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Precision measurement of the 9.641 MeV, 3^- state in ^{12}C

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High-energy-resolution magnetic spectrometer measurements have been used to determine the width of the 9.641 MeV ^{12}C, 3^- excited state. The width is found to be 48(2) keV with an R-matrix analysis. This would correspond to 30% of the Wigner limit, indicating a significant α-particle content to the state. This is a marked improvement on results of earlier studies that yielded 34(5) keV.

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Advances in nuclear theory and computing now permit detailed testing of our understanding of nuclear structure. In particular light nuclei are a key testing ground. In this sense ^{12}C is extremely important in that it lies at the extreme of the range of the Green's function Monte Carlo (GFMC) approach [1] and has the potential to constrain models of the nucleon-nucleon interaction. The structure of this nucleus contains a range of phenomena ranging from the single-particle nature of the ground state to the clusterization of the 7.65 MeV, Hoyle state. Providing precision measurements of the properties of the excited states is extremely important. Recently, measurements have indicated that there is a hitherto unknown $I^\pi = 2^+$ state close to 9.6 MeV [2,3] and that a previously tabulated 2^+ state at 11.16 MeV [4] does not exist [5].

In the case of the third excited state of ^{12}C at 9.641 MeV ($I^\pi = 3^-$), its width is tabulated as 34 ± 5 keV [4]. This value was the result of measurements made over 50 years ago using spectrometers with photographic plates [6,7]. Modern spectrometers have not only high energy resolution but active focal plane detectors which permit precision studies. In particular, it is possible to project reconstructed excitation energy spectra against experimental parameters to ensure the resolution is optimized. Here we report an improved measurement of the width of the 9.641 MeV state. The width is found to be 40.4(0.4) keV from an analysis using a Lorentzian line shape, but 48(2) keV with an R-matrix analysis.

In the present studies the ^{12}C 9.641 MeV state was populated using the ^{12}C(p,p') inelastic scattering reaction and a 66 MeV proton beam. The measurements were performed at iThemba LABS, in South Africa with a 1 mg/cm^2 natural carbon target. Inelastically scattered protons were detected at the focal plane of the K600 spectrometer ($\theta_{\rm lab} = 10^\circ$, 16°, and 28°). For each of these measurements the angle of the target was adjusted such that the angle with respect to the beam direction was 0°, 5°, and 14°, respectively, for the three measurements. Depending on the angle, the beam is calculated to lose between 9.0 and 9.3 keV as it traverses the target. Assuming the interaction takes place at the upstream face of the target the energy loss of the protons scattered following the excitation of the 9.641 MeV excited state range from 10.4 to 10.6 keV (from 10° to 28°). Thus, the contribution to the experimental resolution from the uncertainty in the location of the interaction in the target is expected to be less than 2 keV.

Figure 1 shows the ^{12}C excitation energy spectra, focusing on the region associated with the 3^- excitation. In addition to the 3^- state the 7.65 MeV 0^+ state was also on the focal plane. This state has been shifted in Fig. 1(a) such that its centroid coincides with that of the 3^- state. The natural width of the 7.65 MeV resonance is 8.5 eV and hence is a good test of the resolution of the K600 spectrometer including the energy loss and straggling in the target.

A fit to the 7.65 MeV peak with a Gaussian line shape indicates an experimental resolution of 23(1) keV (FWHM).

A fit to the 3^- peak has been performed using a Voigt line shape:

$$V(E) = \int_{-\infty}^{\infty} \frac{e^{-\frac{(E-E')^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \frac{\Gamma/2}{\pi[(E-E_x)^2 + (\Gamma/2)^2]} dE', \tag{1}$$

computed using

$$V(E) = \frac{\mathrm{Re}[w(z)]}{\sigma\sqrt{2\pi}} \tag{2}$$

where $w(z)$ is the Faddeeva function [8] and $z = (E + i\Gamma/2)/\sigma\sqrt{2}$. The resolution σ was fixed at 23(1) keV and the centroid E_x and resonance width Γ were left as free parameters. In addition, it is believed that there is a broad ($\Gamma \sim 600$ keV) 2^+ component in the region of 9.6 MeV [3]. This has been accounted for through the inclusion of an additional broad component with the width and centroid as free parameters. In this instance a series of line shapes for this component were explored, including Gaussian and Lorentzian and with the broad component removed. Finally a quadratically varying background component was included.

The optimal fits for the angles 10°, 16°, and 28° were 40.9(1.0), 39.0(1.4), and 40.6(1.1) keV, respectively. The uncertainties correspond to the variation of the energy resolution by 1 keV taken in quadrature with the variation in the fit parameters by the three different types of background conditions described above. As shown in Fig. 1(b) the three line shapes are very similar. In each case the states fall on different parts of the focal plane detector and it has been

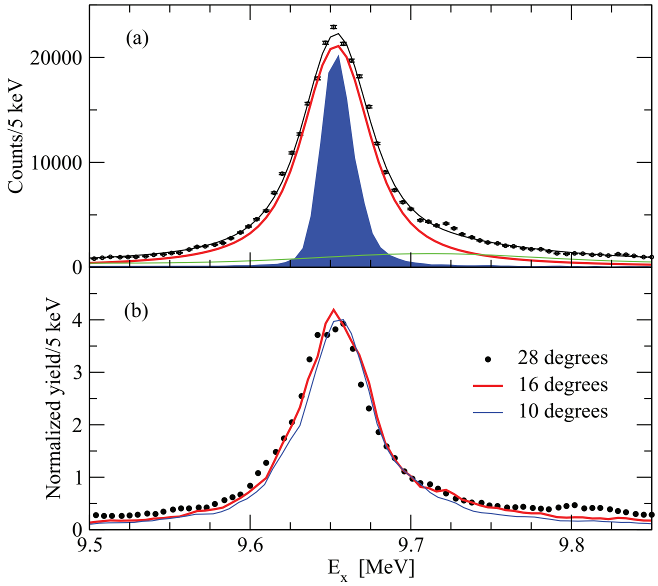

FIG. 1. (Color online) The ^{12}C 9.641 MeV 3^- excited state populated in proton inelastic scattering. (a) The 16° data. The fit to the full spectrum is given by the black solid line (the upper most solid line) and the 3^- peak the red solid line (the middle solid line). The green line (the lowest solid line) corresponds to the contribution from the 2^+ state at this energy which has been simulated using a Gaussian line-shape. The blue shaded histogram corresponds to the measured 7.65 MeV, 0^+ state which has been used to determine the experimental resolution. (b) Shows the scaled spectra for the measurements at 10 (the lower solid line), 16 (the upper most solid line) and 28 degrees (data points).

possible to check for dependencies, for example, on the angular acceptance (horizontal and vertical) of the spectrometer. In this way any residual kinematic dependence and aberration have been removed. The $\chi^2/\text{d.o.f.} = 10$, the magnitude of which partially reflects the fact that the response of the focal plane detector has a slightly differential nonuniform response which results in a ripple effect that is larger than the statistical uncertainties. This effect can be seen in Fig. 1(b), where there is a fluctuation at the top of the peak for the 28° data. These fluctuations are typically larger than the statistical uncertainties, which, as shown in Fig. 1(a), are small. The weighted average of these three measurements is $\Gamma = 40.4(0.4)$ keV.

The 9.641 MeV, 3^- state decays predominantly to the ^{8}Be ground state, through an $L = 3$ centrifugal-plus Coulomb barrier. This has the effect of modifying the Lorentzian line shape making it asymmetric. The corresponding line shape has been calculated using the R-matrix formalism with the amplitude of the resonance line shape *A(E)* given by the form

$$A(E) = N\frac{\Gamma_\alpha}{(E_{\text{res}} - E - \Delta)^2 + (\Gamma_\alpha/2)^2}, \tag{3}$$

where $\Gamma_\alpha = 2P_l(E)\gamma_\alpha^2$, E_{res} is the resonance energy, E the energy in the center-of-mass system, γ_α^2 the reduced α width, and $P_l(E)$ the barrier penetrability factor for the given orbital angular momentum l; $l = 3$ in the present case. N is a normalization constant. The energy shift is given by $\Delta = \gamma_\alpha^2[S(E) - B]$, where $S(E)$ is the shift function and B is the boundary condition defined as the value of $S(E_{\text{res}})$, where

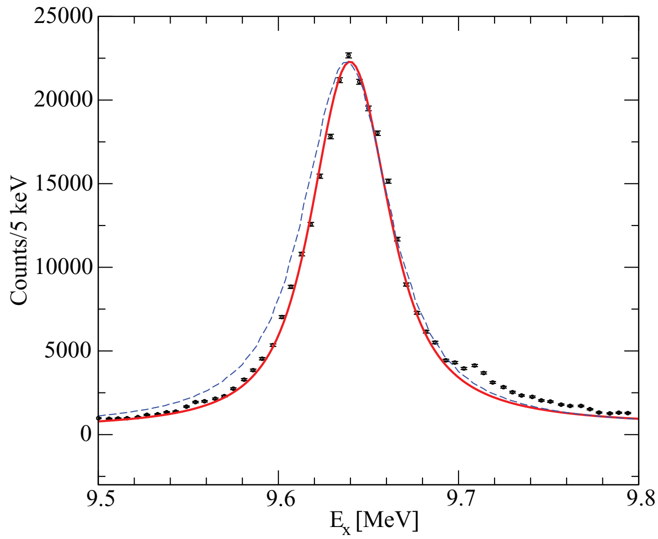

FIG. 2. (Color online) Comparison between the 16° data (data points) and an R-matrix calculated line shape with $\Gamma = 48$ keV convoluted with a Gaussian 23 keV resolution response (red line) and a Lorentzian with a 48 keV width again folded with a 23 keV resolution (blue dashed line).

$$S(E) = \frac{\rho(FF' + GG')}{F^2 + G^2}, \tag{4}$$

where $\rho = kR$ and F, G, F', and G' are regular and irregular Coulomb wave functions and their derivatives, respectively. For these calculations the channel radius $R = 1.3(4^{1/3} + 8^{1/3})$ was used. To reproduce the data, γ_α^2 was set equal to 30% of the Wigner limit ($3\hbar^2/2\mu R^2$ [9], where μ is the reduced mass). This line shape is slightly asymmetric with a high-energy tail and is shown in Fig. 2 convoluted with a Gaussian 23 keV resolution.

The width calculated at the resonant energy E_{res} is 48(2) keV, i.e., greater than 40.4(0.4) keV. The suppression of the low-energy side of the resonance line shape of the same width is clear in Fig. 2, where a Lorentzian line shape with $\Gamma = 48$ keV has been overlaid. The corresponding large width [48(2) keV] compared with the Wigner limit indicates that the state has a reasonably well-developed α-cluster structure.

It is also possible to calculate the single-particle width using a simple potential model. This is the width which would correspond to the α particle being preformed. The Gamow model [10] has been used, which computes the complex energy of a pole of the scattering function for a defined potential; here the imaginary component corresponds to the width of the decaying state. The wave function within the potential is defined in terms of the number of internal nodes n in the radial wave function and can be linked to the global quantum number $G = 2n + L$, with L being the orbital angular momentum. In the present case for $L = 3$, the cases $G = 5, 7$, and 9 are considered, which would correspond to 1p-1h, 2p-2h, and 4p-4h excitations, respectively. The calculations indicate widths of 31, 53, and 75 keV for these three cases, respectively, for a $^{8}\mathrm{Be}+\alpha$ center-of-mass energy of 2.275 MeV with the widths being rather insensitive to the choice of potential (Woods-Saxon or Cosh). The experimental width of 40.4(0.4) keV is a substantial fraction of these, again indicating a well-developed cluster structure.

In conclusion, a determination of the width of the 9.641 MeV, 3^- excited state in ^{12}C is reported. The width is found to be 48(2) keV with an R-matrix analysis. This latter width would correspond to 30% of the Wigner limit, suggesting a significant α-particle content to the state.

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