Proton-induced α-cluster knockout from ^{12}C

A. A. Cowley[1,2]*, J. Mabiala*[1,2]*, S. V. Förtsch*[2]*, E. Z. Buthelezi*[2]*, R. Neveling*[2]*, F. D. Smit*[2]*, G. F. Steyn*[2]*, and J. J. van Zyl*[1]
[1] Department of Physics, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[2]iThemba LABS, PO Box 722, Somerset West 7129, South Africa,

Abstract
Results of a study of the (p, $p\alpha$) reaction on ^{12}C with polarized incident protons of 100 MeV are reviewed. Experimental cross section and analyzing power distributions are compared with predictions of a distorted wave impulse approximation (DWIA) theory. The theory reproduces the data reasonably well, suggesting that a quasifree knockout mechanism dominates the reaction. Spectroscopic information extracted from the cross section data is in agreement with a shell model prediction.

1 Introduction

The kinematic distribution of reaction products from (p, $p\alpha$) knockout reactions is able to reveal details of cluster structure of atomic nuclei. Cluster preformation probabilities and momentum distributions may in principle be extracted by comparing measured cross section distributions with predictions of distorted wave impulse approximation calculations. Furthermore, analyzing power distributions are very sensitive to details of the reaction mechanism, and they provide information on the extent to which the core of the target system acts merely as a spectator to the cluster knockout.

Recent results [1, 2] for the reaction ^{12}C(p, $p\alpha$)^{8}Be(g.s.) at an incident energy of 100 MeV show that, to a very good approximation, the coincidence cross section factorizes into one component that represents the two-body projectile-cluster collision, and another part that contains the convolution of the distortions with the target structure. This manifests itself as a remarkable correspondence between two-body cross sections extracted from the coincident (p, $p\alpha$) distributions and the differential cross section angular distributions of free p–^{4}He elastic scattering. In addition, the analyzing power distributions of the two reactions are also in agreement. Not only does this confirm the factorization of the cross section of the (p, $p\alpha$)–reaction, but it also suggests that the polarization of the projectile involves mainly the two-body interaction.

In this review we interpret the significance of the main results obtained from Ref. [1, 2]. The most prominent details of the agreement between the predictions of a distorted wave impulse (DWIA) approximation theory and the experimental distributions are discussed. In addition, we examine the experimental results for validity of the impulse approximation. Finally, we investigate the factorization of the cross section for non-zero recoil momenta of the heavy residual nucleus.

2 Comparison of theory with experimental data

The work of Refs. [1,2] studied the (p, $p\alpha$) reaction on ^{12}C at an incident energy of 100 MeV. Coincident cross sections and analyzing power distributions were measured at 10 coplanar angle pairs, selected in such a way that zero recoil momentum of the unobserved heavy nuclear residue is kinematically allowed at all angular settings. The missing-mass resolution was good enough to resolve knockout to the ground state of the residual nucleus, which is of interest, from the reaction to the first excited state. For each angle pair the experimental data in the kinematic locus corresponding to ground-state knockout could be selected. The resulting energy sharing cross section and analyzing power distributions were plotted as a function of the proton energy.

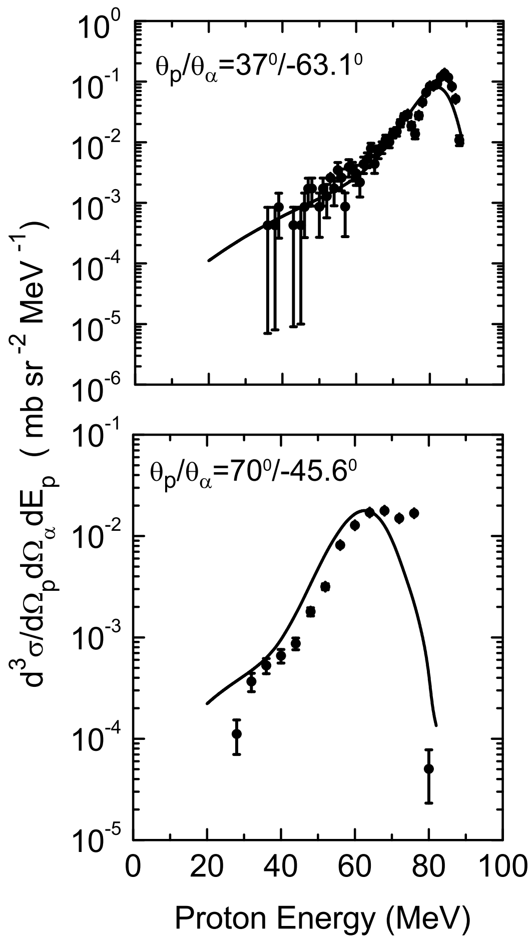

Fig. 1: Cross section distributions projected onto the proton energy axis for the reaction $^{12}C(p,\ p\alpha)^8Be$(g.s.). Statistical error bars on the experimental values are indicated. The curves represent results of DWIA calculations as described in the text.

The DWIA [3, 4] gives a fairly good reproduction of the experimental distributions with distorted waves generated with standard optical model potential parameters, which were also used in earlier work [5]. The results are fairly insensitive to the exact choice of parameter sets of the incident and outgoing protons. However, different α–^{8}Be sets, or alternatively bound state parameter sets, could provide even better agreement with the cross section distributions. Representative results are displayed in Fig.1 for two angle sets that almost mirror the proton and α–particle positions. The DWIA calculations which are shown, are calculated with the α–^{8}Be parameter set labeled III in Ref. [2]. The DWIA calculations are normalized to the experimental data, which then gives the spectroscopic factor. The full set of experimental data in Ref. [2] provides a spectroscopic value of 0.7 $\pm$ 0.5, which is consistent with a shell model prediction [6]. This result supports the suspicion that the nucleus ^{12}C has a very low α-clustering component in its ground state.

For the data in Fig.1, experimental distorted momentum distributions are extracted by dividing the cross section data by the projectile-cluster two-body cross section (calculated with optical model parameters [2], which describe free scattering [7] and thus approximate the proper half-shell quantity [5]) and the known kinematic factor. In Fig.2 the results are plotted as a function of recoil momentum. We

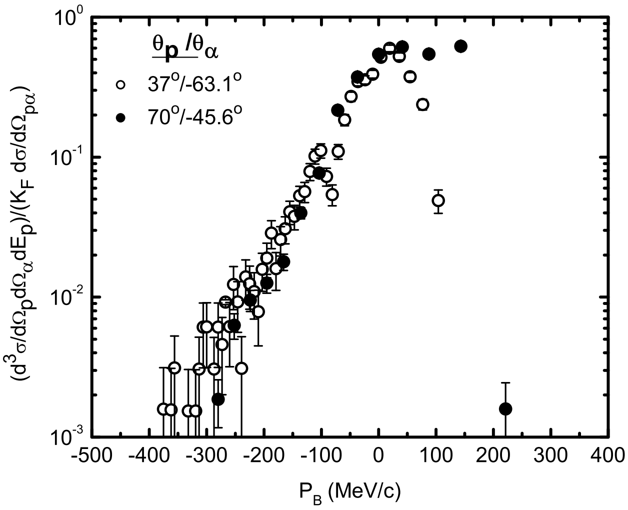

Fig. 2: Momentum distributions at two angle pairs extracted from the experimental cross sections for the ^{12}C(p,$p\alpha$)^{8}Be(g.s.) reaction. Statistical error bars on the experimental values are indicated. The scale on the vertical axis is in arbitrary units, but is nevertheless the same for both angle pairs.

find that the distorted momentum distributions at the two angle pairs are in excellent agreement with each other on the low-momentum side, in spite of the fact that the energy sharing distributions in Fig.1 are very different. This result confirms the validity of the impulse approximation, which relates the momentum of the bound α–cluster to the recoil of the residual nucleus.

Note that the difference at the top positive momentum range in Fig.2 is probably ascribable to sequential α–particle decay [2, 5] at the large proton emission angle. This hypothesis is supported by the fact that the momentum distribution for θ_p=37° is fairly symmetric around zero momentum, as would normally be expected.

In Fig.3 analyzing power distributions for the reaction ^{12}C(p, $p\alpha$)^{8}Be, from Ref. [2], are presented for four representative angle pairs. For this experimental observable, which provides a different sensitivity than cross sections to the details of the DWIA calculations, we also find reasonably good agreement between the experimental results and predictions of the theory. At the largest proton angle shown, the trend of the experimental distribution is reproduced well by the DWIA, although the theoretical curve is systematically higher than the measured data. However, it should be pointed out that this discrepancy is caused simply by a slightly flawed description of the analyzing power of the two-body p–α cluster interaction (which is derived in approximation from the analyzing power of p+^{4}He elastic scattering [8]) at large scattering angles (see Ref. [2] for further details). Therefore, the observed failure of the DWIA for large proton scattering angles is neither surprising, nor is it of any consequence.

It was shown previously [1, 2, 9] that, for the reaction ^{12}C(p, $p\alpha$)^{8}Be as a function of the two-body p–α centre-of-mass scattering angle, at zero recoil momentum of the heavy residual nucleus, the experimental analyzing power agrees with the angular distribution of the free p+^{4}He interaction. This means that the knockout cross section factorizes. It was also found that the DWIA reproduces the experimental distribution remarkably well under the so-called quasifree knockout condition. This implies that the ^{8}Be core of the target-cluster system acts as a spectator to the knockout process, and as such it is insensitive to the polarization of the projectile. In other words, the amplitude which consists of an overlap of distorted wave functions with the cluster wave function, is not very sensitive to spin-orbit interactions.

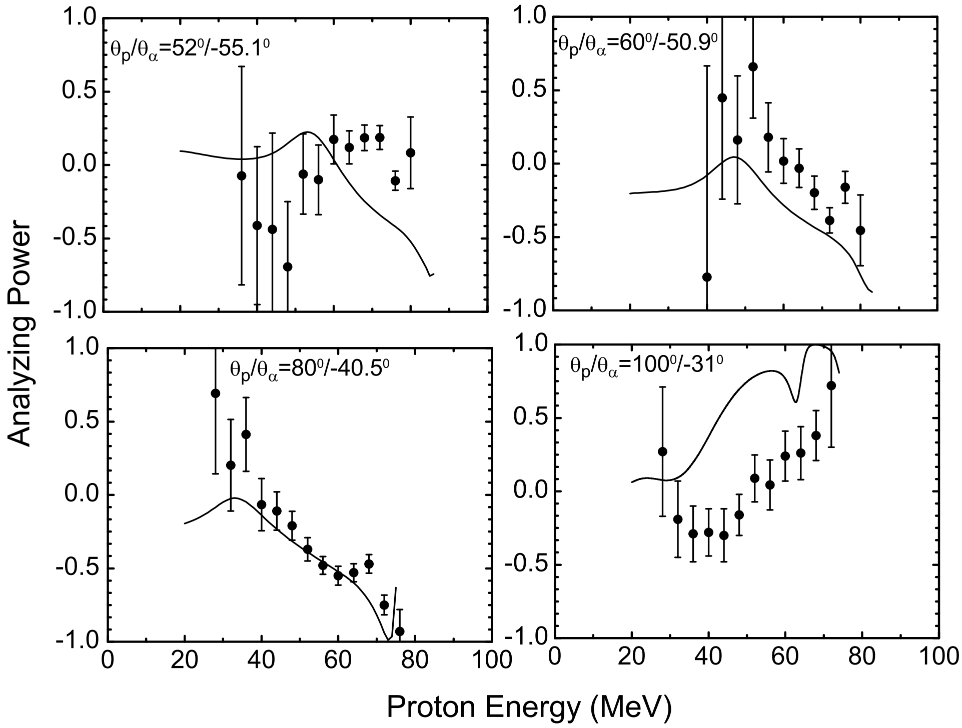

Fig. 3: Analyzing power distributions projected onto the proton energy axis for the reaction ^{12}C(p, $p\alpha$)^{8}Be(g.s.). Statistical error bars on the experimental values are indicated. The curves represent predictions of DWIA calculations. See Ref. [2] for results of a complete set of available angle pairs.

In Fig.4 results are presented for analyzing power angular distributions which were not measured at the quasifree kinematic condition. We find that the observed experimental trend is nevertheless reproduced by the DWIA calculations. For example, as the recoil momentum in the ^{12}C(p, $p\alpha$)^{8}Be reaction changes from a positive to an (increasingly higher) negative value, the analyzing power at a centre-of-mass scattering angle near 90° changes from large negative to positive. The trend of the DWIA results is consistent with this behaviour, and it presumably caused simply by the kinematic change with recoil momentum which affects a variation in the effective two-body kinetic energy.

Consequently we now find that the correspondence between experimental results and DWIA predictions also holds for large absolute values of the recoil momenta, thus the quasifree character of the knockout reaction is retained under those conditions. Conclusions regarding the simplicity of the reaction mechanism follows exactly as before.

3 Summary and conclusion

Results of cross section and analyzing power distributions for the reaction ^{12}C(p, $p\alpha$)^{8}Be at an incident energy of 100 MeV at a number of quasifree angle pairs were presented. Reasonably good agreement between results of DWIA calculations and the experimental distributions were obtained.

The observed agreement, especially for the analyzing power, is significant as it reveals details of

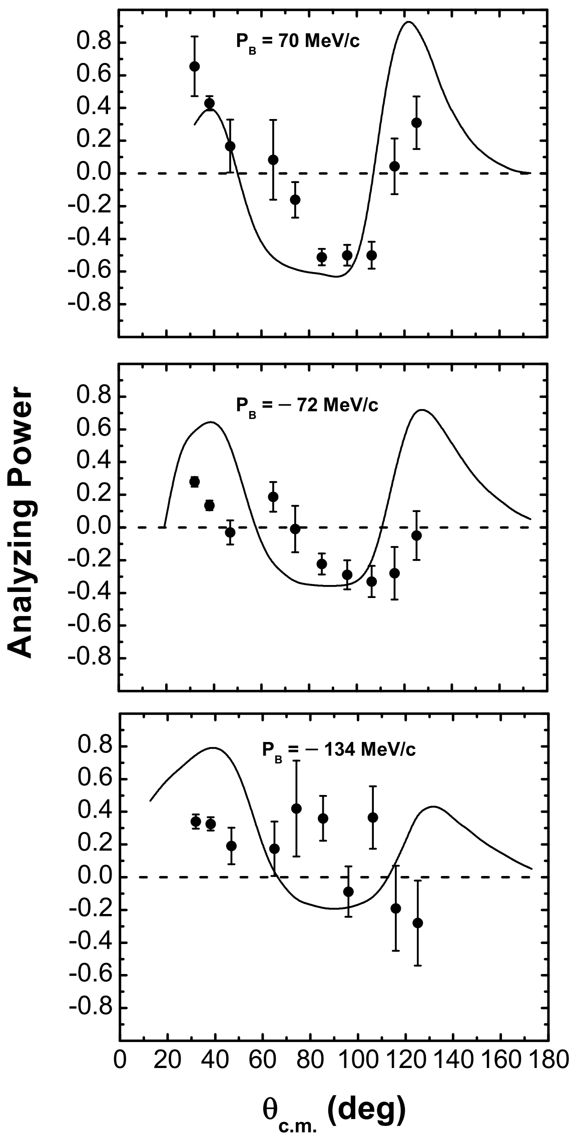

Fig. 4: Analyzing power distributions for the reaction $^{12}C(p, p\alpha)^{8}Be(g.s.)$ displayed as a function of the two-body centre-of-mass scattering angle. Results are shown for three values of the recoil momentum of the heavy residue. Statistical error bars on the experimental values are indicated. The curves represent results of DWIA calculations.

the reaction mechanism as a quasifree process in which the core in the target system acts as a mere spectator to the knockout process in which the projectile and the α–cluster participate.

Acknowledgements

This work was performed with funding from the South African National Research Foundation (NRF). The financial support is gratefully acknowledged. One of us (JM) thanks iThemba LABS and NITheP (National Institute for Theoretical Physics, Stellenbosch, South Africa) for bursaries.

References

[1] A. A. Cowley, J. Mabiala, E. Z. Buthelezi, S. V. Förtsch, R. Neveling, F. D. Smit, G. F. Steyn, and J. J. van Zyl, *Europhys. Lett.* **85**, 22001 (2009).

[2] J. Mabiala, A. A. Cowley, S. V. Förtsch, E. Z. Buthelezi, R. Neveling, F. D. Smit, G. F. Steyn, and J. J. van Zyl, *Phys. Rev. C* **79**, 054612 (2009).

[3] N. S Chant, and P. G. Roos, *Phys. Rev. C* **15**, 57–68(1977).

[4] N. S Chant, and P. G. Roos, *Phys. Rev. C* **27**, 1060–1072 (1983).

[5] P. G. Roos, N. S. Chant, A. A. Cowley, D. A. Goldberg, H. D. Holmgren, and R. Woody, *Phys. Rev. C* **15**, 69–83 (1977).

[6] D. Kurath, *Phys. Rev. C* **7**, 1390–1395 (1973).

[7] N. P. Goldstein, A. Held, and D. G. Stairs, *Can. J. Phys.* **48**, 2629–2639 (1970).

[8] A. Nadasen, P. G. Roos, D. Mack, G. Ciangaru, L. Rees, P. Schwandt, K. Kwiatkowski, R. E. Warner, and A. A. Cowley, Indiana University Cyclotron Facility Scientific and Technical Report, p.13 (1983).

[9] A. A. Cowley, J. Mabiala, E. Z. Buthelezi, S. V. Förtsch, R. Neveling, F. D. Smit, G. F. Steyn, and J. J. van Zyl, Proc. Int. Conf. on Nuclear Structure and Dynamics, Dubrovnik, Croatia, May 2009 (AIP Conference Series), to be published.