THE 1·67 MeV LEVEL IN ^{9}Be

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Abstract

A study has been made of the 1·67 MeV level in ^{9}Be using 6·0 MeV protons to populate it via the ^{9}Be(p, p′)^{9}Be* reaction. The spectrum of protons inelastically scattered at a 90° laboratory angle was fitted with a line shape based on R-matrix theory. The position of the line-shape peak above the ^{8}Be+n threshold is 25^{+15}_{-11} keV; this value and deduced level parameters are in disagreement with recent results from a similar fit to the ^{9}Be(γ, n)^{8}Be reaction.

I. Introduction

The first excited state at 1·67 MeV in ^{9}Be as studied, for example, by inelastic proton scattering in ^{9}Be, arouses interest because of its strongly asymmetric shape and nearness to the ^{8}Be+n threshold. These properties have prompted suggestions, such as that of Spencer, Phillips, and Young (1960), that it is "not a state in the usual sense". Barker and Treacy (1962) showed that a straightforward description of this level is possible in terms of R-matrix theory (Lane and Thomas 1958). In their analyses they assumed a channel radius of 4·35 fm (as with all analyses to be discussed here) and a reduced width γ^2 of 1·01 MeV, as estimated by Barker (1961) from a weak-coupling shell model. A good fit was obtained to the data of Spencer, Phillips, and Young with a resonance energy E_{r} of 0·11 MeV and a peak energy (energy of the line-shape peak above the ^{8}Be+n threshold) of 19 keV. More recently Barker and Fitzpatrick (1968) examined data on the same level excited in the ^{9}Be(γ, n)^{8}Be reaction from experiments by Gibbons *et al.* (1959), John and Prosser (1962), and Berman, Van Hemert, and Bowman (1967). They found $\gamma^2 = 1·00$ MeV and $E_{\mathrm{r}} = 0·063$ MeV, with a fit giving a peak energy of only 6 keV. The apparent divergence between the two analyses suggests a need for more accurate data. The present paper describes a further study of the ^{9}Be(p, p′)^{9}Be* reaction with good (6·8 keV) resolution and an R-matrix analysis with a detailed study of the way in which fits to the data depend on the parameters of the level.

II. Experimental Results

A 300 nA proton beam of energy 6·0 MeV from the A.N.U. Tandem accelerator was focused through a narrow defining slit of height 0·037 cm onto a thin ^{9}Be metal target, of surface density 12 μg cm^{-2} deposited on a 15 μg cm^{-2} backing of carbon. Inelastically scattered protons were detected at a laboratory angle of 90° with Ilford K2 nuclear emulsions in a broad range Buechner spectrograph. In order to minimize the energy spread of the detected protons, the normal to the target surface

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was set at 58° to the beam in "transmission" geometry, at which angle the sum of the energy losses of ingoing and outgoing protons was most nearly constant. A knowledge of the overall detected energy profile was considered essential for the analysis. For this purpose, a spectrum was built up by short exposures of a separate emulsion, at regular intervals through the main run, to the intense group of protons elastically scattered from the ^{9}Be target.

The spectrum of protons for transitions to the $1 \cdot 67$ MeV level is shown in Figure 1. The energy profile for elastic scattering (not illustrated) was approximately Gaussian and of width $6 \cdot 8$ keV (FWHM). This value could be fully accounted for by the expected spectrograph resolution, kinematic broadening by the finite detector size, straggling in the target and backing, and the beam energy spread of the accelerator.

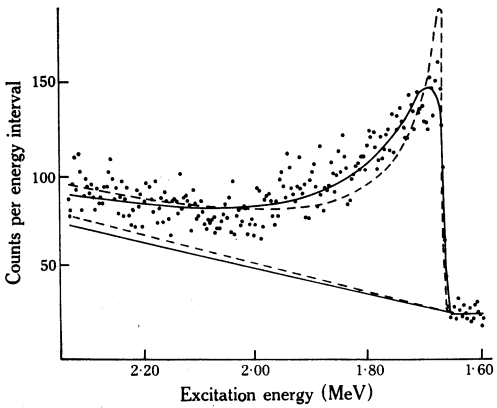

Fig. 1.—Spectrum from the inelastic scattering of $6 \cdot 0$ MeV protons to the $1 \cdot 67$ MeV level of ^{9}Be in the reaction $^9\mathrm{Be(p, p')}^9\mathrm{Be}^*$ at a laboratory angle of 90°. The full curves represent the best fit and background from an R-matrix fit with parameters $E_{\mathrm{r}} = 0 \cdot 11$ MeV and $\gamma^2 = 0 \cdot 8$ MeV. The dashed curves represent a corresponding fit to the $^9\mathrm{Be}(\gamma, \mathrm{n})^8\mathrm{Be}$ cross section with $E_{\mathrm{r}} = 0 \cdot 063$ MeV and $\gamma^2 = 1 \cdot 00$ MeV (Barker and Fitzpatrick 1968).

III. Analysis of Results

As shown by Barker and Treacy (1962) the energy dependence of the cross section for the $^9\mathrm{Be(p, p')}^9\mathrm{Be}^*$ process leading to the $1 \cdot 67$ MeV level of ^{9}Be may be written as

$$\sigma(E) = C P_{\mathrm{p}}(E) P_{\mathrm{n}}(E) \gamma^2 / [(E_{\mathrm{r}} - E)^2 + \{P_{\mathrm{n}}(E) \gamma^2\}^2], \tag{1}$$

where C is a normalization constant; $P_{\mathrm{p}}(E)$ and $P_{\mathrm{n}}(E)$ are penetration factors for the outgoing proton and for the neutron in the subsequent decay of the $^9\mathrm{Be}^*$ nucleus, of channel energy E above the $^8\mathrm{Be}+\mathrm{n}$ threshold; and the constants E_{r} and γ^2 are the resonance energy and the reduced width of the $1 \cdot 67$ MeV level, of spin and parity $\frac{1}{2}^+$ (Lauritsen and Ajzenberg-Selove 1966).

To represent the experimental line shape of Figure 1 certain assumptions were necessary. First, P_{p} was not known explicitly, as the detailed mechanism of the (p, p′) process is not understood; because of the known high density of levels of ^{10}B excited in the region of interest, P_{p} values corresponding to s-, p-, and d-waves were considered possible. Secondly, it was necessary to assume a background underlying the level, to allow for contributions from the very broad resonances at higher excitation energies, and possibly also from three-body breakup. For the observed excitation energies up to $2 \cdot 3$ MeV, backgrounds of flat, linear, and quadratic character in E were considered. Arguments are given below to justify the exclusion of more complicated possibilities.

Data were fitted to the form of $\sigma(E)$ defined in (1) by using a nonlinear least-squares program to minimize the quantity

$$X^2 = \frac{1}{N-M}\sum_{i=1}^{N}\left|\frac{\sigma_{\rm ex}(i)-\sigma_{\rm th}(i)}{\epsilon(i)}\right|^2$$

as a function of the M independent parameters (C, $E_{\rm r}$, etc.), where $\sigma_{\rm ex}(i)$ and $\sigma_{\rm th}(i)$ are the experimental and theoretical values at the N datum points i and $\epsilon(i)$ is the assigned error in $\sigma_{\rm ex}(i)$. The $\sigma_{\rm th}(i)$ values were obtained by numerically folding $\sigma(E)$ with the profile obtained for the elastically scattered protons. Fits were first obtained over a range of values of $E_{\rm r}$ and γ^2 with $P_{\rm p}$ assumed to be that of an s-wave proton.

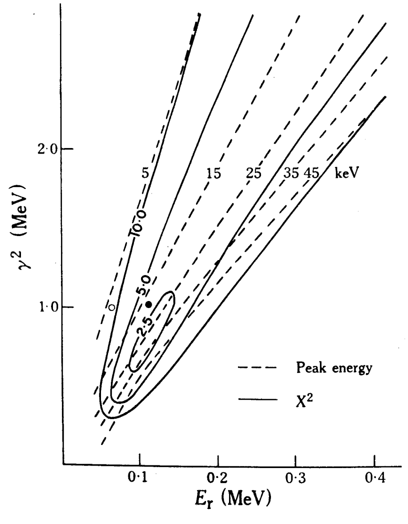

Fig. 2.—Contours in the $E_{\rm r}, \gamma^2$ plane of constant goodness-of-fit X^2 to the data of Figure 1, and also contours of constant peak energy for the theoretical function $\sigma(E)$ defined by equation (1). The points o and ● correspond to values of $E_{\rm r}, \gamma^2$ for fits by Barker and Fitzpatrick (1968) and Barker and Treacy (1962) respectively to other data as described in the text.

Optimum fits were obtained with the quadratic background coefficient essentially zero. The fits obtained are shown in the form of contours of constant X^2 in the $E_{\rm r}, \gamma^2$ plane in Figure 2. There is an ill-determined minimum with $X^2 = 2\cdot47$ at $E_{\rm r} = 0\cdot11$ MeV, $\gamma^2 = 0\cdot80$ MeV with a long flat valley extending up to higher values of these parameters. The best fit and background are plotted as full curves in Figure 1.* Also plotted in Figure 1 (dashed curves) are the best fit and background corresponding to Barker and Fitzpatrick's (1968) parameters for the $(\gamma, \rm n)$ reaction. The latter fit as well as that of Barker and Treacy (1962) are represented by an open and solid circle respectively in Figure 2. Also shown in Figure 2 are dashed curves connecting points of constant peak energy for the function $\sigma(E)$; reference to these curves shows that the $(\gamma, \rm n)$ data correspond to a peak closer to threshold than those for the $(\rm p, p')$ data.

The assumption of an s-wave proton penetration factor underlies all the analyses discussed so far. However, it was found that the inclusion of p- or d-waves led to almost identical values of E_γ and γ^2 with X^2 only about 3% less. We may conclude that the level parameters implied by the fit to Figure 1 are not influenced significantly by the two assumptions noted above.

* From the absolute yield of the reaction and known target thickness, this fit corresponds to a 90° laboratory differential cross section of 250 ± 40 μb sr^{-1} for the complete line.

IV. Discussion

The cause of the discrepancy between the fits to the (p, p′) and (γ, n) data is not known. Certainly, most of the (γ, n) data analysed by Barker and Fitzpatrick (1968) were obtained with thick targets (1·25 and 2·5 cm thick blocks of beryllium) and the effect of multiple scattering of the outgoing neutrons was not taken into account. However, one would not expect such an effect to lead to an erroneously *low* value for peak energy, as seems implied by comparison with the (p, p′) data.

It should be emphasized that the contour plots of Figure 2 imply rather ill-defined, though interrelated, values of E_r and γ^2. However, the minimum X^2 does not occur at a point significantly different from that corresponding to Barker's (1961) value of $\gamma^2 = 1 \cdot 01$ MeV. Taking this, and allowing for errors corresponding to a doubling of X^2 in the contours of Figure 2, we find $E_r = 0 \cdot 11 \pm 0 \cdot 03$ MeV with a corresponding peak energy of 25^{+15}_{-11} keV above the ^{8}Be+n threshold.

V. References

Barker, F. C. (1961).—*Nucl. Phys.* **28**, 96.

Barker, F. C., and Fitzpatrick, B. M. (1968).—*Aust. J. Phys.* **21**, 415.

Barker, F. C., and Treacy, P. B. (1962).—*Nucl. Phys.* **38**, 33.

Berman, B. L., Van Hemert, R. L., and Bowman, C. D. (1967).—*Phys. Rev.* **163**, 958.

Gibbons, H. J., Macklin, R. L., Marion, J. B., and Schmidt, H. W. (1959).—*Phys. Rev.* **114**, 1319.

John, W., and Prosser, J. M. (1962).—*Phys. Rev.* **127**, 231.

Lane, A. M., and Thomas, R. G. (1958).—*Rev. mod. Phys.* **30**, 257.

Lauritsen, T., and Ajzenberg-Selove, F. (1966).—*Nucl. Phys.* **78**, 1.

Spencer, R. R., Phillips, G. C., and Young, T. E. (1960).—*Nucl. Phys.* **21**, 310.