# Interference of $Be^{8*}$ Levels and Final-State Coulomb Interactions*

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Recent precision measurements of the interfering levels in $Be^8$ at 16.6 and 16.9 MeV are in good agreement with a simple two-level formula with interference when it is properly corrected for the effects of final-state Coulomb interactions. The widths used in the formula are $\Gamma(16.6) = 90$ keV and $\Gamma(16.9) = 70$ keV. It is not necessary to assume that the $T = 1$ components of the $Be^8$ wave functions are excited in the reactions $B^{10}(d,\alpha)Be^{8*}$ and $Li^6(Li^6,\alpha)Be^{8*}$. Using the latter reaction, it is shown that the background is too small to have an appreciable effect on the spectral shape for the two levels.

The formation of the 16.6 and 16.9-MeV states in $Be^8$ has been studied extensively for the reactions $B^{10}(d, \alpha)Be^{8*}$ [1-5] and $Li^6(Li^6, \alpha)Be^{8*}$.[6-9] High-resolution experiments showing the detailed shape of the resonant peaks have been done for the $B^{10}(d, \alpha)Be^{8*}$ reaction.[4,5] Coincidence experiments to determine the effect of the $Be^8$ breakup angle on the $\alpha$-particle spectrum have been done for $Li^6(Li^6, \alpha)Be^{8*}$.[8,9] The less precise experiments determined the ratio of the areas under the two peaks but could do little to determine the shapes. It was found that this ratio was essentially the same for both the $B^{10}$ and $Li^6$ reactions and for a variety of energies and angles. Figure 2 of Ref. 3 showed the angular distributions for the $B^{10}$ reaction with a 7.5-MeV deuteron beam. The two angular distributions appeared to be identical. Reference 7 was a study of the angular correlation between the direction of the $\alpha$ particle and the direction taken by the $Be^8$ breakup fragments. Again the behavior of the two states was identical within the errors of the measurements.

When the more precise magnetic-spectrograph measurements were made of the $B^{10}(d, \alpha)Be^{8*}$ reaction,[4,5] all of the characteristics of the two levels seemed to be a function of the reaction parameters. Not only the ratios of the areas of the peaks but also their widths and locations and the character of the interference between them varied with angle and beam energy.

The more precise coincidence measurements showed that the location and the shape of the peaks in the $\alpha$-particle spectrum were a systematic function of the angle taken by the $Be^8$ breakup fragments. These effects were shown to arise from the electrostatic repulsion between the $Be^8$ breakup fragments and the original $\alpha$ particle. It is these final-state Coulomb interactions that are responsible for the anomalies found in the high-precision magnetic-spectrograph measurements.

Kirilyuk[10] has offered the suggestion that the observed anomalies could be explained as interference between the 16.6- and 16.9-MeV levels and the large background that appears in the high-precision spectra. The coincidence measurements show that this large background is due almost entirely to $\alpha$ particles which arise from the breakup of the various states in $Be^8$. By choosing appropriate coincidence angles this background can be avoided. Figure 1 shows a spectrum taken in this manner. The small remaining background is the maximum that could be attributed to the tails of distant broad levels and to direct three-body processes. This residual background is too small to have an appreciable effect on the shape of the resonant peaks.

It has been suggested that the anomalies with the $B^{10}(d, \alpha)Be^{8*}$ reaction could be caused by population of the $T = 1$ components of the 16.6- and 16.9-MeV states. This possibility cannot be ruled out, but after taking into account the effects of final-state Coulomb interactions there is nothing in the experimental results for either this reaction or the $Li^6(Li^6, \alpha)Be^8$ reaction that demands this additional complication.

One of the most interesting features of the spectrum of the 16.6- and 16.9-MeV states is the interference that deepens the valley between the two peaks. Callender and Browne[5] used the coherent sum of two Breit-Wigner amplitudes

$$\sigma \sim \left| \frac{\Gamma_a}{E - E_a + \frac{1}{2} i \Gamma_a} + \frac{\Gamma_b}{E - E_b + \frac{1}{2} i \Gamma_b} \right|^2 ,$$

which can be written as

$$\sigma \sim \left| \frac{E(\Gamma_a + \Gamma_b) - (\Gamma_a E_b + \Gamma_b E_a) + i \Gamma_a \Gamma_b}{(E - E_a + \frac{1}{2} i \Gamma_a)(E - E_b + \frac{1}{2} i \Gamma_b)} \right|^2 . \qquad (1)$$

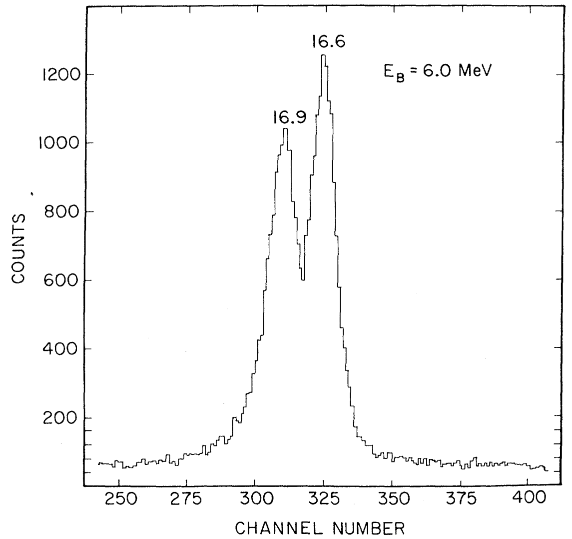


FIG. 1. $\alpha$-particle spectrum from the $Li^6(Li^6,\alpha)Be^{8*}$ reaction depicting the low background associated with the peaks from the 16.6- and 16.9-MeV states in $Be^8$. The detector, at a laboratory angle of +15°, was gated by $\alpha$ particles at −70°. Better resolution would have produced a deeper valley between the peaks. The asymmetry on the left side of the peaks is due to final-state Coulomb interactions.

Kirilyuk[10] has recommended adding the two amplitudes with a phase factor chosen so that the $S$ matrix for the $\alpha$-$\alpha$ two-body reaction remains unitary,

$$S=\frac{(E-E_a-\frac{1}{2}i\,\Gamma_a)(E-E_b-\frac{1}{2}i\,\Gamma_b)}{(E-E_a+\frac{1}{2}i\,\Gamma_a)(E-E_b+\frac{1}{2}i\,\Gamma_b)}\,.$$

This gives a cross section

$$\sigma\sim\left|\frac{E(\Gamma_a+\Gamma_b)-(\Gamma_a E_b+\Gamma_b E_a)}{(E-E_a+\frac{1}{2}i\,\Gamma_a)(E-E_b+\frac{1}{2}i\,\Gamma_a)}\right|^2. \qquad (2)$$

Although the valley dips all the way to zero in the second formula, the difference between the two formulas is so small that the present magnetic-spectrograph experiments are not able to distinguish between them, even in the absence of final-state Coulomb interactions.

To apply the calculations for the coincidence experiments to the high-precision measurements, it is necessary to integrate over all possible $Be^8$ breakup angles. Since these states have spin 2, the $Be^8$ breakup pattern is not isotropic. The largest uncertainty in the interpretation of the integrated spectra comes from the lack of knowledge of the angular-correlation patterns. In the calculations, the angular correlations were used as free parameters, subject to the restriction that the amount of anisotropy not be any greater than that which has been measured[7,11] for other reactions that produce the same pair of states in $Be^8$.

By using calculational techniques similar to those described in Ref. 8, we were able to fit all of the high-precision integrated spectra from the $B^{10}(d,\alpha)Be^{8*}$ reaction using a single set of energies and widths in Eqs. (1) and (2). These parameters were $(E_a-E_b)=290$ keV, $\Gamma(16.6)=90$ keV, and $\Gamma(16.9)=70$ keV. The uncertainty in the separation energy, which was chosen only to match the data given in Ref. 5, was about 7 keV. The widths should be within 5 keV of the true widths of these $Be^8$ states. It will be interesting to compare these values with those from precision $\alpha$-$\alpha$ scattering when such measurements become available.

Final-state Coulomb interactions are a conspicuous feature of the $\alpha$-particle spectra from the reactions $B^{10}(d,\alpha)Be^{8*}$ and $Li^6(Li^6,\alpha)Be^{8*}$. To get an unambiguous separation of these effects from genuine nuclear effects, it is necessary to make use of coincidence measurements. Such a separation is essential if useful information is to be gained from the details of the spectral shapes.

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