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Sensitivity of Analyzing Power to Details of the Reaction Mechanism of Cluster Knockout

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Abstract. Recently the analyzing power of the reaction ^{12}C(p,$p\alpha$)^{8}Be under quasifree kinematic conditions was investigated at an incident energy of 100 MeV. A distorted-wave impulse approximation (DWIA) theoretical expression formally shows a convolution of the two-body projectile-cluster matrix, on the one hand, with the interaction of the light particles and the core of the target system, on the other hand. However, it is found that, to a remarkable extent the analyzing power angular distribution resembles free ^{4}He$(p,p)^{4}$He elastic scattering. This behaviour of the analyzing power requires an unexpected degree of factorization of the knockout cross section. Explicit DWIA calculations reveal that this outcome is, fortuitously, true to a very good approximation. Clearly, the spin-orbit interaction in the distorted waves is simply too weak to retain the convoluted structure of the formal theoretical expression in this case. Theoretical calculations predict that the same considerations as in the case of the (p,$p\alpha$) reaction on the target nucleus ^{12}C should also hold for ^{40}Ca at the same incident energy, but this is not found experimentally. It is shown that, in the case of ^{40}Ca, the deviation of the analyzing power angular distribution from a simple trend is explained if the well-known anomalous large angle scattering effect of the outgoing α-particles with the heavy residual nucleus is taken into account.

1 Introduction

Nucleon-induced knockout reactions are useful to unravel details of the intranuclear nucleon-nucleon interaction, and considerable progress has been made towards the appropriate theoretical formulation to achieve this objective. Correlated nucleon groups, such as α-clusters are also of interest, consequently an understanding of the reaction mechanism of cluster knockout is crucial.

In an extensive study Roos *et al.* [1] have shown that the $(p, p\alpha)$ reaction at an incident energy of 100 MeV on light nuclei can be described fairly accurately in terms of a distorted wave impulse approximation (DWIA) theory [2]. It was demonstrated that, due to the flexibility offered by three-body kinematics in the final state, the knockout reaction is more versatile than a pickup reaction. Of course, in principle the latter reaction type has access to the same spectroscopic and dynamic information, but due to momentum matching requirements it is not possible in that case to disentangle the two-body projectile-cluster interaction from the details of the bound cluster in the target system. On the other hand, by a careful choice of kinematic arrangement, in a knockout experiment it is possible to either keep the cluster spectroscopic information at a fixed selection while the two-body angular distribution is explored, or keep the latter at a specific condition while the momentum distribution of the cluster bound in the target is investigated.

Carey *et al.* [3] investigated the $(p, p\alpha)$ reaction on a larger range of target masses, and again it was found that the DWIA description of the reaction appears to be sound. In addition, results were found to be consistent with those from pickup and stripping studies, and also more or less with shell-model estimates of α-clustering in the ground state of atomic nuclei.

Investigations with polarized projectiles are expected to be more sensitive to details of the reaction mechanism than unpolarized experiments. Such studies were performed in a number of cases [4–8]. It was found that in the majority of cases [4–7], on target masses up to ^{12}C, the two-body intranuclear interaction retains the angular distribution of free p-^{4}He elastic scattering of both the cross section and analyzing power. This is a very surprising result, especially if one keeps in mind that when spin-orbit interactions are included in the DWIA theory [9], the factorization of the knockout cross section into a two-body half-shell cross section and a distorted momentum distribution strictly no longer holds. Therefore it is tempting to ascribe the difference between the intranuclear p-α analyzing power distribution and free scattering encountered [8] for the reaction ^{40}Ca$(p, p\alpha)^{36}$Ar as a breakdown of the factorization due to the spin-orbit potentials of the protons in the incoming and outgoing channels of the knockout reaction.

In this work results on the $(p, p\alpha)$ reaction will be reviewed and it will be shown that a consistent description of all experiments, especially recent polarized studies, is obtained. The initial failure of the DWIA to reproduce the analyzing power angular distribution for the ^{40}Ca$(p, p\alpha)^{36}$Ar reaction is due to the simple reason that the global optical model parameters which were originally employed [8] to generate distorted waves for the outgoing α-^{36}Ar interaction are, in retrospect, clearly inappropriate.

2 Theoretical Details

We use the notation of Chant and Roos [9] by writing a knockout reaction as $A(a, cd)B$ in general, where $A = B+b$ and c is the quasifree-scattered projectile a after an interaction with the bound particle b, which is emitted from the target nucleus as particle d. When applied to a $(p, p\alpha)$ reaction, this means that $b = d$, which is a spinless particle, and $a = c$.

The differential cross section for such a reaction is expressed by Chant and Roos as

$$\frac{d^3\sigma}{d\Omega_c d\Omega_d dE_c} =$$
$$= S_\alpha F_K \sum_{\rho_c' L\Lambda} \Big| \sum_{\rho_a \sigma_a \sigma_c \sigma_c'} D^{s_a}_{\rho_a \rho_a'}(R_{ap}) D^{s_a^*}_{\sigma_c \sigma_c'}(R_{ac}) T^{L\Lambda}_{\sigma_a \sigma_c' \rho_a \rho_c'} \langle \sigma_c | t | \sigma_a \rangle \Big|^2 , \quad (1)$$

where S_α is a spectroscopic factor, F_K is a kinematic factor, the $D's$ are rotation matrices and $\langle \sigma_c | t | \sigma_a \rangle$ denotes the matrix element of the two-body p-α transition operator.

The quantity $T^{L\Lambda}_{\sigma_a \sigma_c' \rho_a \rho_c'}$ is expressed as

$$T^{L\Lambda}_{\sigma_a \sigma_c' \rho_a \rho_c'} = (2L+1)^{-1/2} \int \chi^{(-)*}_{\sigma_c' \rho_c'}(\mathbf{r}) \chi^{(-)*}_a(\mathbf{r}) \phi_{L\Lambda}(r) \chi^{(+)}_{\sigma_a' \rho_a}(\gamma \mathbf{r}) d\mathbf{r} \ , \quad (2)$$

where $\gamma = A/B$, $\chi's$ represent the distorted waves for the incoming and outgoing particles, $\phi_{L\Lambda}$ is the bound state wave function of the α-cluster in the target nucleus which represents the projection of the target wave function on the product of α-cluster and residual nucleus wave functions. The detailed notation of Eq. 1 is provided in Refs. [2, 9].

As is known, when spin-orbit terms are omitted in the distorting potentials for the protons (projectile and ejectile), the triple differential cross section reduces to the factorized form for the $(p, p\alpha)$ reaction

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p} = S_\alpha F_K \left\{ \sum_\Lambda |T^{\alpha L\Lambda}_{BA}|^2 \right\} \left. \frac{d\sigma}{d\Omega} \right|_{p-\alpha} , \quad (3)$$

where $\left. \frac{d\sigma}{d\Omega} \right|_{p-\alpha}$ is a half-shell two body cross section for p-α scattering. The distorted momentum distribution for an α-cluster in the target is the quantity $\sum_\Lambda |T^{\alpha L\Lambda}_{BA}|^2$.

In order to investigate to what extent factorization holds when spin-orbit forces are not neglected, the experimental $(p, p\alpha)$ cross section is divided by quantities which remain approximately fixed by a proper choice of kinematic conditions. To be more specific, we measure cross section data at angles and emission energies such that zero recoil of the heavy residual nucleus is kinematically allowed, yielding a quantity which is proportional to the two-body projectile-cluster cross section, as in the following expression:

$$\left. \frac{d\sigma}{d\Omega} \right|_{p-\alpha} = \left[\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p} \right]_{\text{EXP}} \Bigg/ S_\alpha F_K \left\{ \sum_\Lambda |T^{\alpha L\Lambda}_{BA}|^2 \right\} \ , \quad (4)$$

where $\left[\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p} \right]_{\text{EXP}}$ now represents the experimental (p,$p\alpha$) cross section. Exploring the angular distribution of the constructed quantity in the centre-of-mass of the colliding particles, and establishing how closely it follows free elastic scattering of protons from ^{4}He at the same incident energy, we are able to investigate to what extent the cluster reacts as a free entity to the projectile.

In the DWIA the coincident analyzing power for the $(p,p\alpha)$ reaction is given by

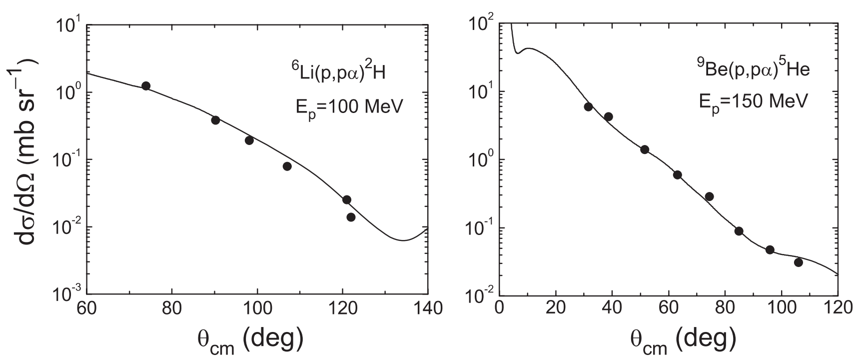
$$A = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}, \tag{5}$$

where $\sigma^{\uparrow(\downarrow)} \equiv \left[\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p}\right]^{\uparrow(\downarrow)}$ corresponds to Eq. 1 for spin up $\uparrow$ or down $\downarrow$ respectively.

A correspondence between the coincident $(p,p\alpha)$ experimental analyzing power angular distribution and free scattering is a very sensitive test of factorization, although lack of similarity between the two sets of distributions should be interpreted with caution, as will be shown later.

3 Results and Discussion

Two-body projectile-cluster cross section angular distributions extracted from the experimental $(p, p\alpha)$ cross sections, corresponding to zero recoil momentum of the heavy residual nucleus in the knockout reaction, are shown in Figure 1



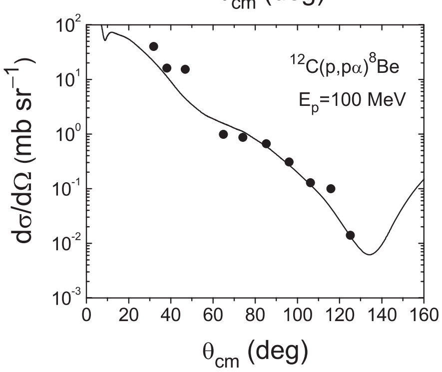


Figure 1. Intranuclear two-body projectile-cluster cross sections extracted from the $(p, p\alpha)$ reaction data (circles) at incident energies as indicated for targets ^{6}Li [1], ^{9}Be [4] and ^{12}C [6,7]. The lines are smooth curves through the p+^{4}He elastic scattering data of Refs. [10, 11], respectively, at incident energies of 100 and 150 MeV.

for the targets ^{6}Li [1], ^{9}Be [4] and ^{12}C [6]. These cross section angular distributions are compared with ^{4}He$(p,p)^4$He elastic scattering at the same incident energies. Clearly the projectile interaction with a bound α-cluster tracks the reaction with a free ^{4}He target remarkably well. Thus the spin-orbit potentials of the proton participating in the knockout process does not affect the factorization of the knockout cross section appreciably, and the knockout process proceeds as a quasifree scattering in which the spectator part of the target remains largely unaffected.

Analyzing power distributions for the $(p,p\alpha)$ reaction on ^{9}Be [4], ^{12}C [6] and ^{40}Ca [8] are displayed in Figure 2. As with the cross sections of Figure 1, analyzing power values were selected which correspond to zero recoil momentum of the heavy residual nucleus in the $(p,p\alpha)$ reaction. However, as opposed

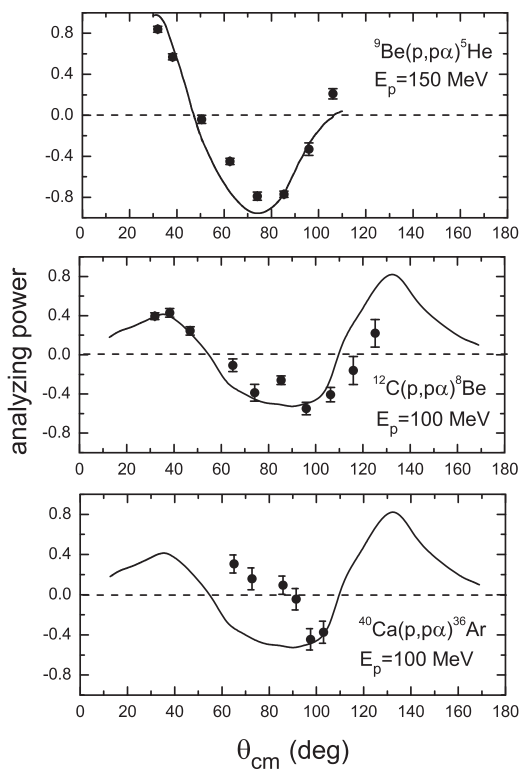


Figure 2. Analyzing power angular distributions for the $(p,p\alpha)$ reaction on ^{9}Be at an incident energy of 150 MeV, as well as ^{12}C and ^{40}Ca at 100 MeV (circles with statistical error bars). Results are displayed as a function of the two-body $p-\alpha$ centre-of-mass scattering angle. The curves represent smooth lines drawn through experimental analyzing power angular distribution for ^{4}He$(p,p)^4$He elastic scattering at the same incident energies from Refs. [10, 12].

to the cross sections, the analyzing powers are compared directly with the free p+^{4}He interaction. Of course, this is appropriate if factorization of the cross sections holds, as quantities that remain constant cancel in the analyzing power, which is a ratio of cross sections. On the other hand, it should be kept in mind that a crucial part of those quantities are related to the distorted momentum distribution, which although kept constant in the selection of the kinematic conditions, are nevertheless influenced by the spin orientation of the projectile. In other words there may be some influence on the analyzing power.

As is shown in Figure 2, the $(p, p\alpha)$ analyzing power distributions track the free ^{4}He$(p, p)^4$He elastic scattering quantities exceedingly well for the targets ^{9}Be and ^{12}C. For ^{40}Ca, however, the two distributions are very dissimilar. The unsuccessful attempt by Neveling *et al.* [8] to understand this result in terms of a DWIA calculation, was due the use of various standard optical potentials in the distorted waves, which of course all failed to reproduce the experimental distribution. As was pointed out, even if the cross section follows a simple factorization, the nuclear structure part, which is kept constant with respect to unpolarized projectiles in the experimental arrangement, would in principle still affect the analyzing power. This means that the results for the targets ^{9}Be and ^{12}C are actually the unusual cases.

Figure 3 displays DWIA predictions of analyzing power distributions for ^{12}C and ^{40}Ca. Initial calculations (solid curve for ^{12}C and dashed line for ^{40}Ca) correspond to a good agreement with the ^{12}C experimental distribution, and very poor for ^{40}Ca. Of course, this result is consistent with those shown in Figure 2 when $(p, p\alpha)$ results are compared with free scattering. From the work of Mabiala *et al.* [6] it is clear that for ^{12}C some sensitivity to cross sections comes from the choice of α-particle optical model potential set in DWIA calculations, with extremely low sensitivity to the proton potentials. Keeping this in mind, we are reminded that the "standard" α-particle optical potential which is employed in generating the dashed curve for ^{40}Ca in Figure 3 was chosen by Carey *et al.* [3], together with other preferred sets, precisely because those represent good average global sets for various incident energies and target masses. The residual nucleus in the ^{40}Ca$(p, p\alpha)^{36}$Ar reaction, however, is a nuclear species which suffers from so-called anomalous large elastic scattering, which the global potentials of Carey *et al.* [3] reproduce very poorly.

Use of appropriate potentials for ^{36}Ar$(\alpha, \alpha)^{36}$Ar in the required projectile energy range from Reidemeister *et al.* [13] results in the solid curve for ^{40}Ca in Figure 3, thus resolving the issue. Explicit DWIA calculations prove that due to its heavier target mass, ^{40}Ca is somewhat more sensitive to the exact distorting potentials than ^{12}C or ^{9}Be, but not excessively so. Nevertheless, it stands to reason that the use of an α-potential in the DWIA that fails to reproduce elastic scattering for a specific nucleus is clearly unacceptable.

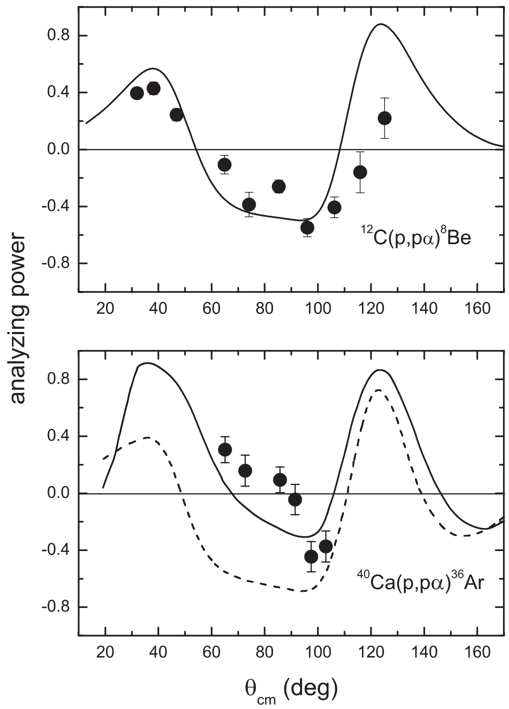


Figure 3. Analyzing power angular distributions for the $(p, p\alpha)$ reaction on ^{12}C and ^{40}Ca at an incident energy of 100 MeV (circles with statistical error bars). Results are displayed as a function of the two-body $p-\alpha$ centre-of-mass scattering angle. The curves represent results of DWIA calculations as described in the text.

4 Summary and Conclusion

The $(p, p\alpha)$ reaction at incident energies from 100 to 150 MeV was found to be dominated by a simple quasifree knockout mechanism in target nuclei ranging from atomic mass 6 to 40. Cross sections and analyzing power distributions follow characteristics of the projectile striking a preformed α-cluster, with the rest of the target nucleus acting mostly as a spectator to the projectile-cluster collision. Early concerns about results from ^{40}Ca$(p, p\alpha)^{36}$Ar are resolved when optical model distorting potentials that accurately describe α-^{36}Ar elastic scattering are introduced in a DWIA model.

This study demonstrates that especially analyzing power measurements offer a powerful method to determine the dominant reaction mechanism by means of which cluster knockout reactions proceed. Clearly an understanding of the reaction mechanism of knockout reactions is useful in the attempt to extract spectroscopic information and α-cluster preformation probabilities in the ground state of atomic nuclei.

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