Quasifree alpha cluster knockout studies

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Abstract. Cluster-like structures in the shell-model description of the ground state of nuclei can be conveniently studied by means of knockout reactions. Of these the (p, $p\alpha$) reaction is perhaps the simplest, especially from the viewpoint of the tractability of theoretical calculations used to interpret experimental results. Analyzing power angular distributions, which are simple ratios of cross sections, are investigated, as these are expected to be very sensitive to details of the reaction mechanism. The distorted wave impulse approximation (DWIA) is a versatile theory which is applicable to knockout reactions. Fortunately its results appear to be reasonably insensitive to uncertainties in the exact ingredients, such as distorting optical potentials, which are obtained from unrelated elastic scattering studies. It is shown that surprisingly simple approximations in the DWIA hold for α–cluster knockout from light nuclei. Furthermore, results for a medium-mass nuclear target such as ^{40}Ca are also consistent with expectation if the appropriate distorting optical potentials for the outgoing α–particle are employed in the DWIA formulation.

1. Introduction

Spectroscopic factors for pickup, stripping and knockout of α–clusters from and to the ground state of atomic nuclei appear to be in reasonable agreement with shell model estimates, for example as shown by Chung *et al.* [1]. Knockout, such as (p, $p\alpha$) reactions to the ground state of the final residual nucleus, offer a convenient experimental technique to study such cluster-like subsets of normal shell model wave functions. The virtue of knockout experiments is that the intrinsic three-body kinematics in the exit channel can be selected in such a way that the nuclear α-cluster structure of the target nucleus can be studied separately from the two-body projectile-cluster interaction. This feature is in strong contrast with either pickup or stripping reactions, for which the nuclear structure is convoluted with the reaction part, which complicates interpretation of experimental results. More specifically, in knockout experiments the angles and energies of the observed outgoing light ejectiles can be varied in such a way that the residual nucleus always remains at rest. This so-called quasi-free angle pair setup allows the proton-α two-body interaction to be studied and to be directly compared with free scattering of protons from ^{4}He. Alternatively, the geometry can be adjusted to keep the two-body kinematic condition fixed in order to investigate the momentum distribution of α–clusters in the ground state of the target nucleus. In this work the emphasis will be on the two-body aspect of the knockout reaction.

A schematic diagram of the knockout process is shown in figure 1. The upper vertex in the diagram represents the projectile α-cluster interaction, and the lower vertex accounts for the cluster structure of the target nucleus. Of course, in a theoretical treatment distorted waves, which are required to reproduce elastic scattering, are used to take interactions in the incident and outgoing channels into account (not explicitly shown in the diagram).

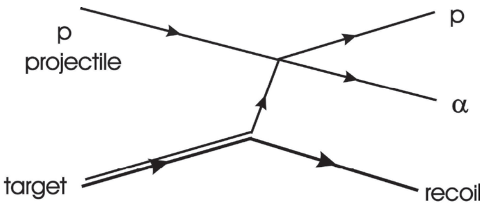

Figure 1: Schematic diagram of the knockout process.

An angular distribution of the analyzing power, which represents a measure of the left-right asymmetry experienced in the scattering of a spin-polarized projectile, for the (p,$p\alpha$) reaction on ^{12}C [2] will be compared with the results of the target nucleus ^{40}Ca [3]. The coincident analyzing power distribution, which is strongly influenced by the collision of the projectile with the α–cluster bound in the target ^{12}C, retains the characteristic features of the corresponding observables of ^{4}He(p,p)^{4}He elastic scattering at the same incident energy to a remarkable extent. This is consistent with a distorted wave impulse approximation [4] (DWIA) calculation. It should be noted that projectile-cluster optical model potentials [2], which give a reasonably good account of experimental cross section [5] and analyzing power distributions [6] of free ^{4}He(p,p)^{4}He scattering at an incident energy of 100 MeV, are used for the two-body system in our DWIA calculations.

In strong contrast with the simple results of the light-mass target, the analyzing power distribution of knockout from ^{40}Ca is profoundly affected by the heavier mass of the spectator part of the target. This results in an induced asymmetry, which is evidently caused by an increased distortion affecting the outgoing wave functions. Nevertheless, the DWIA theory provides an excellent description of the observed analyzing power distributions also for knockout α–cluster knockout from the target nucleus ^{40}Ca if care is taken to use a distorting potential for the outgoing α–particle which reproduces elastic scattering well, as will be shown in the next section.

Cross sections of the (p,$p\alpha$) knockout reaction have been investigated relatively frequently in the past, but because the analyzing power should be more sensitive to details of the reaction mechanism, it is the observable which is studied in this work. A relevant review of clustering in general, including knockout reactions, is provided by Hodgson and Běták [7].

It should be mentioned that in the DWIA theory those ingredients such as distorting potentials are, as usual, obtained from elastic scattering experiments and are not treated as free parameters. Of course, these parameters are of variable reliability. For example, the α–projectile optical potentials extracted from elastic scattering are known to suffer from discrete ambiguities at low incident energies, but fortunately guidance [8] may be obtained from higher-energy experiments. Various global parameter sets that reproduce elastic scattering of protons from target nuclei very well, over a large mass and incident energy range, are fortunately freely available.

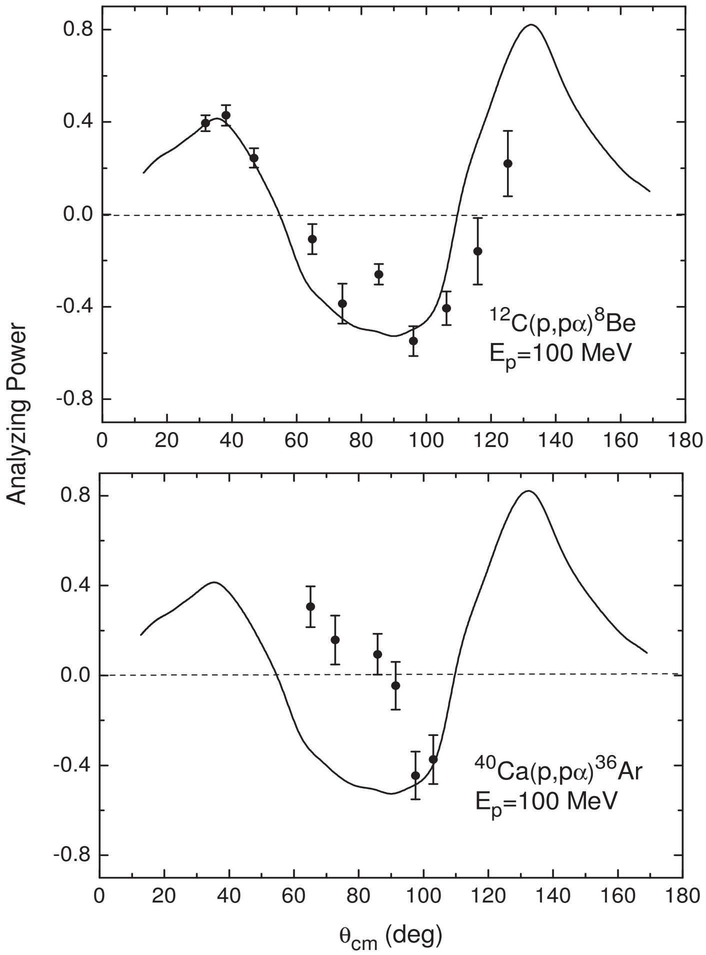

Figure 2: Analyzing power distributions as a function of the two-body *p*-α centre-of-mass scattering angle for the (*p*,*p*α) reaction on ^{12}C and ^{40}Ca at an incident energy of 100 MeV. Experimental values are shown with statistical error bars. Appropriate kinematics is selected for zero recoil momentum of the heavy residual nucleus. The impulse approximation implies that the struck cluster is at rest in the laboratory co-ordinate system. The curves represent a smooth line drawn through experimental analyzing power angular distributions for ^{4}He(*p*,*p*)^{4}He elastic scattering at the same incident energy from reference [6].

2. Results and discussion

The analyzing power angular distributions as a function of the two-body p-α centre-of-mass scattering angle for the (*p*,*p*α) reaction on ^{12}C and ^{40}Ca at an incident energy of 100 MeV are shown in figure 2. The experimental values are compared with results measured for elastic scattering of protons from ^{4}He at the same incident energy. Clearly the two experimental distributions are very similar for ^{12}C, as would be expected on simplistic grounds. Furthermore explicit DWIA calculations demonstrate that this relationship holds simply because the spectator part of the target nucleus, ^{8}Be, does not influence the knockout reaction to an appreciable extent [2].

Unfortunately angular limitations of the detectors used to measure the ^{40}Ca(*p*,*p*α)^{36}Ar knockout reaction (magnetic spectrometer in coincidence with a Si-Ge telescope) prevented measurements over a wider angular range. Results for the ^{40}Ca(*p*,*p*α)^{36}Ar reaction clearly differ extensively from the analyzing power of free elastic scattering. In fact, over this restricted range the free elastic scattering distribution has mostly a different sign from the knockout data.

Initial calculations [3] with the DWIA failed to reveal the reason for this discrepancy and it suggested that the analyzing power data of the knockout reaction should follow the trend of free scattering. These earlier calculations [3] relied mainly on an optical potential for the outgoing α–particle which was derived by Carey *et al*. [8] for use in (p,$p\alpha$) cross section distributions over a large mass-range of target nuclei. Because, as was mentioned before, α–particle potentials are not as well-established as proton global potentials, Carey *et al.* used a procedure, which was sound for the purpose of generating a global set of α–particle potentials from the available literature that describes

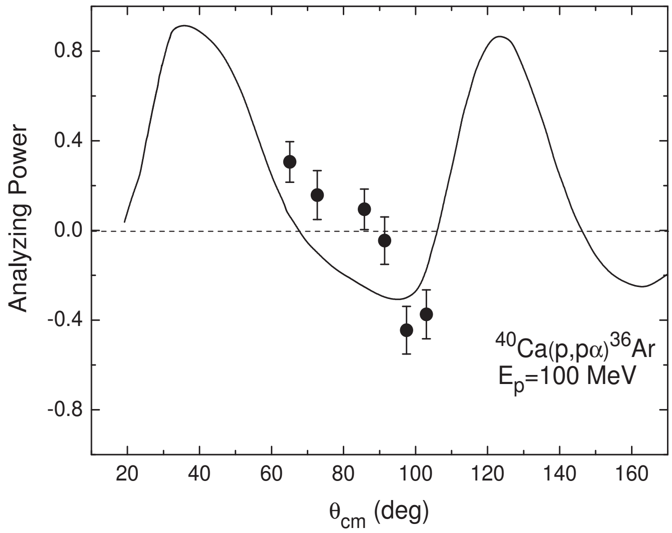

Figure 3: Analyzing power distribution for the reaction ^{40}Ca(p,$p\alpha$)^{36}Ar at an incident energy of 100 MeV. Also see caption to figure 1. The curve is a prediction of the DWIA as described in the text.

the average target mass and incident energy dependence very well. However, for the present application to the target nucleus ^{40}Ca, it turns out that elastic scattering of α–particles from the residual nucleus ^{36}Ar is subject to the so-called anomalous large angle (ALAS) effect, first observed by Gruhn and Wall [9]. Use in the DWIA of a distorting potential that describes the ^{36}Ar(α,α)^{36}Ar elastic scattering correctly (as opposed to the Carey global potential which predicts elastic scattering cross sections that differ from experimental values for ^{36}Ar by up to two orders of magnitude at backward angles) results in the theoretical prediction shown in figure 3. Of course, due to the fact that the projectile-cluster interaction (upper vertex in figure 1) is nevertheless affected by the distorted waves associated with the lower vertex, the correct treatment of distortions becomes crucial, especially for this fairly massive target-recoil system.

The α–particle optical model potential parameters employed in the DWIA calculation displayed in figure 3 are from the work of Reidemeister *et al*. [10]. The α–particle potential used was the Woods-Saxon squared version of the form factor for both the real as well as the imaginary parts of the optical potential, with parameters from [10].

The DWIA result of figure 3 is evidently a considerable improvement on the curve shown in figure 2 for ^{40}Ca. For example, the difference between the DWIA and the first data point (figure 3) is less than 0.2, whereas figure 2 gives a discrepancy of 0.8 (-0.4 as opposed to 0.4; a difference in sign, as was mentioned before!).

Clearly, further improvement is required, but guidelines to achieve this are not clear. It would not be meaningful, for example, to merely adjust the parameters further to get best agreement with the experimental distribution. Nevertheless, it is apparent that the introduction of a more appropriate α-particle optical model potential improves the DWIA calculation of the analyzing power from something that is far out of line to a distribution which is comparable to the experimental values. In other words, the results which are shown in figure 3 are encouraging.

It should be mentioned that Carey *et al.* [8] did indeed explore alternative α-particle optical model parameterizations of Woods-Saxon shape, but they found only a very small sensitivity to the cross section. Of course, the present study indicates that the analyzing power is much more sensitive to this ingredient. In fact, if we compare a DWIA calculation using the appropriate parameter with the cross section measurement of Carey *et al.* [8], a similar insensitivity as encountered by them is observed. The only effect is that the spectroscopic factor, which is extracted by means of a normalization of the theory to the experimental cross sections, changes by a modest 10%. This change in the DWIA results is well within the differences found by Carey *et al*. Furthermore, the modification of the shape of the cross section energy distribution is insignificant.

3. Summary and conclusion

The (p,$p\alpha$) knockout reaction at an incident energy of 100 MeV to the ground state of the residual nucleus on the target ^{12}C displays an analyzing power distribution which follows the trend of elastic scattering of protons from ^{4}He. This resemblance of quasifree knockout to free scattering is in agreement with a DWIA prediction. The knockout α–cluster analyzing power angular distribution for the target nucleus ^{40}Ca, however, shows a significant deviation from a free interaction between a proton projectile and ^{4}He. Only when an optical model parameter set, which reproduces the elastic scattering between the residual nucleus ^{36}Ar and the emerging α–particle, does the DWIA predict the experimental distribution reasonably accurately.

The mere fact that ^{40}Ca is so much heavier than ^{12}C is probably not the only, or even the crucial difference between these two cases that accounts for the observed behaviour of the analyzing power distributions. It appears that it is of more importance that in the former situation the DWIA theory requires a distorted wave in the α–^{36}Ar outgoing channel that gives an accurate account of anomalous large angle elastic scattering.

It would be useful to investigate the (p,$p\alpha$) knockout reaction for other adjacent medium-mass target nuclei, most of which do not involve an outgoing system that is subject to anomalous elastic scattering. The basic formulation of the DWIA appears to be sound, but more refined analysis would require a better understanding of the distorting optical model parameters for especially the α–particle. Consequently there is a need for further experimental as well as theoretical development.

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