Analyzing power of the ^{40}Ca($\vec{p}$, $p\alpha$) reaction at 100 MeV

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Analyzing powers have been measured for the ^{40}Ca($\vec{p}$, $p\alpha$)^{36}Ar reaction at an incident energy of 100 MeV for coplanar scattering angles corresponding to zero recoil momentum of the residual nucleus. Predictions based on the distorted wave impulse approximation fail to reproduce the data.

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The cluster structure of nuclei has been a subject of study for many years. Since a free α particle is a relatively stable configuration of four nucleons, it is tempting to postulate the existence of α clusters in nuclei. The question is then whether one should consider these clusters as real entities, or merely as a convenient way of handling many-body calculations for describing the relevant observables successfully.

The most direct experimental method to test the notion of ground state α-clustering in nuclei is by means of a knockout reaction in which the knocked out cluster is observed in coincidence with the projectile. The assumption that clusters of nucleons exist in nuclei would be strongly supported if the momentum distribution of the clusters as inferred from the coincidence spectra of emitted particles is in agreement with that expected from a preformed cluster bound in a target nucleus. In addition the absolute spectroscopic factors extracted from the coincidence results should be in agreement with the theoretical expectation.

The alpha cluster structure of the ground state wave function of the light nuclei ^{6}Li, ^{7}Li, ^{9}Be, and ^{12}C has been fairly extensively studied by means of the (p, $p\alpha$) quasifree reaction at energies between 100 MeV and 296 MeV [1–5]. Based on the good shape agreement between distorted wave impulse approximation (DWIA) calculations and experimental energy sharing differential cross section data, as well as agreement between extracted spectroscopic values and theoretical predictions thereof, it was concluded that the reaction is a quasifree process. Such a conclusion is consistent with the existence of preformed α clusters in light nuclei.

For heavier targets it has also been shown that the DWIA provides an appropriate description of the reaction. Carey *et al.* [6] investigated the ground state (p, $p\alpha$) reaction at an incident energy of 100 MeV at quasifree kinematics (i.e., kinematics where knockout of alpha particles at rest in the target nucleus is kinematically accessible) for a range of target nuclei heavier than ^{12}C (^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca, ^{48}Ti, ^{54}Fe, and ^{66}Zn). DWIA calculations successfully described experimental energy sharing cross section distributions. Similar conclusions followed studies of the ^{40}Ca(p, $p\alpha$) reaction for noncoplanar kinematics [7].

In addition, Carey *et al.* also found a remarkable similarity of the relative spectroscopic factors extracted from (p, $p\alpha$) and (^{6}Li, d) reactions for target nuclei covering a large mass range across the periodic table. In view of the crucial differences between a knockout and transfer reaction with respect to kinematics, reaction dynamics and optical potentials, Carey *et al.* concluded that the observed similarity points to a real cluster structure of these nuclei.

However, the ability to reproduce experimental analyzing powers A_y acts as a more stringent test of the reaction dynamics [5]. This sensitivity was clearly illustrated for the ^{58}Ni(p, α) reaction at an incident energy of 72 MeV [8], where it was shown that although the theoretical cross section angular distributions for events in the continuum are very similar for either a pickup or knockout based multistep reaction, the theoretical analyzing power distributions are very different and clearly identify the ^{58}Ni(p, α) reaction in the continuum to be a multistep process based on a knockout reaction.

In addition, DWIA cross sections are sensitive to inaccuracies in the often poorly known optical potentials used to generate wave functions of composite particles with nuclei, thus affecting the absolute value [9] and shape of the calculated cross sections. On the other hand, for the zero recoil kinematics of interest, it has been shown for the ($\vec{p}$, $2p$) reaction that the exclusive analyzing power of quasifree scattering is insensitive to the detail of the optical potential [10,11].

Indeed, if the reaction is driven by a quasifree knockout mechanism, one expects the analyzing power at the quasifree peak to correspond to that of free p-α elastic scattering. Wang *et al.* [3] illustrated that the analyzing powers for the ^{9}Be(p, $p\alpha$) reaction at 150 MeV correspond to free

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p-α elastic scattering data, thus confirming the existence of ground state α clusters inferred from cross section studies.

Analyzing power results for the $(p, p\alpha)$ reaction in the energy range 100–300 MeV exists only for light nuclei up to ^{12}C. In order to extend the results to heavier nuclei it was decided to investigate the ^{40}Ca$(p, p\alpha)$ reaction at 100 MeV. The choice of target was based on the relative spectroscopic factor results of Ref. [6], which suggest that, for nuclei in the medium mass range, the probability of alpha cluster formation approaches a local maximum for the ^{40}Ca nucleus.

The experimental work was performed at the separated sector cyclotron facility of the iThemba Laboratory for Accelerator Based Sciences, Faure, South Africa. A proton beam of energy 100 MeV, polarized normal to the scattering plane and with beam intensities of up to 30 nA, was delivered to the magnetic spectrometer experimental area. The beam polarization was switched from up to down at 10 s intervals in order to minimize systematic errors in analyzing power measurements. The degree of beam polarization was determined with a polarimeter in the high energy beamline leading to the various experimental areas. The polarimeter consisted of a CH_2 target and two NaI(Tl) detectors and utilized the known analyzing power of elastic scattered protons from ^{12}C. The deterioration of beam quality due to the presence of this target precluded continuous monitoring of the beam polarization. However, as it was found to be relatively stable for periods of a few hours, beam polarization was measured every two hours. Typically the polarization ranged between 70% and 80%, with the difference in the polarization between the two orientations being routinely less than 6%, and always less than 15%. The targets used were self-supporting natural ^{40}Ca foils of thicknesses $\approx$2.0–2.7 mg cm^{-2}, which was sufficiently thin to allow for a clean separation between the ground state and the 2^+ first excited state at 1.970 MeV.

Protons were detected with a 5.8 msr $K = 600$ QDD magnetic spectrometer, where K is the well-known magnetic spectrometer constant. The coincident alpha particles were detected with a 2.36 msr ΔE-E detector telescope. These detectors were mounted coplanar on opposite sides of the incident beam. The detector telescope consisted of a 30 μm thick Si surface barrier ΔE detector, followed by a 2000 μm thick Si surface barrier E detector. A 1000 μm thick silicon surface barrier detector, mounted behind the ΔE-E telescope, was used to veto high energy proton events. Due to the limited size of the proton momentum range accessible with the magnetic spectrometer, only those coincidence events at or very close to the quasifree peak were detected. Analyzing powers were measured for the ^{40}Ca$(\vec{p}, p\alpha)$ reaction at 100 MeV for six different coplanar quasifree angle pairs in order to obtain a center-of-mass scattering angle $\theta_{\text{c.m.}}$ distribution in the proton-alpha rest frame. The kinematics measured, with $\theta_{\text{c.m.}}$ ranging from 64.8° to 103.2°, represents the accessible range where the energy of the α particles is high enough to allow them to pass through the ΔE Si detector, and where the cross sections are high enough to make a measurement feasible within a reasonable time.

The ground state and first excited state are well separated, as shown in the binding energy spectrum in Fig. 1. The analyzing

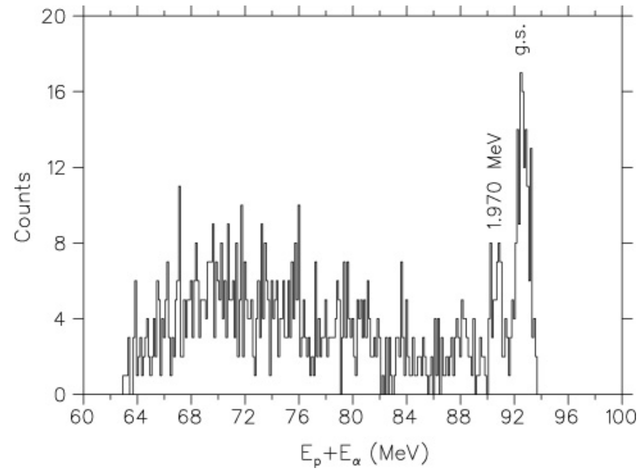

FIG. 1. A typical binding energy spectrum for the ^{40}Ca$(p, p\alpha)$ reaction at 100 MeV. The reaction Q-value is -7.04 MeV. The ground state and first excited state are clearly separated.

power is calculated as

$$A_y = \frac{C^{\uparrow} - C^{\downarrow}}{C^{\uparrow} p^{\downarrow} + C^{\downarrow} p^{\uparrow}}\ , \tag{1}$$

where $C^{\uparrow(\downarrow)}$ denotes the ground state quasifree scattering yield for upward (downward) polarized incident protons, and $p^{\uparrow(\downarrow)}$ represents the degree of upward (downward) polarization. Systematic errors in the analyzing power, due to uncertainty in the measured polarization, were found to be negligible compared to the statistical errors to the analyzing power.

Theoretical predictions were performed within the framework of the DWIA [12] with the code THREEDEE [13]. The optical potential, as parametrized by Cooper *et al.* [14], was used to calculate the distortion of the incoming and outgoing proton wave functions, while the ^{36}Ar-α interaction was approximated with an optical potential obtained from Carey *et al.* [6]. The radial part of the single particle bound state wave function was generated as a solution of the Schrödinger equation with a Woods-Saxon potential, with the parameters from Ref. [6]. The t-matrix elements of the two-body p-α interaction were approximated from p-α optical potential sets generated from p-α elastic scattering cross section data [15].

The choice of quasifree kinematics ensures that our analyzing power results are unlikely to be affected appreciably by final-state interactions. It was found that the theoretical calculation is quite insensitive to the details of the distorting optical potentials. In fact, a plane wave impulse approximation (PWIA) calculation yields results that are very similar to the DWIA calculation, as may be seen in Fig. 2. As mentioned earlier, this is not too surprising as it is known that the exclusive $(\vec{p}, 2p)$ analyzing power at the quasifree peak is relatively insensitive to the details of the distorting optical potential. The shape of the A_y distribution is thus mostly dependent on the details of the p-α interaction.

Previously measured data for coplanar studies of the ^{40}Ca$(p, p\alpha)$ reaction at 100 MeV [6] exist for cross sections only and only at $\theta_{\text{c.m.}} = 86°$. The results for the present

TABLE I. Comparison of cross section results at the peak of the quasifree momentum distribution for the $\theta_{c.m.} = 86^\circ$ measurement. The error represents the statistical error.

	Angle pair	Cross section (μb sr^{-2} MeV^{-1})
Carey *et al.* [6]	(70.0°;−45.7°	2.0 ± 0.3
Present study	(70.5°;−45.45°)	1.90 ± 0.19

study under similar experimental conditions are summarized in Table I, and are clearly in agreement within the statistical error.

Experimental and theoretical analyzing power results for the ^{40}Ca(p, $p\alpha$) reaction at 100 MeV are compared in Fig. 2 with free p-α analyzing power data at 100 MeV [16]. The DWIA and PWIA calculations that utilize the p-α potential parameter set at 100 MeV follow the trend displayed by the free p-α data, while the DWIA calculations for the p-α potential parameter set at 91 MeV fail to reach positive analyzing power values beyond $\theta_{c.m.} \approx 105^\circ$. Clearly, both the free p-α data as well as the various DWIA calculations disagree with the experimental ($\vec{p}$, $p\alpha$) analyzing power data.

It was observed in the cross-section studies of Refs. [6,17] that sequential decay processes appear to contaminate the ^{40}Ca($\vec{p}$, $p\alpha$) quasifree results only for excitation energies of the target nucleus below 30 MeV. This condition applies to the two A_y data points at and below $\theta_{c.m.} = 73^\circ$ in Fig. 2. However, these data points still follow the trend of the other four data points where such a contamination is of no concern. Similarly it can be seen in Ref. [5] that no clear signature of sequential decay is evident in the energy sharing analyzing power data, and that the trend established by the uncontaminated data is simply continued into the region of possible sequential decay contamination.

Taking this into account we conclude that the significant difference in the trend displayed by the six ^{40}Ca(p, $p\alpha$) data points on the one hand, and the theoretical calculations and free p-α analyzing power data on the other hand, illustrate that quasifree scattering is an inadequate description of the reaction mechanism. Such a conclusion casts doubt on the notion of preformed alpha particle clusters in the ^{40}Ca nucleus. While the successful prediction of the cross section results [6] has proven useful in the estimation of knockout contributions to other reactions (see, e.g., Ref. [18]), the reaction mechanism is clearly not understood.

Evidence for such an inconsistency between the apparent reaction mechanisms as suggested by cross section and analyzing power results was indeed seen in an earlier study by Yoshimura *et al.* [5]. It was found that DWIA calculations reproduce energy sharing analyzing power distributions fairly well for the (p, $p\alpha$) reaction at 296 MeV for the targets ^{6}Li, ^{7}Li, and ^{9}Be, but not for the case of ^{12}C. In contrast to findings based solely on cross section data [1,5] the differences between

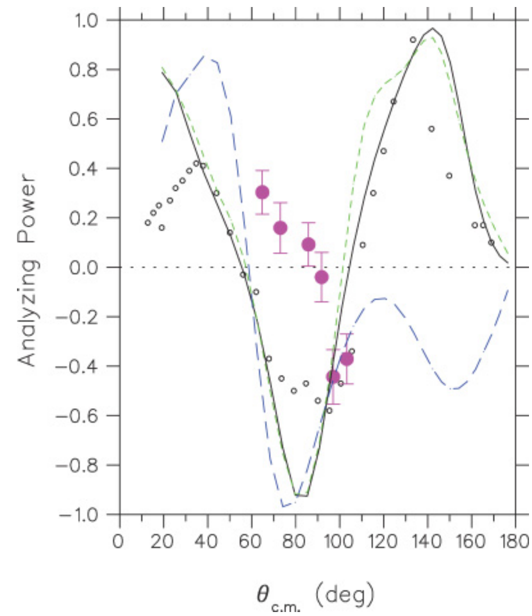

FIG. 2. (Color online) Analyzing powers for the ^{40}Ca($\vec{p}$, $p\alpha$) reaction at 100 MeV, represented by the six filled circles, are displayed as a function of the two-body center-of-mass p-α scattering angle. The error bars denote the statistical error. The small empty circles represent free p-α analyzing power data at 100 MeV [16]. The solid and dashed lines represent DWIA calculations for the Van Oers [15] p-α potential parameter set at 100 MeV and an interpolated parameter set at 91 MeV, respectively. The small-dashed line represents a PWIA calculation with the 100 MeV p-α potential parameter set.

the experimental analyzing power and the DWIA calculations for the ^{12}C(p, $p\alpha$) reaction at 296 MeV suggest significant contributions from processes other than quasifree scattering [5]. However, one has to keep in mind that the energy resolution of that particular measurement was such that the ground state and first excited states could not be resolved, which could shed some doubt on whether the theoretical cross sections were added in the proper proportions for the corresponding analyzing power predictions. A higher resolution study of the ^{12}C(p, $p\alpha$) analyzing power is required in order to address this particular inconsistency.

In conclusion, analyzing powers for the ^{40}Ca($\vec{p}$, $p\alpha$)^{36}Ar reaction were obtained at an incident energy of 100 MeV for different quasifree angle pairs in order to obtain data at zero recoil momentum of the residual nucleus for different two-body p-α scattering angles. Although the DWIA theory adequately describes experimental cross section distributions, it fails to predict the analyzing power data. This study represents the first investigation of the analyzing power on a target as heavy as ^{40}Ca.

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[1] P. G. Roos, N. S. Chant, A. A. Cowley, D. A. Goldberg, H. D. Holmgren, and R. Woody, Phys. Rev. C **15**, 69 (1977).

[2] A. Nadasen, N. S. Chant, P. G. Roos, T. A. Carey, R. Cowen, C. Samanta, and J. Wesick, Phys. Rev. C **22**, 1394 (1980).

[3] C. W. Wang, P. G. Roos, N. S. Chant, G. Ciangaru, F. Khazaie, D. J. Mack, A. Nadasen, S. J. Mills, R. E. Warner, E. Norbeck, F. D. Becchetti, J. W. Janecke, and P. M. Lister, Phys. Rev. C **31**, 1662 (1985).
[4] A. Nadasen, P. G. Roos, N. S. Chant, C. C. Chang, G. Ciangaru, H. F. Breuer, J. Wesick, and E. Norbeck, Phys. Rev. C **40**, 1130 (1989).
[5] T. Yoshimura, A. Okihana, R. E. Warner, N. S. Chant, P. G. Roos, C. Samanta, S. Kakigi, N. Koori, M. Fujiwara, N. Matsuoka, K. Tamura, E. Kubo, and K. Ushiro, Nucl. Phys. **A641**, 3 (1998).
[6] T. A. Carey, P. G. Roos, N. S. Chant, A. Nadasen, and H. L. Chen, Phys. Rev. C **29**, 1273 (1984).
[7] A. Nadasen, P. G. Roos, N. S. Chant, A. A. Cowley, C. Samanta, and J. Wesick, Phys. Rev. C **23**, 2353 (1981).
[8] R. Bonetti, F. Crespi, and K.-I. Kubo, Nucl. Phys. **A49**, 381 (1989).
[9] P. E. Hodgson and E. Běták, Phys. Rep. **374**, 1 (2003).
[10] C. A. Miller, K. H. Hicks, R. Abegg, M. Ahmad, N. S. Chant, D. Frekers, P. W. Green, L. G. Greeniaus, D. A. Hutcheon, P. Kitching, D. J. Mack, W. J. McDonald, W. C. Olsen, R. Schubank, P. G. Roos, and Y. Ye, Phys. Rev. C **57**, 1756 (1998).
[11] R. Neveling, A. A. Cowley, G. F. Steyn, S. V. Förtsch, G. C. Hillhouse, J. Mano, and S. M. Wyngaardt, Phys. Rev. C **66**, 034602 (2002).
[12] N. S. Chant and P. G. Roos, Phys. Rev. C **27**, 1060 (1983).
[13] N. S. Chant and P. G. Roos, program THREEDEE, University of Maryland (unpublished).
[14] E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, Phys. Rev. C **47**, 297 (1993).
[15] W. T. H. van Oers, B. T. Murdoch, B. K. S. Koene, D. K. Hasell, R. Abegg, D. J. Margaziotis, M. B. Epstein, G. A. Moss, L. G. Greeniaus, J. M. Greben, J. M. Cameron, J. G. Rogers, and A. W. Stetz, Phys. Rev. C **25**, 390 (1982).
[16] A. Nadasen, P. G. Roos, D. Mack, C. Ciangaru, L. Rees, P. Schwandt, K. Kwiatkowski, R. E. Warner, and A. A. Cowley, IUCF Scientific and Technical Report, No. 13, 1983 (unpublished).
[17] T. A. Carey, P. G. Roos, N. S. Chant, A. Nadasen, and H. L. Chen, Phys. Rev. C **23**, 576 (1981).
[18] J. Carter, A. A. Cowley, H. Diesener, R. W. Fearick, S. V. Förtsch, J. J. Lawrie, P. von Neumann-Cosel, J. V. Pilcher, A. Richter, K. Schweda, G. F. Steyn, and S. Strauch, Phys. Rev. C **63**, 057602 (2001).