster-core wave function. Indeed, our lack of knowledge of this wave function is a major limitation in the extraction of α-cluster nuclear structure information.

The extraction of information on the higher momentum components from coplanar energy sharing data is hampered by two effects. Firstly, the distortion effects are large and energy dependent, thereby requiring accurate knowledge of the distorting potentials over a wide range of energies. Secondly, the two-body p-α vertex varies across the energy sharing distribution. One possible experimental alternative for the measurement of the higher momentum components is to maintain the coplanar geometry but to move away from the quasifree angle pair. In this manner constant energies of the outgoing particles can be selected for study, so that variation of the distortion effects arise simply from the effect of the angle change on the overlap of the distorted waves. However, the two-body p-α vertex still varies significantly.

An improved procedure is to vary the out-of-plane angle of one of the detectors. In this fashion the variation in distortion effects is further lessened due to a reduction in angle change, and the two-body p-α vertex may be kept essentially constant. The advantages of this geometry were utilized in a measurement of the $^9Be(p,p\alpha)\,^5He$ reaction.[5] In this work it was demonstrated that there was indeed a significant reduction in distortion in comparison to other geometries. Since both S- and D-state configurations contribute to the $^9Be(p,p\alpha)$ reaction, the higher momentum component (100–250 MeV/c) measurements were dominated by the D-state contributions and no information on the high momentum S-state components was obtained.

To examine higher momentum S-state components we have measured the $^{40}Ca(p,p\alpha)^{36}Ar$ reaction in which the ground state transition is pure $L=0$. Furthermore, the selection of a heavier target permits an examination of the influence of noncoplanar geometries under more severe distortion conditions. In particular, one can examine the data for evidence of pole cap interference such as that suggested by Jacob and Maris.[6]

The experiment was carried out using a 101.3 ± 0.5 MeV proton beam from the University of Maryland Isochronous Cyclotron. The momentum analyzed beam ($\Delta p/p \simeq 0.02\%$) was focused at the center of a 1.5 m diameter scattering chamber on a 0.74 mg/cm^2 self-supporting natural Ca target. The proton detector telescope consisted of a 500 μm silicon surface barrier ΔE detector followed by a 15 mm hyperpure germanium E detector, placed at an angle of 70° with the beam and subtending a solid angle of 5.2 msr. On the opposite side of the beam, three α-detector telescopes were mounted on a precision out-of-plane device set at an in-plane angle of 45.7°. This angle pair was chosen because it is a quasifree angle pair for coplanar measurements. The three α telescopes, separated vertically by out-of-plane angles β of 10°, consisted of 100 or 200 μm Si ΔE followed by 3 or 5 mm Si(Li) E detectors, each subtending a solid angle of 0.83 msr. Two sets of measurements were made, one with $\beta = 0°$, $10°$, and $20°$ and another with $\beta = -5°$, $+5°$, and $15°$. The $-5°$ and $+5°$ data were identical within statistics and were summed.

All ΔE-E coincidences were handled with fast electronics such that individual beam bursts could be separated. For the p-α coincidences, a time-to-amplitude converter (TAC), started by the proton fast ΔE signal and stopped by the α fast ΔE signals, was used for simultaneous storage of real and random coincidences. The amplified linear signals, gated by the respective coincidences, were fed to 4096 channel analog-to-digital converters interfaced to an IBM 360/44 computer. All particle identifications were carried out by software. Pulser signals fed to all preamplifiers and analyzed together with the data served as monitors for dead time.

Energy sharing distributions (cross section as a function of outgoing proton energy) for the

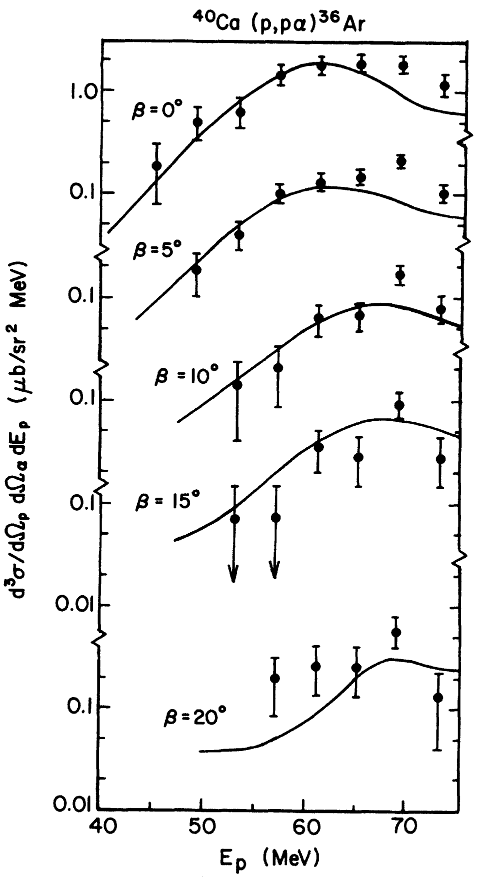

FIG. 1. Energy sharing distributions for the ^{40}Ca($p,p\alpha$)^{36}Ar(g.s.) reaction at 101.3 MeV. The in-plane angles are $\theta_p = 70.0°$ and $\theta_\alpha = -45.7°$, and β represents the out-of-plane angle. The curves are DWIA calculations with a bound state potential radius parameter of $r_0 = 1.3$ normalized at a single point.

^{40}Ca($p,p\alpha$)^{36}Ar(g.s.) reaction at five out-of-plane angles from 0° to 20° were obtained for proton energies ranging from 45 to 70 MeV. The data, summed over 4-MeV bins, are shown in Fig. 1. The data show a smooth variation both with proton energy and out-of-plane angle. The shape of the energy sharing distributions show the characteristics of an S-state quasifree knockout reaction, except for some enhancement near 70 MeV, which appears to result from the sequential α decay of states in ^{40}Ca excited by inelastic scattering.

The data were analyzed using a factorized form of the DWIA, in which the triple differential cross section for ($p,p\alpha$) reactions can be written as

$$d^3\sigma/d\Omega_p d\Omega_\alpha dE_p = S_\alpha F_k \frac{d\sigma}{d\Omega_{p-\alpha}} \sum_\lambda |T_L^\lambda|^2 ,$$

where S_α is the α-spectroscopic factor, F_k is a known kinematic factor, and $(d\sigma/d\Omega)_{p\text{-}\alpha}$ represents the p-α interaction. The distorted momentum distribution is $\sum_\lambda |T_L^\lambda|^2$, where

$$T_L^\lambda = (2L+1)^{-1/2} \int \chi_p^{(-)*}(\vec{r})\,\chi_\alpha^{(-)*}(\vec{r})\,\phi_L^\lambda(\vec{r})\,\chi_p^{+}\left(\frac{B}{A}\vec{r}\right) d\vec{r} .$$

The χ's are distorted waves for the incoming and outgoing particles and ϕ_L^λ is the momentum wave function of the α cluster in the target nucleus. The DWIA calculations were carried out with the code THREEDEE written by Chant.[7]

The bound α-cluster wave function was approximated by an eigenfunction of a Woods-Saxon potential well with an energy eigenvalue equal to the separation energy of the α particle from the target nucleus. The principal quantum number of the bound state wave function was chosen on the basis of the conservation of oscillator shell model quanta for the ($2s1d$) shell giving a $5S$ cluster wave function.

The potential parameters used in the calculations are those of Ref. 4. For comparison with transfer reactions, initial calculations were carried out using the bound state parameters ($r_0 = 1.30$, $a_0 = 0.65$) employed by Anantaraman *et al.*[8] The proton parameters were obtained from the global analysis of Nadasen *et al.*[9] For the α potentials, the values derived by Carey[4] from the compilation of Perey and Perey[10] were used. An extensive study of the sensitivity of the calculations to both the distorting and bound state parameters by Carey[4] clearly indicated that the above choice of parameters provided results consistent with ($p,p\alpha$) reactions and transfer reactions on a wide range of targets.

The results of these calculations with the same normalization for all out-of-plane angles are shown as solid lines in Fig. 1. Except for the enhancement around 70 MeV (presumably due to sequentials), the data are fairly well reproduced both in shape and absolute normalization for all out-of-plane angles. Clearly, the noncoplanar $(p,p\alpha)$ data are well described by the distorted wave impulse approximation. Somewhat disappointingly, neither the data nor the calculation exhibit any special effects arising from distortion, such as "pole cap" contributions.

The absolute spectroscopic factor obtained for this bound state geometry ($S_\alpha = 0.86$) is a factor of 20 higher than s-d configuration shell model calculations,[11] indicating a much stronger clustering of α particles than theoretical predictions. These results are in excellent agreement with the value obtained by Carey,[4] and are more similar to the values of 0.38 and 1.59 obtained in studies of the reactions $(d,{}^6\mathrm{Li})$ and $({}^6\mathrm{Li},d)$, respectively.[8,12] Carey *et al.* have noted an enhancement of the spectroscopic factor at the closed shells of ^{16}O

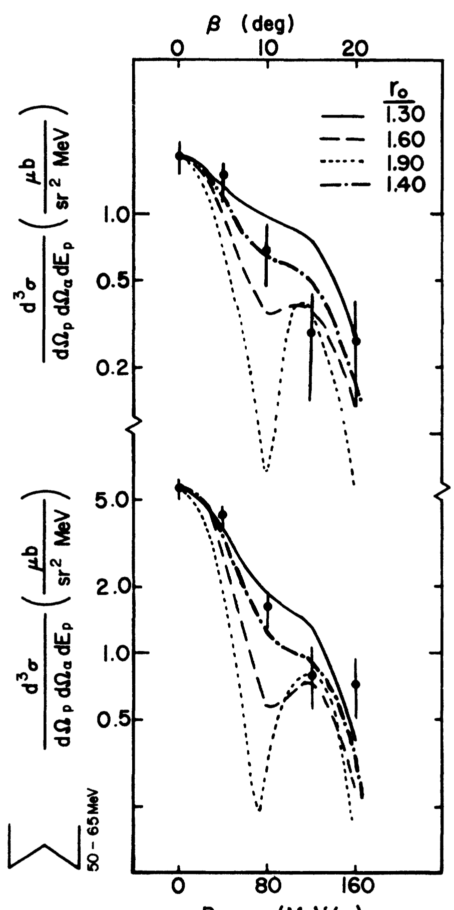

FIG. 2. The differential cross sections for fixed $E_p = 65$ MeV and the sum of the differential cross sections for $E_p = 50$–65 MeV plotted as a function of recoil momentum or out-of-plane angle β. The curves are DWIA calculations for different bound state potential radii normalized at $p_{\mathrm{recoil}} = 0$.

and ^{40}Ca. Two-particle–two-hole and four-particle–four-hole admixtures in these ground states, not contained in the shell model calculations, may lead to this enhancement. The $(p,p\alpha)$ reaction should be sensitive to these admixtures since not only do these terms enter coherently but also they involve 6S and 7S α-cluster wave functions which produce larger cross sections than the 5S wave function.

It can thus be concluded the $(p,p\alpha)$ knockout reactions analyzed by means of the DWIA can provide information on nuclear structure and reactions for low as well as high momentum components of α clustering in nuclei with the aid of coplanar and noncoplanar measurements. In particular, we find that the high momentum transfer (~150–200 MeV/c) $(p,p\alpha)$ reactions are well described by the DWIA and that the extracted spectroscopic factors are in agreement with low momentum transfer $(p,p\alpha)$ reaction and the very high momentum transfer $({}^6\mathrm{Li},d)$ and $(d,{}^6\mathrm{Li})$ reactions.

The major uncertainty in the extraction of spectroscopic factors from the $(p,p\alpha)$ reaction (as well as transfer reactions) lies in our uncertainty in the bound cluster wave function. Carey *et al.*[4] have shown the strong sensitivity of the DWIA calculations to the bound state potential radius. Changes of 10% in the radius lead to a factor of 2 change in the cross section and thereby in the extracted spectroscopic factor. As discussed in the introduction, we hope that the present noncoplanar data better define the higher momentum components of the wave function, thus better defining the bound state potential geometry.

To more carefully examine the out-of-plane dependence, we have plotted in Fig. 2 (upper portion) the cross section for 65 MeV outgoing proton energy, corresponding to the minimum value of recoil momentum, as a function of recoil momentum. Also shown are the DWIA calculations for four different bound state potential radii normalized at $p_{\mathrm{recoil}} = 0$. It is clear that the calculations are very sensitive to the geometry. Setting the distorting parameters equal to zero indicates that the minima arise from nodes in the cluster wave function, slightly shifted and filled in by distortion effects. It should be noted that calculations of the in-plane energy sharing distribution with these same wave functions show no evidence of these nodes, supporting our supposition that the noncoplanar results are much less sensitive to distortion effects. A comparison of the calculations to the data suggests a radius parameter $r_0 \simeq 1.4$ fm. However, the statistical uncertainty in the data greatly limits our ability to be more quantitative. In an attempt to improve this comparison we have summed both the data and the calculations over the range $E_p = 50$ to 65 MeV. This energy range was chosen to avoid the sequential contributions in the data near 70 MeV. The summed results are also presented in Fig. 2 (lower portion). Again, a radius parameter of approximately $r_0 = 1.4$ fm appears to be most suitable for ^{40}Ca. The use of this geometry reduces the extracted spectroscopic factor by about a factor of 2, still significantly larger than simple shell model calculations.

In conclusion, the present study of the noncoplanar $(p, p\alpha)$ reaction shows improved sensitivity to higher momentum components due to reduced distortion effects, allowing better definition of the cluster-core wave function and hence a more reliable value for the absolute spectroscopic factor. Thus, the measurement of $(p, p\alpha)$ reactions in a noncoplanar geometry can provide useful quantitative nuclear structure information on α clustering in nuclei.

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