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# Alpha-cluster structure in the ground state of $^{40}\text{Ca}$ displayed in a $(p,p\alpha)$ knockout reaction

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**Abstract.** The analyzing power is very sensitive to details of the reaction mechanism of  $(p,p\alpha)$  knockout reactions in the incident energy range of approximately 100 MeV and higher. Whereas distorted wave impulse approximation calculations in the past proved to give an excellent reproduction of analyzing power angular distributions for quasifree  $(p,p\alpha)$  reactions on light targets such as  $^6\text{Li}$ ,  $^9\text{Be}$  and  $^{12}\text{C}$ , the situation for  $^{40}\text{Ca}$  was not as simple. It is now shown that the theory also offers good agreement with the experimental distribution of the heaviest target nucleus if care is taken to use proper distorted waves which treat  $\alpha$ - $^{36}\text{Ar}$  properly as a system for which  $\alpha$ -elastic scattering is anomalous. Thus it is shown that  $^{40}\text{Ca}$  reveals its ground state  $\alpha$ -cluster structure in an unambiguous way similar to the light target nuclei.

## 1. Introduction

Whereas clustering in specific excited states of atomic nuclei is a clearly-identified phenomenon, the presence of  $\alpha$ -cluster configurations in the ground-states of nuclides is more controversial. This scepticism is directly due to the success of shell-model descriptions of nuclei. However, it should be recognized that by exploiting single particle shell-model wave functions, it is possible to project ground-state  $\alpha$ -like cluster structures out of those configurations. Experimentally it is consequently of interest to determine whether knockout and pickup reactions support this refined theoretical expectation.

Of course, the  $(p,p\alpha)$  reaction at energies of 100 to 300 MeV, not surprisingly, provides direct evidence of ground state clustering in very light target nuclei, such as  $^6\text{Li}$  and  $^9\text{Be}$ . However, for even such a light-mass target as  $^{12}\text{C}$  a very clear signature in terms of a  $(p,p\alpha)$  analyzing power energy and angular distribution was only recently demonstrated [1, 2]. On the other hand, the analyzing power, which is very sensitive to details of the reaction mechanism of knockout, recently failed to confirm the expected response from clustering in the ground state of  $^{40}\text{Ca}$  [3].

## 2. New results for $^{40}\text{Ca}$

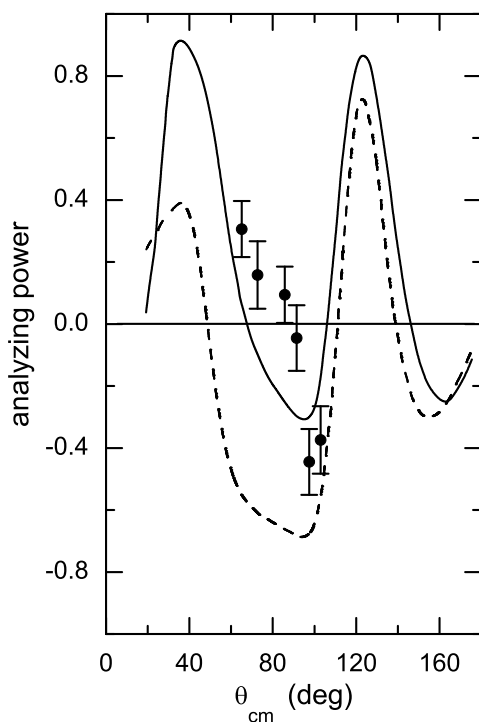
We have further investigated the  $^{40}\text{Ca}(p,p\alpha)^{36}\text{Ar}(\text{g.s.})$  reaction at an incident energy of 100 MeV. The results are shown in Figs. 1 and 2.

It is found that, in contrast with the cross section, the analyzing power depends very strongly on the optical potential employed in a distorted-wave impulse approximation (DWIA) [4, 5]

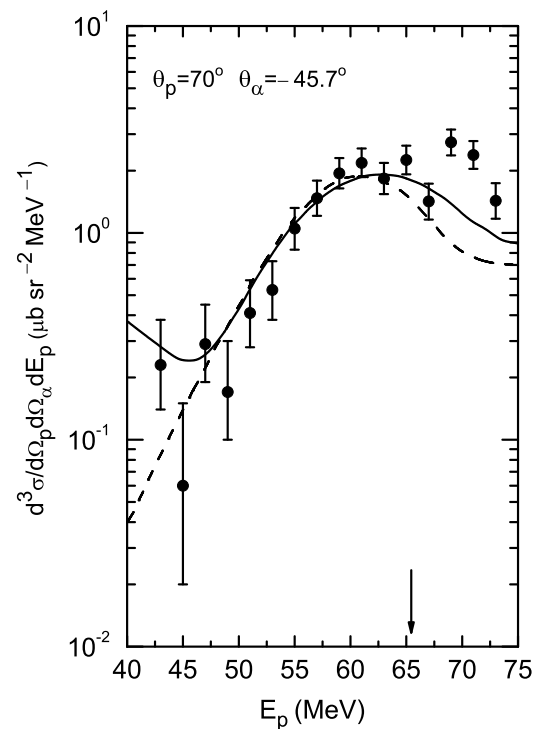


description of the outgoing  $\alpha$  channel of the reaction. More specifically, this observable requires an optical potential for the  $\alpha$ -particle which generates a wave function that describes the  $\alpha$ - $^{36}\text{Ar}$  interaction accurately. This system manifests an anomalous large angle effect [6], which is not present for adjacent target masses. This is shown in Fig. 1 where a DWIA calculation of the analyzing power with an  $\alpha$ -particle optical potential from the work of Reidemeister *et al.* [6] is compared with results employing a standard global optical potential. The Reidemeister potential is of a Woods-Saxon squared shape, which is needed to describe elastic scattering of  $\alpha$ -particles, and we use a parameter set appropriate to the projectile energy corresponding to that required by the kinematics of the  $(p,p\alpha)$  knockout reaction.

The result with an  $\alpha$ -particle optical potential, which gives a reasonable description of elastic scattering in a global mass range, but not specifically for  $^{36}\text{Ar}$ , is clearly unacceptable, as may be seen from Fig. 1.



**Figure 1.** Analyzing power angular distribution for the  $^{40}\text{Ca}(p,p\alpha)^{36}\text{Ar}$  reaction at an incident energy of 100 MeV. Results are shown as a function of the centre-of-mass scattering angle  $\theta_{cm}$  of the  $p$ - $\alpha$  two-body system under quasifree kinematic conditions. Experimental data are from Ref. [3]. The solid line corresponds to a DWIA calculation with an  $\alpha$ -particle potential set [6] which fits anomalous large angle elastic scattering from the  $^{36}\text{Ar}$  residual nucleus. The dashed line is a calculation with a standard representative potential from Carey *et al.* [7].



**Figure 2.** Energy sharing cross section distribution for the reaction  $^{40}\text{Ca}(p,p\alpha)^{36}\text{Ar}$  at an incident energy of 100 MeV. Results for the quasifree angle pair indicated in the figure are shown as a function of the energy of the observed scattered proton. Experimental data from Ref. [7]. The solid curve is from a DWIA calculation with the  $\alpha$ -particle optical potentials of Ref. [6]. The dashed line is calculated with a standard potential set from Carey *et al.* [7] which fits elastic scattering from the general target-mass range of the residual nucleus.

The cross section distribution, on the other hand is not sensitive to this detail (See Fig. 2), and  $\alpha$ -potentials extracted for generic target masses are equally acceptable for that case, as was also found in earlier investigations [7]. Differences are observed at the extreme ends of the cross section distribution where the quality of experimental data is poor (low proton energy) or where sequential  $\alpha$ -particle decay [8] may contribute at higher proton energies. Those two regions are far removed from the zero recoil kinematic condition (shown as an arrow in Fig. 2) at which the data in Fig. 1 were measured for that specific angle pair.

Clearly the use of standard Woods-Saxon type potential shapes for the  $\alpha$ -particle in the work of Neveling *et al.* [3] is the direct cause of the difficulty encountered in that study. However, because cross section distributions did not suffer from this deficiency, it was not realised that those potential shapes are inappropriate for analyzing power, with its increased sensitivity to correct distorted waves in the DWIA.

Such an effect is not encountered for the proton channels, for which elastic scattering is generally accurately reproduced by a number of global optical model parameter sets. As long as the different optical parameter sets all give reasonable fits to elastic scattering in the relevant mass and incident energy range, DWIA results are roughly similar for all sets.

The increased sensitivity of the analyzing power distribution relative to cross section data in the knockout reaction  $^{40}\text{Ca}(p,p\alpha)^{36}\text{Ar}$ , together with the agreement between the DWIA calculation and the experimental data when an appropriate  $\alpha$ -particle optical potential is used in the DWIA, removes any doubt as to the ground state clustering of the target nucleus.

### 3. Summary and conclusion

We have investigated the DWIA description of the knockout reaction  $^{40}\text{Ca}(p,p\alpha)^{36}\text{Ar}(\text{g.s.})$  at an incident energy of 100 MeV. It is shown that previous difficulties in the theoretical reproduction of the analyzing power angular distribution, which is expected to be directly related to knockout of a preformed cluster in the target nucleus, is sensitive to the use of correct distorted waves for the outgoing  $\alpha$ -particle in the calculations.

The observed sensitivity of the analyzing power to the specific distorting potentials used is very different from the behaviour experienced for lighter target masses. In the case of mass 12 and lighter, results do not differ appreciably for different sets of equivalent optical potentials.

The present analysis clearly supports a cluster interpretation of the reaction. Thus  $^{40}\text{Ca}$  displays a degree of  $\alpha$ -clustering in the ground state similar to lighter target nuclei such as  $^{12}\text{C}$ .

Further experimental and theoretical work are desirable. An investigation of the trend as one moves away from stable to rare nuclear species may be especially useful.

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