LINE SHAPES OF LOW LEVELS IN ^{8}Be VIA THE ^{9}Be(p, d)^{8}Be REACTION

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Summary

Reaction mechanisms and line shapes of energy levels in ^{8}Be have been studied in the bombardment of ^{9}Be by protons of energies up to $5\cdot2$ MeV. The (p, d) process was found to follow a pick-up mechanism, and with this information the detailed line shape of the ^{8}Be ground state was inferred. An R-matrix description using a conventional channel radius of $3\cdot5$ fm was found to be not in agreement with the results.

I. Introduction

The concept of line shape, or "density-of-states", of a nuclear level is relevant to the case where a level is populated by a reaction and is itself unstable with respect to breakup into one or more pairs of particles. The theory is well established (Lane and Thomas 1958) that a line shape may be asymmetric when the level is near a particle threshold. In an extreme case such a level may split into a narrow main peak and a quite distinct, subsidiary ghost peak (Barker and Treacy 1962). A fairly definite case is that of the ^{8}Be ground state, whose line shape shows structure (Beckner, Jones, and Phillips 1961) in a region of excitation near 1 MeV above the main peak, where there are no known levels. It was felt that a study should be made of this region with resolution good enough to show the expected structure of the low excitation side of the ghost, to see whether a straightforward single-level R-matrix term would be adequate to describe it. A choice should be possible here between R-matrix and complex eigenvalue theories (Humblet 1964; Mahaux 1965); these have so far been compared in cases where only marginal differences could be expected.

II. Experimental Details

Because the ghost peak is relatively weak, it was essential to use a clean beam profile. The beam from the A.N.U. tandem accelerator was focused through a $\frac{1}{16}$ in. diameter hole (collimator) placed 1 in. after the target. Beam that had been scattered before the target chamber was stopped by thin tantalum apertures, the smallest of which had a diameter of $\frac{1}{8}$ in., was 6 in. upstream from the target, and picked up less than $0\cdot17$ % of the beam intensity. By use of the Buechner spectrograph, a $5\cdot2$ MeV proton group elastically scattered from a thin carbon foil was analysed and found to have a degraded "tail" of differential intensity 1 % per MeV at 30 keV below the peak, dropping to less than $0\cdot1$ % per MeV at 1 MeV further down. This measure of the "tail" in a spectrum, namely in percentage per MeV, is appropriate to the present paper and will be referred to repeatedly. Spectra are normalized to the total intensity of the main peak unless otherwise mentioned.

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For the $^9Be(p, d)$ process, thin self-supporting beryllium targets of approximately 160 $\mu g/cm^2$ were used and reaction products detected with the Buechner spectrograph. A typical deuteron spectrum is shown in Figure 1. The sharp peak is from a very intense transition proceeding to the ^8Be ground state. Figure 2 shows an angular distribution observed for this group, which displays a conventional stripping pattern as is discussed later.

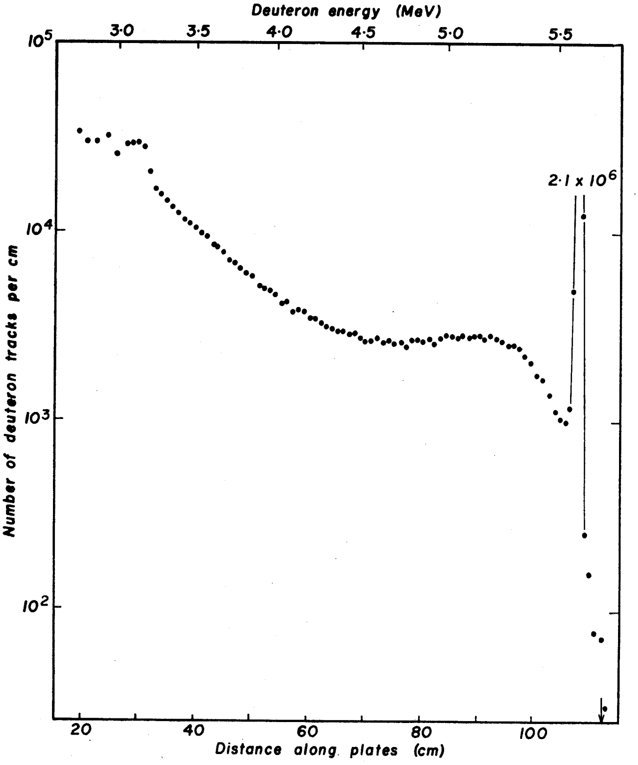

Fig. 1.—Deuteron spectrum obtained at a laboratory angle of 10° from bombardment of a beryllium foil, surface density 160 $\mu g/cm^2$, by 5·2 MeV protons. The ordinate represents data measured along the spectrograph plates, uncorrected for variations of laboratory solid angles.

Figure 3 illustrates the effect on the observed spectrum of varying the beam energy. This also is discussed below, but it should be noted that these results show clear evidence for transitions proceeding via intermediate states of the system other than ^8Be.

III. Analysis of Data

Figure 1 shows transitions to the ground and 2·9 MeV states in ^8Be as well as a pronounced anomaly within 1 MeV of the ground state. Figure 4 gives a composite plot of spectra for 10° and 60°, normalized to a common ^8Be scale of excitation, and shows that the anomaly rises to a definite maximum at $0 \cdot 5$ MeV. It was assumed naturally (Barker and Treacy 1962) that the $0 \cdot 5$ MeV anomaly is the ground-state ghost and that interference between levels of different spins does not occur (Swan 1965). Therefore, the data of Figure 4, together with those from a 20° observation angle, were analysed numerically into two parts, each a smooth function of ^{8}Be

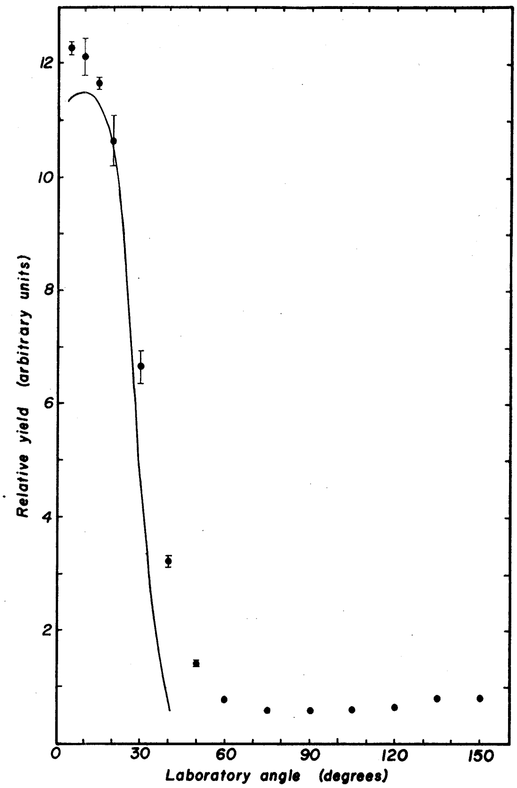

Fig. 2.—Angular distribution of deuterons from ^{9}Be(p, d)^{8}Be transitions to the ^{8}Be ground state, at a bombarding energy of $5 \cdot 2$ MeV. The curve is a theoretical Butler–Born fit calculated as described in the text, arbitrarily normalized at a laboratory angle of 20°.

excitation, namely, one proportional at each angle to the ground-state peak and another (presumably chiefly the $2 \cdot 9$ MeV) independent of it. Although there is no unique solution for such an analysis unless the angular distribution of each component is known exactly, the solutions obtained cannot be very different from the curves plotted in Figure 4. In fact, the spectra from the three angles suggested that there was present in addition a small continuous background, of order $0 \cdot 4$ % per MeV near $0 \cdot 5$ MeV excitation. The results were therefore re-analysed with a background component assumed initially to be isotropic. It was found that details of the background were unimportant below the ghost peak but led to considerable uncertainty at higher excitation energies. The part associated with the ground-state peak is illustrated finally in Figure 5(i), which shows the ghost rising to a maximum of ($6 \cdot 7 \pm 0 \cdot 2$) % per MeV at an excitation energy of 0·45 MeV. The error range shown in Figure 5 represents the centre 50% of the extreme upper and lower limits deduced from our analysis. Statistical errors in the original spectrum were less than one-third of the uncertainties due to the analysis.

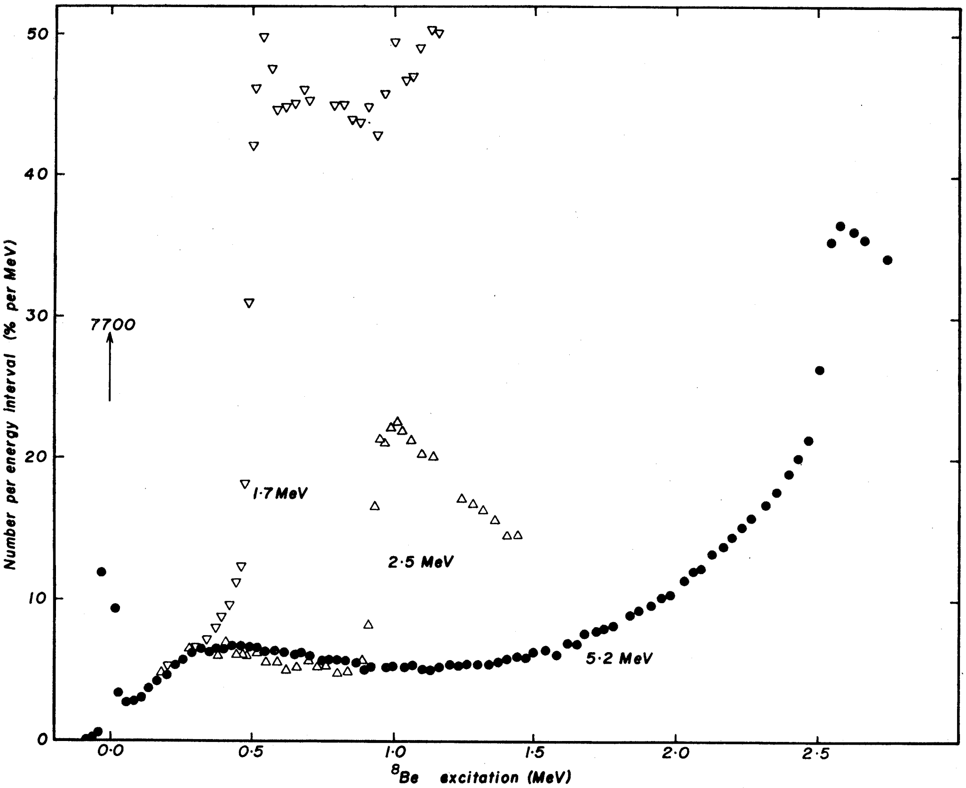

Fig. 3.—Deuteron spectra observed from ^{9}Be+p at a laboratory angle of 10°. The beam bombarding energy is as indicated: ▽ 1·7 MeV; △ 2·5 MeV; ● 5·2 MeV. The arrow indicates the number of counts in the main ground-state peak at zero excitation.

IV. Interpretation

Before discussing the details of the observed curve of Figure 5, it is necessary to understand the reaction mechanism for the (p, d) process. A fit, shown in Figure 2, was made to the angular distribution, using a Butler–Born pattern (Macfarlane and French 1960). This curve was calculated for angular momentum transfer $l_n = 1$ and an interaction radius of 5·3 fm. Agreement over the main peak is reasonably satisfactory, and it was thought justified to assume that the spectrum of Figure 5(i) could be described by a line-shape function multiplied by a p-wave neutron penetration factor. This factor amounts to a 14% change in the ratio of points at 0 and 1·0 MeV excitations, which change is within the errors of points of Figure 5(i). The resultant line shape is plotted in Figure 5(ii). The peak height of the ghost is (7·15±0·2) % per MeV at a channel energy 0·6 MeV.

We note that in another study of this reaction at 4·8 MeV (Read and Calvert 1961) reasonable agreement with the angular distribution was obtained with a smaller radius of 5·0 fm.

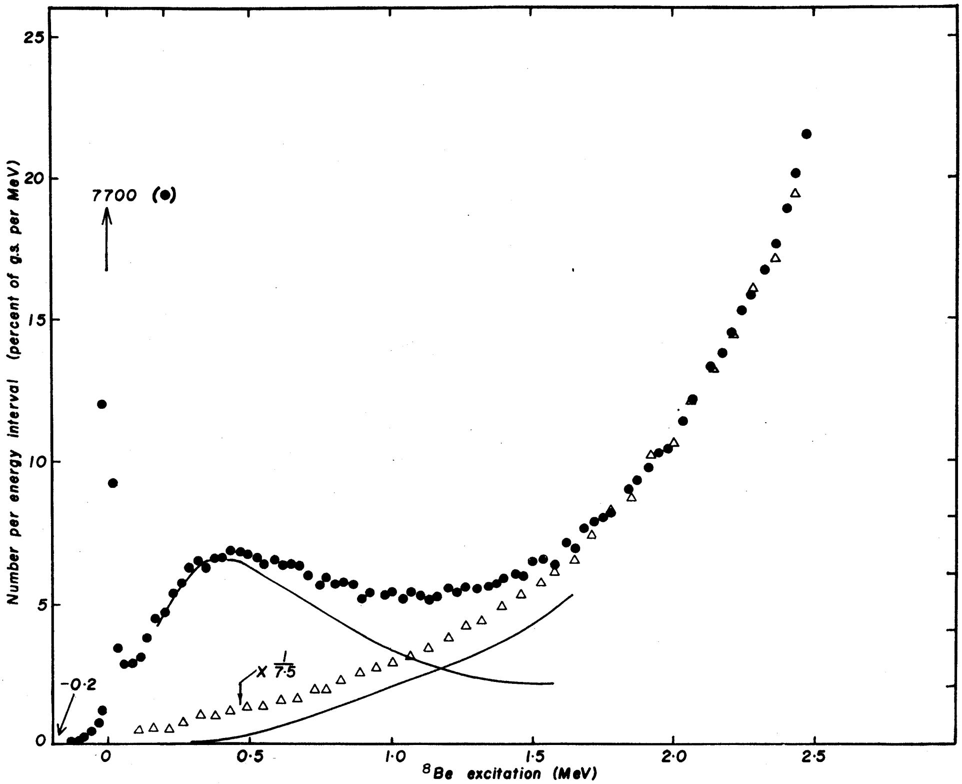

Fig. 4.—Experimental deuteron spectra obtained from ^{9}Be(p, d) with 5·2 MeV protons at angles of 10° (●) and 60° (△). The curves represent approximate contributions to the 10° spectrum associated with the ^{8}Be ground state (excitation zero) and first excited state (excitation 2·9 MeV). The arrow indicates the number of counts in the main ground-state peak at zero excitation.

In the special case of single-level R-matrix theory, a unique line-shape function can be defined (Lane and Thomas 1958) once level parameters (position E_0 and reduced width γ_0^2 (Lane and Thomas 1958)) are known. Such a function applicable to ^{8}Be is

$$\rho(E) = \frac{P\gamma_0^2}{(E_0 - S\gamma_0^2 - E)^2 + (P\gamma_0^2)^2},$$

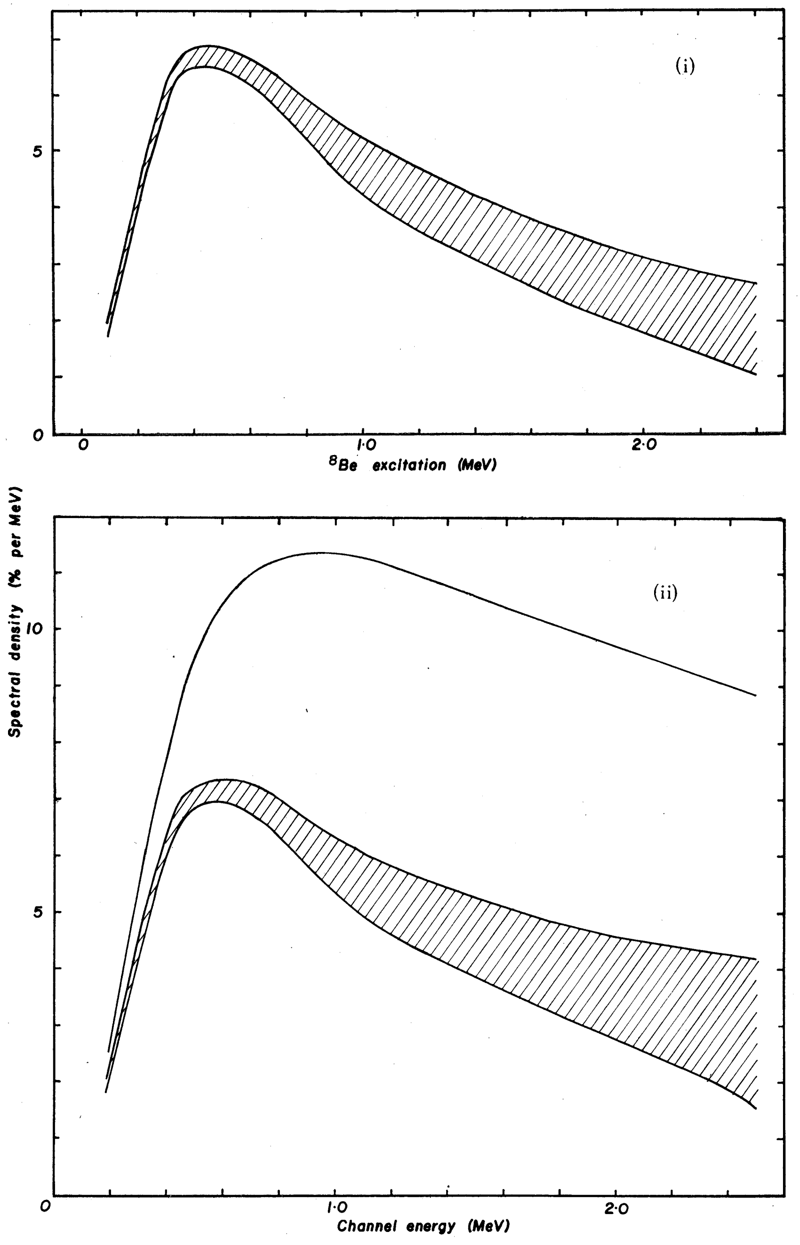

Fig. 5.—(i) Spectral density (deuteron spectrum) measured as percentage (per MeV excitation) of the ground-state peak; the curves containing the cross-hatched area are drawn at 50% of the extreme variations obtained from the analysis described in the text; (ii) spectral density (line-shape function) associated with the results shown above corrected for a neutron penetration factor; the separate curve drawn above the cross-hatched area is a theoretical line-shape function expected on the basis of α–α scattering data and assuming a ^{8}Be channel radius of 3·5 fm.

where E is the channel energy (here, excitation plus $0\cdot094$ MeV) and S and P are the shift and penetration factors appropriate to the chosen ^{4}He plus ^{4}He channel radius. The boundary condition parameter has no influence on this function, since it can be absorbed completely into E_0. Barker and Treacy (1962) calculated a "best fit" set of parameters from scattering data up to 3 MeV and deduced a channel radius of $3\cdot5$ fm. A calculated line shape with the same parameters is plotted in Figure 5(ii). Agreement with the data is not good. Though the general shape of the curve is correct, the ghost peak comes out at $11\cdot3$ % per MeV, compared with a peak of $(7\cdot1\pm0\cdot2)$ % observed at a significantly lower energy.

One possible reason for the discrepancy is that the observed spectrum might suffer interference from the alternative mode of decay ^{9}Be(p, d)^{6}Li(d)^{4}He, which has indeed been observed (Browne and Bockelman 1951). Figure 3 shows direct evidence for a peak due to excitation of the $2\cdot18$ MeV level of ^{6}Li. There is a rise near $2\cdot5$ MeV which corresponds to the lower limit to an expected continuous spectrum. As the beam energy is lowered (Fig. 3) this continuum comes down. At $1\cdot7$ MeV proton energy it starts at an excitation of $0\cdot5$ MeV. Below this point the spectrum cannot be fed from ^{6}Li except from the low energy tail of the $4\cdot57$ MeV level (Lauritsen and Ajzenberg-Selove 1966) which populates this region at excitation of $3\cdot66$ MeV by emission of α-particles of zero energy in the centre-of-mass system. It is significant, therefore, that the ghost region is unaltered between the $5\cdot2$ and $1\cdot7$ MeV runs, and this suggests that levels of ^{6}Li higher than $2\cdot18$ MeV do not contribute here, apart from perhaps the small residual ($0\cdot4$ % per MeV) background already mentioned. The possibility remains that some interference might be attributed to direct three-body breakup. However, the data plotted in Figure 1 for excitation *below* the ground state do not extrapolate in the ghost region to a significant amount of a three-body spectrum of conventional form.

From these considerations it seems likely that more than one spin-zero level of ^{8}Be may contribute to the line shape or to the scattering, or both. This problem is to be discussed in another paper, in which a consistent R-matrix description of these processes will be attempted (Barker, Hay, and Treacy, paper in preparation).

A comparison of the present data with predictions of complex eigenvalue theory (Humblet 1964; Mahoux 1965) cannot be made uniquely, since the concept of line shape has not been defined in that theory. However, a plausible definition for such a function (Treacy 1965) would seem to imply the existence of a ground-state ghost of about 22 % per MeV, i.e. about three times that observed in the present experiment.

V. Acknowledgments

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VI. References

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