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The Ghost Anomaly in the ^{9}Be(p, d)^{8}Be Reaction†

F. C. Barker,[A] *G. M. Crawley,*[A,B] *P. S. Miller*[C] *and W. F. Steele*[C]

[A] Research School of Physical Sciences, Australian National University, P.O. Box 4, Canberra, A.C.T. 2600.
[B] On leave from the Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, U.S.A.
[C] Cyclotron Laboratory, Michigan State University.

Abstract

The ghost of the ^{8}Be ground state has been observed in the ^{9}Be(p, d)^{8}Be reaction, and fitted using a many-level *R*-matrix formalism.

Introduction

When a level is close to the threshold of a channel for which it has an appreciable spectroscopic factor, the line shape in a reaction in which the level is populated may consist of a narrow main peak and a broad but much weaker ghost peak at a higher excitation energy (Barker and Treacy 1962). If the level is isolated, the size of the ghost peak relative to the main peak should remain constant, independent of the reaction, the bombarding energy and the angle of observation. The ghost may, however, be modified by interference with other levels of the same spin and parity.

Hay *et al.* (1967) observed an anomaly in the ^{9}Be(p, d)^{8}Be reaction and identified it as the ghost of the ^{8}Be ground state. The ghost peak reached a maximum about $0 \cdot 5$ MeV above the main peak with an intensity of about 7% per MeV relative to the main peak. Simultaneous fits to these data and to the α–α s-wave phase shift, using a three-level *R*-matrix formalism, enabled properties of 0^+ states of ^{8}Be to be obtained, and required the s-wave α–α channel radius a_0 to be about 7 fm (Barker *et al.* 1968). Similar fits to data involving 2^+ levels of ^{8}Be gave $a_2 \approx 6 \cdot 75$ fm (Barker 1969).

About the same time, however, Fisher *et al.* (1967) interpreted the anomaly they observed in the ^{9}Be(p, d)^{8}Be reaction not in terms of a ghost of the ^{8}Be ground state but as the result of three-particle breakup due to the alternative mode of decay ^{9}Be(p, α)^{6}Li*(d)^{4}He.

In a more recent survey of the ^{8}Be ghost anomaly, Berkowitz *et al.* (1971) studied the dependence of the anomaly on the reaction and the angle of observation. They found anomalies that differed markedly in shape and size for different reactions, with intensities up to 70% per MeV, and concluded that their results cast doubt on the interpretation of the anomalies in terms of a ghost peak.

In view of the discrepancies between these measurements and between their interpretations, and because the ^{9}Be(p, d)^{8}Be experiment of Hay *et al.* (1967) was done at low bombarding energies ($E_{\mathrm{p}} \leqslant 5 \cdot 2$ MeV), where some of the assumptions made may be questioned, it was decided to make a new measurement of the ghost line shape in ^{9}Be(p, d)^{8}Be with $E_{\mathrm{p}} \approx 40$ MeV. Here compound nucleus formation

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is expected to be negligible, the energy dependence of the penetration factor of the emitted deuterons may be neglected in the region of interest, and the background from alternative modes of decay should be small.

Experimental Procedure

The experiment used a beam of 39·91 MeV protons from the Michigan State isochronous cyclotron and the deuterons were detected in nuclear emulsions placed at the focal plane of an Enge spectrograph. The target consisted of a self-supporting ^{9}Be foil 1·8 mg cm^{-2} thick. The energy resolution obtained was about 25 keV, arising predominantly from the target thickness contribution. The background from slit scattering was checked by examining the spectrum from the ^{13}C(p, d$_0$) reaction using a thin carbon foil.

Exposures were made at laboratory angles of 10° and 15° where the direct pickup process should dominate. Since the ground state main peak and the 2·9 MeV 2$^+$ peak both have much higher counting rates than the ghost region, each spectrum was obtained by making three exposures on three regions of the same plate with 1, 10 and 100 μC of charge so that good statistics could be obtained for all regions of the spectrum. Normalization of the three exposures was made using the collected charge and was checked by comparison with the elastic scattering from the target recorded with a monitor counter at 90°. A check on this procedure was made by recording the complete spectrum in a single-wire proportional counter (Lanford *et al.* 1972). While the resolution was poorer for the counter data, the ratio of counts in the ghost region to counts in the ground state peak was consistent with those from the plate data.

Results and Analysis

The anomaly seen in the 10° spectrum shown in Fig. 1 peaks about 0·6 MeV above the ground state main peak with an intensity of about 10% per MeV. Contributions from the tail of the 2·9 MeV 2$^+$ level and from a possible background are still included. These results are much more consistent with those of Hay *et al.* (1967) than with those of Berkowitz *et al.* (1971). It is possible that most of the anomalies seen by Berkowitz *et al.* were due to the poorer quality of their beam profiles. The only example they give shows the spectrum of α-particles elastically scattered from ^{7}Li, which indicates a low-energy tail of the incident beam with intensity about 40% per MeV in the region corresponding to the energy of the ghost peak. This is to be compared with values of about 0·3% per MeV for the beam achieved by Hay *et al.* (1967) and 0·18% per MeV in the present experiment (as measured by the ^{13}C(p, d$_0$) reaction).

We first consider the possibility of interpreting the anomaly as due to the reaction ^{9}Be(p, α)^{6}Li*(d)^{4}He, as was suggested by Fisher *et al.* (1967). In their experiment, the proton bombarding energy was 5–8 MeV and states of ^{6}Li as low as 4–6 MeV excitation could contribute to the region of the anomaly. Because of the high bombarding energy in the present experiment, only states of ^{6}Li above 27 MeV can contribute, and it is unlikely that the low energy α-particles required to populate such a region would be preferentially emitted. We therefore interpret the observed anomaly in terms of an ^{8}Be ground state ghost.

Fits to the spectrum of Fig. 1 are made using *R*-matrix formulae, with three-level approximations for both the 0^+ and 2^+ contributions (Barker *et al.* 1968; Barker 1969). Initially it is assumed that there is no background, and that the feeding amplitudes g_2 and g_3 for the upper levels are zero for both 0^+ and 2^+ contributions. These g_λ are expected to be small from the nature of the levels (Barker *et al.* 1968), and experimental support comes from the observed weak population of the similar 0^+ excited states in ^{12}C and ^{16}O in neutron pickup reactions. Thus the ratio g_2^2/g_1^2 of spectroscopic factors observed for the 7·65 MeV and ground states of ^{12}C is about

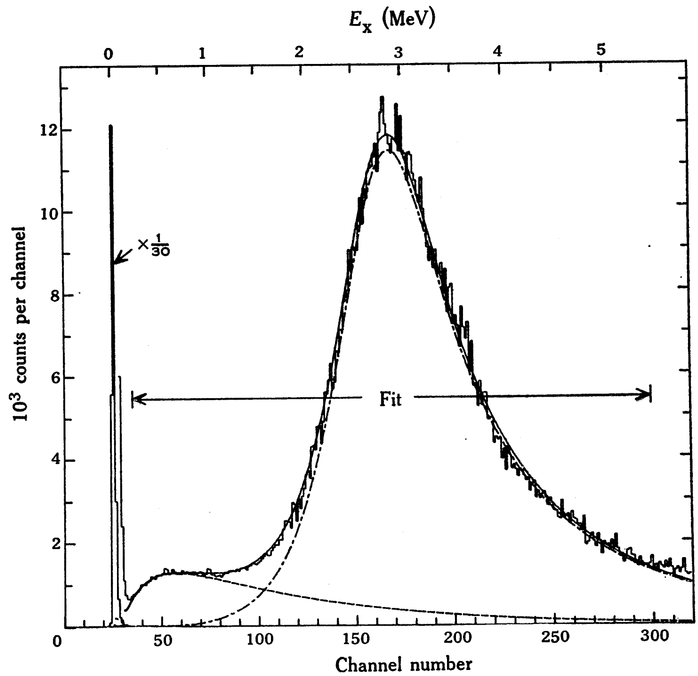

Fig. 1. Calculated (solid curve) and measured (histogram) spectra of deuterons at 10° from the reaction ^{9}Be(p, d)^{8}Be with a proton bombarding energy of 39·91 MeV. The $l = 0$ and 2 components of the calculated curve are plotted as dashes and dot–dashes respectively. For channel numbers less than 30 or greater than 110, the counts per channel are renormalized to 100 μC of collected charge. The data in channels 35 to 300 are used in the fitting procedure, with the $l = 0$ component normalized to the ground state main peak.

0·05 from ^{13}C(p, d) (Taketani *et al.* 1968), 0·04 from ^{13}C(d, t) (Mayo and Hamburger 1960) and 0·08 from ^{13}C(^{3}He, α) (Kellogg and Zurmühle 1966), while for the 6·05 MeV and ground states of ^{16}O an upper limit on the ratio is about 0·2 from ^{17}O(p, d) (Mendelson *et al.* 1970). In the latter case a calculated ratio is $1 \cdot 6 \times 10^{-4}$ (Zuker *et al.* 1968).

The data are first fitted in the region of the 2·9 MeV peak ($E_x \approx$ 2–5 MeV), using an approximate 0^+ contribution and 2^+ parameters that give best fits for different a_2 to the d-wave α–α phase shift and ^{8}Li and ^{8}B β-decay data (from Table 7 of Barker 1969). This gives $a_2 \approx 6 \cdot 0 \pm 0 \cdot 2$ fm. Then the spectra calculated with this 2^+ contribution and with 0^+ contributions corresponding to various sets of 0^+ parameters that give acceptable fits to the s-wave α–α phase shift (Barker *et al.* 1968) are compared with the data for $E_x \lesssim 2$ MeV. Best agreement is obtained for $a_0 \approx 6 \cdot 5$ fm, and acceptable agreement for a_0 between $5 \cdot 5$ and $7 \cdot 5$ fm. The curves in Fig. 1 show this best fit, together with the separate 0^+ and 2^+ contributions. It should be noted that this fit is obtained with only five adjustable parameters (the channel radii a_0 and a_2, the reduced width γ_{10}^2 of the lowest 0^+ level, and the normalizations of the $l = 0$ and 2 components), all other parameters being determined by fits to other data.

If we now relax the condition $g_2 = 0$ for the 2^+ levels and allow $|g_2/g_1| \lesssim 0 \cdot 3$, then acceptable fits to the spectrum for $E_x \approx 2$–5 MeV are obtained for a_2 values between about $5 \cdot 5$ fm ($g_2/g_1 = 0 \cdot 3$) and $6 \cdot 75$ fm ($g_2/g_1 = -0 \cdot 3$). In all cases the 2^+ contributions to the spectrum for $E_x \lesssim 2$ MeV are very similar. If we allow $|g_2/g_1| \lesssim 0 \cdot 3$ for the 0^+ levels, then best fits for $E_x \lesssim 2$ MeV are obtained with a_0 values between about $6 \cdot 0$ fm ($g_2/g_1 = 0 \cdot 3$) and $8 \cdot 0$ fm ($g_2/g_1 = -0 \cdot 3$). The inclusion of a nonzero, slowly varying background causes increases in the values of both a_0 and a_2 required for best fits. For example, a fit comparable with that shown in Fig. 1 can be obtained with the level parameters given by Barker *et al.* (1968) and Barker (1969) for $a_0 = 7 \cdot 0$ fm ($g_2/g_1 = -0 \cdot 15$) and $a_2 = 6 \cdot 75$ fm ($g_2/g_1 = -0 \cdot 3$), and a constant background of 250 counts per channel between channels 35 and 300.

The 15° spectrum may be similarly fitted without a background contribution, and favours values of a_0 and a_2 smaller by about $0 \cdot 5$ and $0 \cdot 2$ fm respectively. This could be due to the actual background contribution being relatively larger for the 15° spectrum than for the 10° spectrum, as might be expected.

Conclusion

In agreement with Hay *et al.* (1967) and in contrast with Fisher *et al.* (1967) and Berkowitz *et al.* (1971), we conclude that the anomaly seen in the present experiment can be interpreted as a ghost, i.e. that the anomaly at $E_x \approx 0 \cdot 6$ MeV is due essentially to the same 0^+ level of ^{8}Be as that which produces the main ground state peak at $E_x = 0$ MeV.

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