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Zimmerman, W.R.; Freer, M.; Destefano, N.E.; Gai, M.; Smit, F.D.

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Further evidence for the broad 2_2^+ state at 9.6 MeV in ^{12}C

W. R. Zimmerman,[1,2] N. E. Destefano,[1,2] M. Freer,[3] M. Gai,[1,2] and F. D. Smit[4]
[1]*Laboratory for Nuclear Science at Avery Point, University of Connecticut, Groton, Connecticut 06340-6097, USA*
[2]*WNSL, Department of Physics, Yale University, New Haven, Connecticut 06520-8124, USA*
[3]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[4]*iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa*
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We measured the ^{12}C(p, p')^{12}C* reaction at 25 MeV at the three laboratory angles of 20°, 35°, and 45°. The measured spectra support recent evidence for a new broad 2_2^+ state at 9.6 MeV in ^{12}C, but do not support the claim for such a broad state at 11.1 MeV.

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A recent measurement of the ^{12}C(p, p') reaction performed at the iThemba LABS [1] provided evidence for a broad (Γ = 600 keV) 2^+ state at 9.6 MeV in ^{12}C. The existence of this 2_2^+ state in ^{12}C below 10.5 MeV has been the subject of much debate since it was observed in a ^{12}C(α,α') measurement [2], but it was not observed in the beta decays of ^{12}N and ^{12}B [3]. Such a 2^+ state at 9.11 MeV (a member of the rotational band built on top of the Hoyle state at 7.654 MeV in ^{12}C) was predicted [4] to significantly alter the rate of the formation of ^{12}C at high temperatures (T > 3 GK) during stellar helium burning [5]. Such a rotational band was not predicted by the newly suggested low-N limit of a Bose-Einstein condensate (BEC) structure of the Hoyle state [6]. In this model, the 2_2^+ was predicted to be an alpha-vibrational state.

We used a 25 MeV proton beam extracted from the Yale tandem to measure the ^{12}C(p, p') reaction at an energy lower than used in Ref. [1]. As we discuss below, at 25 MeV, we observe small contributions from the broad (Γ = 3.0 MeV) 0_3^+ state at 10.3 MeV that dominated the iThemba LABS data [1]. But our experiment is plagued by another (most likely instrumental) background, hence we do not plan to continue this study (e.g., to achieve higher statistics). However, we present our data in this Brief Report since it gives credence to the findings of Ref. [1] on the observation of the broad 2_2^+ state at 9.6 MeV in ^{12}C.

Measurements with a 25 MeV (∼10 nA) proton beam and thin (40 μg/cm^2) natural ^{12}C and enriched (93%) ^{13}C targets were performed. The protons were detected in the Yale Enge Split Pole Spectrometer [7] with a solid angle of 2.8 msr and angular opening of $\Delta\theta \approx \pm 1°$, at laboratory angles of 20°, 35°, and 45°. The energy resolution was measured using the narrow 0_2^+ Hoyle state at 7.654 MeV as well a the narrow 1^+ state at 12.710 MeV [8]. The large background observed in all three angles (see Fig. 1) cannot be associated with a state in ^{12}C. This background is larger at small angles and for lower-energy scattered protons, hence we conclude that it arises (most likely) from plural scattering of protons (e.g., in the slits, etc.).

The data shown in Fig. 1 allow us to discriminate inelastic scattering from contaminants in the target (e.g., hydrogen, oxygen, or ^{13}C), since the contaminant lines appear at each angle at a different computed "excitation energy" in ^{12}C.

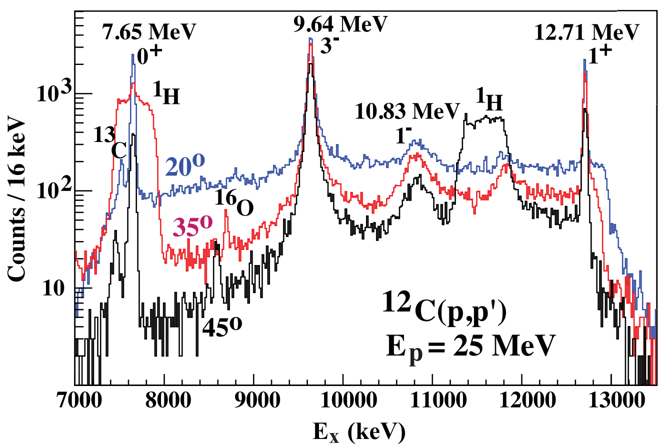

FIG. 1. (Color online) The scattered proton spectra measured at laboratory angles of 20° (top blue line), 35° (middle red line), and 45° (bottom black line).

The contaminant lines were also directly observed using the (93%) enriched ^{13}C target. The contribution of the broad 2_2^+ at 9.6 MeV is observed at all three measured angles as tails on the high- and low-energy sides (i.e. skirt) of the narrow (Γ = 34 keV) 3^- state at 9.641 MeV in ^{12}C, hence it is associated with the new 2^+ state in ^{12}C [1] and is not due to contaminant in the target.

In Fig. 2, we show the data measured at 20° compared to a fit with contributions from all known states in ^{12}C and including a broad 2_2^+ at 9.6 MeV. Each state is represented by a Lorentzian with width and energy fixed to the known values [8]. The (particle) widths are modified by the Coulomb penetrability factors (and the phase space kR factor), leading to the asymmetric Lorentzians shown in Fig. 2. The calculated line shapes are folded with the measured instrumental energy resolution [full width at half maximum (FWHM) = 37.0 keV at this angle]. We note the very small contribution of the 0_3^+ at 10.3 MeV in ^{12}C. The energy and width of the 2_2^+ state are treated in this fit as free parameters, and a linear background term is included in the current fit (other choices such as quadratic background were also used). The energy obtained for the 2_2^+ state from this fit of the 20° data (and the fit at all other angles) is 9.6 MeV, and the extracted width

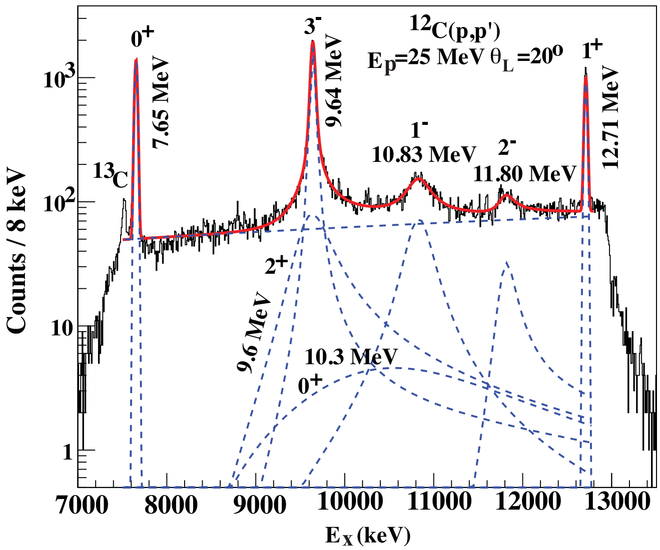

FIG. 2. (Color online) Scattered proton spectrum measured at 20° compared to the sum (red line) of all contributions from all known states plus the broad 2_2^+ at 9.6 MeV and a linear background term (dashed blue lines).

shown in Fig. 2 is 500 keV. The fitted energy is independent of the choice of background, but the extracted width of the 2_2^+ is found to be dependent on the choice of the background. Hence, we do not quote a width for the 2_2^+ state, rather we assert that it is consistent with the width ($\Gamma = 600$ keV) reported in the iThemba LABS publication [1].

In Fig. 3, we show the relevant portion of the background-subtracted spectrum measured at 35° compared to the line shape calculated using the known energy and width ($\Gamma =$ 34 keV) of the 3^- state at 9.641 MeV after folding with the measured instrumental energy resolution. In a separate fit, we also treated the width of the 3^- state as a free parameter that was primarily determined by the data point with large counts

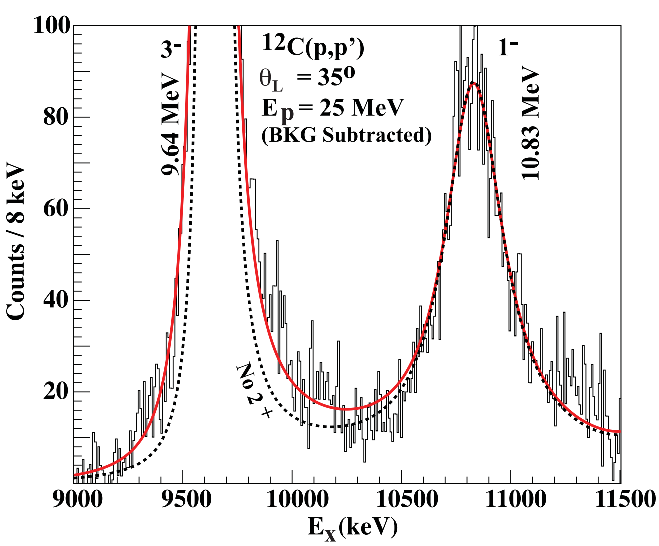

FIG. 3. (Color online) The measured background-subtracted proton spectrum analyzed with (red solid line) and without (black dashed line) the contribution of the 2_2^+ state at 9.6 MeV.

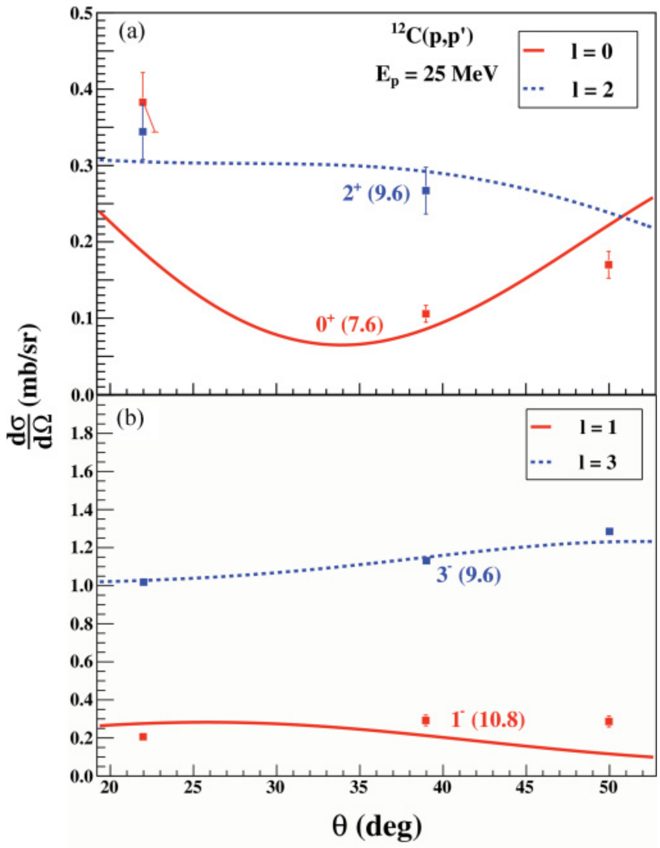

FIG. 4. (Color online) The measured angular distributions compared to coupled channel predictions for (a) positive and (b) negative parity states.

(more than 100 counts per 8 keV) that are not shown in Fig. 3. The obtained width is in agreement with the known width (34 keV) of the 3^- state and this fit serves as a confirmation

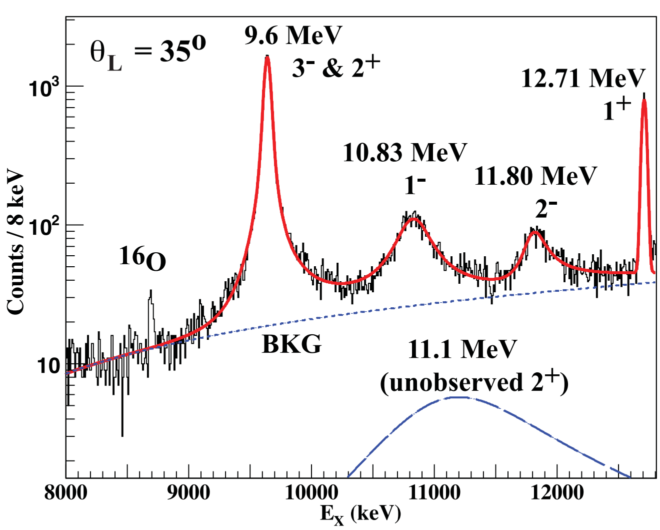

FIG. 5. (Color online) Scattered proton spectrum measured at 35° compared to the sum (red solid line) of all contributions from all known states, plus a linear background term (dashed blue lines). The recommended [12] broad ($\Gamma = 1.4$ MeV) 2_2^+ at 11.1 MeV shown (blue dashed line) is not observed in our data and we place a two-sigma upper limit on the cross section, as discussed in the text.

of previous measurements. The fit that does not include the 2_2^+ is shown in Fig. 3 and it clearly cannot describe the low- and high-energy tails (skirt) of the 3^- state ($\chi^2/\nu = 2.6$). As can be seen in Fig. 3, including the 2_2^+ improves the quality of the fit ($\chi^2/\nu = 1.6$).

In Fig. 4, we show the measured angular distributions for inelastic scattering into the broad 2_2^+ state at 9.6 MeV, the 0_2^+ Hoyle state at 7.654 MeV, the narrow 3^- state at 9.641 MeV, and the broad 1^- state at 10.83 MeV in ^{12}C. The measured cross sections have an overall systematic uncertainty of ±10% due to the uncertainty of the target thickness. At $\theta_L = 45^\circ$, we are only able to deduce a 1σ upper limit of 0.35 mb/sr for the 2_2^+ due to large uncertainty in the background. This large upper limit is not plotted in Fig. 4. Note that the cross sections ($d\sigma/d\Omega$) measured in this work are approximately half of the previous values reported at $E_p = 24.1$ and 26.1 MeV [9]. The measured angular distributions are compared to the calculated angular distribution for $\ell = 2, 0, 3$, and 1 (renormalized upward), where we used the optical model parameter space of Chiba *et al*. [10]. The agreement with the calculated angular distributions suggests that the broad state at 9.6 MeV is consistent with a 2^+ state. A more direct evidence for the spin parity of the broad state at 9.6 MeV is provided by our measured angular distribution of the ^{12}C($\gamma, 3\alpha$) reaction at $E_\gamma = 9.77$ MeV [11], which exhibits a pure $E2$ electromagnetic transition (with a symmetric deep minimum at 90°).

We are indebted to the anonymous referee for suggesting that we search for evidence for the recommended 2_2^+ at 11.1 ± 0.3 MeV [12]. In Fig. 5, we show an attempt to include this state ($E_R = 11.1$, $\Gamma = 1.4$ MeV) in our analysis. No evidence for such a state was found in our data and we place a two-sigma upper limit of 0.077 mb/sr on the cross section for populating this state at the laboratory angle of 35°.

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