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# Direct Observation of a New $2^+$ State in $^{12}\mathrm{C}$ through the $^{12}\mathrm{C}+\gamma \rightarrow 3\alpha$ Reaction

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The photodisintegration of $^{12}$C into three $\alpha$ particles was observed using intense, nearly mono-energetic $\gamma$-ray beams available at the HI$\gamma$S facility. An optical time projection chamber was used to detect the recoiling $\alpha$ particles from the $^{12}$C($\gamma$,$\alpha$)$^{8}$Be reaction. A $J^{\pi} = 2^{+}$ state in $^{12}$C was found at 10.03(11) MeV with a width of 800(130) keV. Recently EFT lattice calculations have been performed in order to understand the structure of the 'Hoyle state' at 7.65 MeV, and extensions of these calculations have identified a $2^+$ excitation of the Hoyle state. This newly observed $2^+$ state in $^{12}$C provides an important test for these calculations as well as for other models of light nuclei. Furthermore, a state in $^{12}$C near this energy increases the rate of stellar thermonuclear helium burning at the high temperatures which occur in core-collapse supernovae and other astrophysical scenarios.

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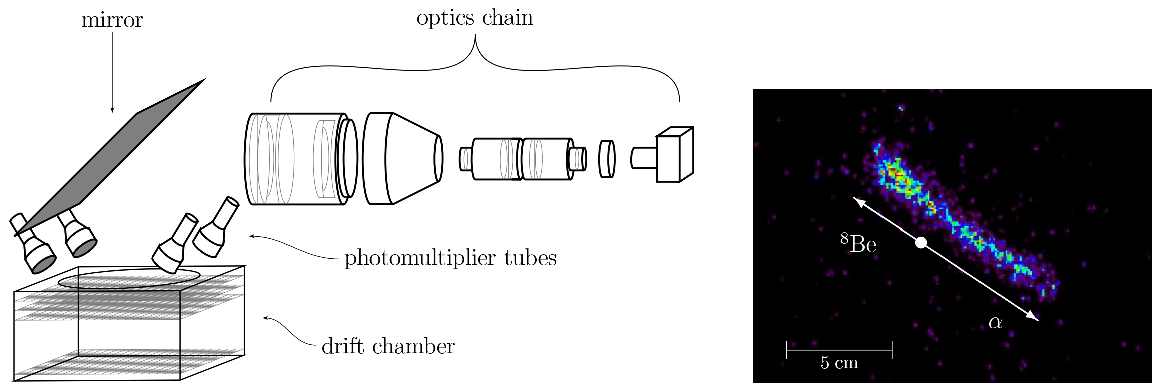

**Figure 1:** Left: layout of the HI$\gamma$S OTPC. Right: photograph of a typical $^{12}$C($\gamma$,$\alpha_0$)$^8$Be event recorded by the optics chain. The colors in the image correspond to the intensity of the scintillation light.

Stellar synthesis of elements heavier than helium is thought to occur through the triple-$\alpha$ process, where two $\alpha$ particles fuse together to create a short-lived $^8$Be nucleus which fuses with another $\alpha$ particle to form $^{12}$C [1]. The observed abundance of carbon led Hoyle [2] to predict a resonance near the $^8\mathrm{Be} + \alpha$ threshold which was subsequently observed [3, 4]. This was the first time that an astrophysical argument correctly predicted specific attributes of nuclear structure, and the 7.65 MeV, $J^\pi = 0^+$ state in $^{12}$C is now known as the 'Hoyle state.'

Quiescent helium burning occurs at a temperature of $10^8$–$10^9$ K, and is completely governed by the Hoyle state [5]. However, during core-collapse supernovae, $\gamma$-ray bursts and other astrophysical phenomena, the temperature rises well above $10^9$ K, and higher energy states in $^{12}$C could have a significant effect on the triple-$\alpha$ reaction rate [6, 7]. In particular, a second $J^\pi = 2^+$ state (written $2_2^+$) was predicted in 1956 as an excitation of the Hoyle state [8]. The exact energy, width, and strength of the $2_2^+$ state are needed to determine the influence of this state on the triple-$\alpha$ reaction rate at high temperatures [6].

Although the second $2^+$ state in $^{12}$C was predicted over fifty years ago, the existence of this state has still not been definitively confirmed [9]. Recently, an analysis [10] of several inelastic scattering experiments [11 – 13] indicated the existence of a state in $^{12}$C at 9.75(15) MeV, albeit with poorly determined $J^\pi$ assignment and $\gamma$-decay width. This state was not observed below 11 MeV in the $\beta$-delayed $\alpha$-decays of $^{12}$N and $^{12}$B [14]. However, an analysis [15] of the $\beta$-delayed $\alpha$-decay data suggests a $2^+$ state at 11.2 MeV which was not observed in the inelastic scattering data. Clearly, more conclusive results are required [9] to confirm the 50-year-old prediction.

The current Nuclear Astrophysics Compilation of Reaction Rates (NACRE) assumes a theoretical $2_2^+$ state at 9.12 MeV [16]. However, the JINA REACLIB compilation [17] uses the results of the $\beta$-delayed $\alpha$-decay experiments and does not include NACRE's state. The reaction rates reported by the two compilations disagree by over a factor of ten at temperatures above $10^9$ K. The present ambiguity in the energy and width of a possible $2^+$ resonance has led to an order-of-magnitude uncertainty of the triple-$\alpha$ reaction rate at high temperatures. In particular, heavy element production during the $\nu p$-process [18, 19], which is thought to occur during core-collapse supernovae, is particularly sensitive to changes in the triple-$\alpha$ rate [20].

Recently, *ab initio* EFT lattice calculations [21] have been performed in order to understand the

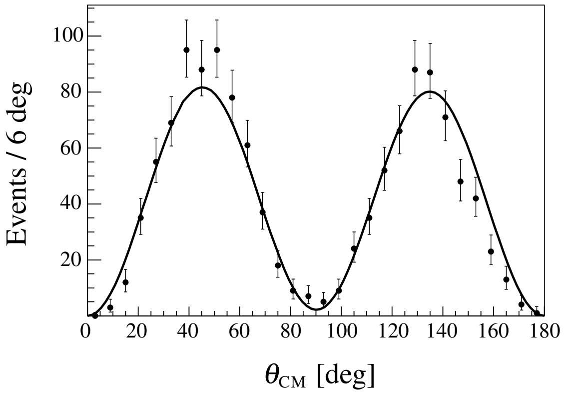

**Figure 2:** Angular distribution for the in-plane subset of $^{12}$C($\gamma$,$\alpha_0$)$^8$Be events at a beam energy of 9.6 MeV. The solid curve is the angular distribution for E2 cross section ratio $\sigma_{\mathrm{E2}}/\sigma_{\mathrm{TOT}}$ = 96.75% and $\phi_{12}$ = 80.3°, normalized to the data. These parameters are taken from the fit to the full data set at this $\gamma$-ray beam energy. The error bars represent the statistical uncertainty associated with the data points.

structure of the Hoyle state. Further calculations [22] have identified a $2^+$ excitation and predicted its electromagnetic decay widths. An unambiguous identification of the $2_2^+$ state would be an important test for the *ab initio* EFT lattice calculations as well as for other models of light nuclei.

In this report, we present the results of a recent experiment performed at the High Intensity $\gamma$-ray Source (HI$\gamma$S) designed to observe a possible $2^+$ state in $^{12}$C through the $^{12}$C($\gamma$,$\alpha$)$^8$Be reaction. By using a the intense, nearly monoenergetic $\gamma$-ray beams available at the HI$\gamma$S facility [23], the $2_2^+$ state in $^{12}$C can be measured without contributions from the $3_1^-$ state at 9.6 MeV or the $0_3^+$ state at 10.3 MeV [24] which have plagued previous experiments. Furthermore, this technique allows a precise measurement of the electromagnetic decay width of the $2_2^+$ state, essential for calculating stellar triple-$\alpha$ reaction rates [16].

An optical time projection chamber (OTPC) was used to detect recoiling $\alpha$-particles from $^{12}$C photodisintegration events. The HI$\gamma$S OTPC (Figure 1) consists of a time projection chamber with an optical chain to record an image of each event [25]. The time projection chamber was filled with a mixture of 80% $CO_2$ target gas and 20% $N_2$ scintillator. The total energy deposited by each event in the detector was read via the charge deposited on high-voltage grids. Six photomultiplier tubes gave time projection signals, and a series of lenses and electrostatic optics focused the scintillation light into a camera, which recorded a photograph of each event. The length, scattering angle and stopping power of each track could be determined by position and brightness of scintillation light in the image. An image of a typical $^{12}$C($\gamma$,$\alpha_0$)$^8$Be event is shown in Figure 1. The optical readout allows for distinguishing between signal and background events and for three-dimensional kinematic reconstruction of charged particle tracks. This provided the complete angular distributions necessary for separating the multipole components of the cross section.

Nearly all ($\sim$98%) of the observed $^{12}$C photodisintegrations decayed through the $^8$Be ground state, written as $^{12}$C($\gamma$,$\alpha_0$)$^8$Be. Since the ground state is relatively long-lived ($\Gamma$ = 5.6 eV), this type of event can be treated as a sequence of two-body decays, and not as a single three-body decay. The small number of events that decayed through the broad first excited state in $^8$Be were identified by the much greater opening angle of the $\alpha$-particle tracks. These $^{12}$C($\gamma$,$\alpha_1$)$^8$Be events were not included in the total cross section or angular distributions.

Apart from the $^{12}$C($\gamma$,$\alpha$)$^8$Be events, there were several types of background events recorded

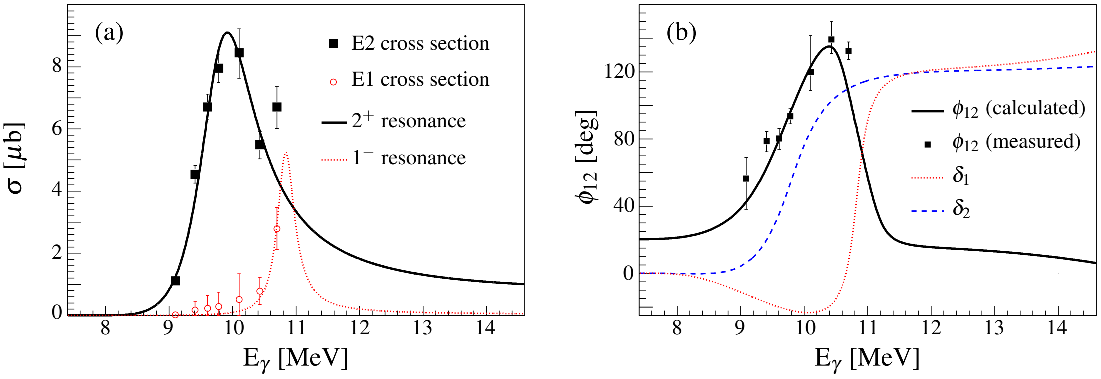

**Figure 3:** Measured $^{12}$C($\gamma$,$\alpha_0$)$^8$Be cross section and relative phase angle. (a) shows the E1 and E2 components of the cross section. The E2 data are fit to a $2^+$ resonance, and the E1 data are fit to a $1^-$ resonance of known width and energy [24]. (b) shows the measured phase difference $\phi_{12}$, along with calculations from a two-resonance model.

by the HI$\gamma$S OTPC: $^{14}$N($\gamma$,p)$^{13}$C from the $N_2$ scintillator, $^{16/18}$O($\gamma$,$\alpha$)$^{12/14}$C from the $CO_2$ target gas, and charged particle tracks induced by cosmic rays. $^{14}$N($\gamma$,p)$^{13}$C, $^{18}$O($\gamma$,$\alpha$)$^{14}$C, and cosmic events were easily rejected based on the total deposited energy, track length, and position of the tracks.

Tracks from $^{16}$O($\gamma$,$\alpha$)$^{12}$C events, however, are very similar to those from $^{12}$C($\gamma$,$\alpha_0$)$^8$Be events in both length and stopping power. Furthermore, the difference in Q-values (205 keV) is less than the typical energy spread of the $\gamma$-ray beam (300 keV), so the $^{16}$O($\gamma$,$\alpha$)$^{12}$C events could not be rejected based on total deposited energy. However, $^{12}$C($\gamma$,$\alpha_0$)$^8$Be and $^{16}$O($\gamma$,$\alpha$)$^{12}$C events have different time projection signals which were used to distinguish between the two types of events. Theoretical time projection line shapes were calculated by taking the known range and stopping power of the charged particles and simulating the drift of the electrons through the gas. Each of the experimentally measured time projection signals was fit using both $^{12}$C($\gamma$,$\alpha_0$)$^8$Be and $^{16}$O($\gamma$,$\alpha$)$^{12}$C line shapes, and the goodness-of-fit parameters ($\chi^2$) were compared to classify the event. Cuts on $\chi^2$ were placed such that fewer than 0.5% of the accepted events were estimated to be $^{16}$O($\gamma$,$\alpha$)$^{12}$C.

Fitted time projection signals together with the photographs of tracks allowed for three-dimensional kinematic reconstructions, yielding scattering angles for each of the events. Angular distributions were fit in terms of E1 and E2 amplitudes and their relative phase $\phi_{12}$ [26]. Since angular information was available for each $^{12}$C($\gamma$,$\alpha_0$)$^8$Be event individually, unbinned maximum likelihood fits were used to avoid losing information through binning. A typical angular distribution is shown in Figure 2. For most beam energies the angular distributions were dominated by the E2 component.

Yields and angular distributions were measured at seven different $\gamma$-ray beam energies between 9.1 and 10.7 MeV. Fig. 3a shows the separated E1 and E2 components of the cross section, fit to Breit-Wigner resonances with energy-dependent level shifts and widths [27], convolved with the measured $\gamma$-ray beam energy distribution. This fit includes three free parameters: the partial widths $\Gamma_\alpha$ and $\Gamma_\gamma$, as well as the resonance energy. The E1 cross section data are consistent with the known $1^-$ resonance at 10.84 MeV [24]. The E2 cross section data establish the existence of a $2^+$ state at 10.03(11) MeV with a width of 800(130) keV. The error bars on the cross sections in Fig. 3a include both statistical and systematic uncertainties. The systematic uncertainties associated with each measured cross section are dominated by a 5% uncertainty in the $\gamma$-ray beam intensity.

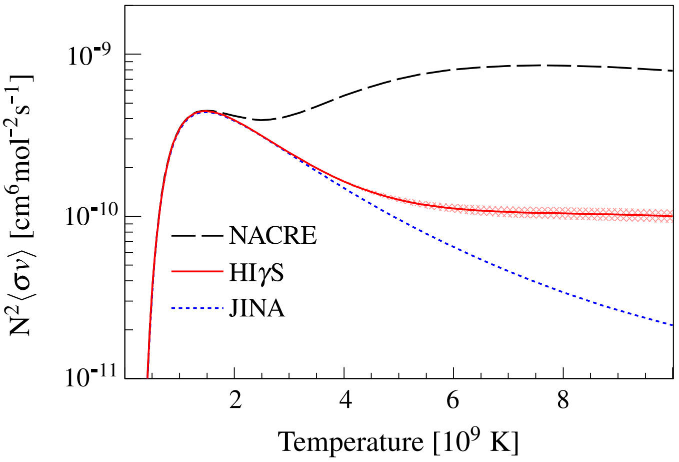

**Figure 4:** Triple-$\alpha$ reaction rates, calculated according to the formalism in Ref. [16]. The NACRE rate includes contributions from the Hoyle state, a $3^-$ state at 9.64 MeV, and a $2^+$ state at 9.12 MeV. The JINA rate is reported in the REACLIB database [17], based on the results of Fynbo *et al.* [14]. The HI$\gamma$S rates are calculated using the same states as NACRE, except substituting the present values in place of NACRE's postulated $2^+$ state. The shaded region represents the propagated uncertainty from the measured $2_2^+$ state.

Fig. 3b shows the E1–E2 phase difference $\phi_{12}$, along with a curve representing a calculation of $\phi_{12}$ using a two-resonance model [27]. The $\ell = 1$ resonance phase shifts were calculated using parameters from the known $1^-$ state [24] and the $\ell = 2$ phase shifts were calculated from the results of the fit to the E2 cross section data. The calculated $\phi_{12}$ curve was averaged over the measured cross section and $\gamma$-ray beam energy distribution. Agreement between the measured phase differences and those predicted by this two-resonance model firmly establishes the resonance nature of the $2^+$ strength reported here and indicates that there is little or no contribution from other amplitudes.

Core-collapse supernovae as well as various other astrophysical scenarios can produce a dense, helium-rich environment with a temperature well above $10^9$ K. Under these conditions, states in $^{12}$C above the Hoyle state can influence the triple-$\alpha$ reaction rate [6, 7]. Fig. 4 shows the triple-$\alpha$ reaction rates calculated for temperatures up to $10^{10}$ K, compared with the rates reported by NACRE [16] and by the JINA REACLIB database [17]. New reaction rates were calculated using the $2_2^+$ state measured in this work. Astrophysical simulations predict that during explosive burning scenarios, the triple-$\alpha$ reaction rate governs the freeze out from nuclear statistical equilibrium at a temperature near 5 GK [7]. At this temperature, the results from this work predict a reaction rate 33% higher than that listed in the JINA REACLIB database, and more than five times smaller than that given by NACRE.

In summary, a theoretically predicted second $2^+$ state in $^{12}$C near 10 MeV has been measured using the HI$\gamma$S OTPC. $^{12}$C($\gamma$,$\alpha_0$)$^8$Be cross sections and angular distributions were measured at seven different $\gamma$-ray beam energies between 9.1 and 10.7 MeV. E2 photoabsorption cross sections were extracted from the angular distributions, and the data show a $2_2^+$ state in $^{12}$C at $E_{res}$ = 10.03(11) MeV with a total width of $\Gamma$(res) = 800(130) keV, and a $\gamma$-decay width to the ground state of $\Gamma_{\gamma_0}$(res) = 60(10) meV. Although the $2_2^+$ state in $^{12}$C was predicted more than 50 years ago as an excitation of the Hoyle state [8], it has not been definitively identified until now. This resonance increases the triple-$\alpha$ reaction rate at high temperatures compared to those listed in the JINA REACLIB database, but the rate is much less than that quoted by NACRE.

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## References

[1] G. Wallerstein, *et al.*, Rev. Mod. Phys. **69**, 995 (1997).

[2] F. Hoyle, D. N. F. Dunbar, W. A. Wenzel, and W. A. Whaling, Phys. Rev. **92**, 1095 (1953).

[3] D. N. F. Dunbar, R. E. Pixley, W. A. Wenzel, and W. A. Whaling, Phys. Rev. **92**, 649 (1953).

[4] C. W. Cook, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. **107**, 508 (1957).

[5] W. A. Fowler, Rev. Mod. Phys. **56**, 149 (1984).

[6] L. Buchmann and C. Barnes, Nucl. Phys. A **777**, 254 (2006).

[7] R. Surman, G. C. McLaughlin, and N. Sabbatino, Astrophys. J. **743**, 155 (2011).

[8] H. Morinaga, Phys. Rev. **101**, 254 (1956).

[9] H. O. U. Fynbo and M. Freer, Physics **4**, 94 (2011).

[10] M. Freer, *et al.*, Phys. Rev. C **86**, 034320 (2012).

[11] M. Itoh, *et al.*, Phys. Rev. C **84**, 054308 (2011).

[12] M. Freer, *et al.*, Phys. Rev. C **80**, 041303 (2009).

[13] W. R. Zimmerman, *et al.*, Phys. Rev. C **84**, 027304 (2011).

[14] H. O. U. Fynbo, *et al.*, Nature **433**, 136 (2005).

[15] S. Hyldegaard, *et al.*, Phys. Rev. C **81**, 024303 (2010).

[16] C. Angulo, *et al.*, Nucl. Phys. A **656**, 3 (1999).

[17] R. H. Cyburt, *et al.*, Astrophys. J. Suppl. Ser. **189**, 240 (2010).

[18] C. Fröhlich, *et al.*, Phys. Rev. Lett. **96**, 142502 (2006).

[19] A. Arcones, C. Fröhlich, and G. Martínez-Pinedo, Astrophys. J. **750**, 18 (2012).

[20] S. Wanajo, H.-T. Janka, and S. Kubono, Astrophys. J. **729**, 46 (2011).

[21] E. Epelbaum, H. Krebs, D. Lee, and U.-G. Meißner, Phys. Rev. Lett. **106**, 192501 (2011).

[22] E. Epelbaum, *et al.*, Phys. Rev. Lett. **109**, 252501 (2012).

[23] H. R. Weller, *et al.*, Prog. in Part. and Nucl. Phys. **62**, 257 (2009).

[24] F. Ajzenberg-Selove, Nucl. Phys. A **506**, 1 (1990).

[25] M. Gai, *et al.*, J. Instrum. **5**, P12004 (2010).

[26] P. Dyer and C. Barnes, Nucl. Phys. A **233**, 495 (1974).

[27] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).