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# $\alpha$ decay of the excited states in $^{12}$C at 7.65 and 9.64 MeV

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High-resolution triple-$\alpha$ coincidence data were used to reconstruct the decay of the excited states in $^{12}$C at 7.65 MeV ($J^\pi = 0^+$) and 9.64 MeV ($J^\pi = 3^-$). These data are consistent with the $\alpha$-particle decay of both levels proceeding exclusively through $^8$Be$_{g.s.}$. In the first of these cases, the Hoyle state, an upper limit of 0.45% (at the 99.75% confidence level) is set for a component producing three nearly equal-energy $\alpha$ particles.

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It has recently been suggested that the state in $^{12}$C at an excitation energy of $E^* = 7.65$ MeV ($J^\pi = 0^+$), the Hoyle state, has a minor decay branch that produces three $\alpha$ particles of almost equal energy and that such a decay provides evidence for $\alpha$-particle condensation [1]. A decay producing three $\alpha$'s of equal energy can be distinguished from the dominant two-step sequential decay through $^8$Be$_{g.s.}$ as the sequential decay leaves the fingerprint of having one of the three $\alpha$-$\alpha$ pairs with 92 keV of relative energy while the equal-energy process yields three $\alpha$ particles, each with about 127 keV in the $^{12}$C rest frame.

Previous high-resolution work of Freer *et al.*, which employed the same general technique as we employ here, demonstrated that while the Hoyle state decays predominately through $^8$Be$_{g.s.}$, a contribution from a mechanism that uniformly spans the three-body phase space could not be excluded from contributing to the decay at a level below 4% [2]. While not explicitly testing for the equal-energy process, the data of Freer *et al.* do indicate that such a process is minor. In the present work, we reanalyze preexisting high-resolution data in an effort to extract potential contributions to the decay of the Hoyle state from processes that either uniformly span the three-body phase space or produce three nearly equal-energy $\alpha$ particles. While our results are consistent with the Hoyle state decaying exclusively via the sequential process we could not exclude, as was the case for Freer *et al.*, a contribution at the few percent level from a mechanism that uniformly samples phase space. On the other hand, we can place an upper limit on a contribution from a mechanism that produces equal-energy $\alpha$ particles at 0.45%, a limit more than an order of magnitude lower than the value reported by Raduta *et al.* [1]. While our new limit is not in conflict with the numerical result of Raduta *et al.*, due to the limited statistical significance of that prior work, it essentially removes the possibility of an exotic particle decay mode for the Hoyle state that was claimed in Ref. [1] and used as evidence for $\alpha$-particle condensation. Using the same data and techniques employed to study the Hoyle state, we show that the excited state in $^{12}$C at $E^* = 9.64$ MeV ($J^\pi = 3^-$) also decays exclusively through $^8$Be$_{g.s.}$.

The details of the experiment and analysis techniques have been presented previously in considerable detail [3]. In brief, starting from a primary beam of $^{10}$B and a $(p, n)$ reaction, a secondary beam of $2 \times 10^5$ s$^{-1}$ $^{10}$C nuclei at $E/A = 10.7$ MeV and 99.5% purity was generated using the Texas A&M University K500 cyclotron facility and the momentum achromat recoil spectrometer (MARS) [4]. This beam interacted with either a 14.1-mg/cm$^2$ Be or a 13.4-mg/cm$^2$ C target. As in the prior work, the data taken with both targets are used to improve the statistical significance of our results. The reaction products were detected in an array of four Si $\Delta E$-$E$ telescopes located in a plane 14 cm downstream of the target. Each telescope consisted of a 65-$\mu$m-thick, single-sided, Si-strip $\Delta E$ detector followed by a 1.5-mm-thick, double-sided, Si-strip $E$ detector. All Si detectors were $6.4 \times 6.4$ cm, with each of the position-sensitive faces divided into 32 strips. The telescopes were positioned in a square arrangement, with each telescope offset from its neighbor to produce a small, central, square hole through which the unscattered beam passed.

The solid circles in Fig. 1(a) show the distribution of $^{12}$C excitation energy, $E^*(^{12}$C), reconstructed from all triple-$\alpha$ events. These events result from multinucleon transfer and can populate continuum states either in $^{12}$C directly or via decays from resonances in heavier nuclei. The peaks at $E^*(^{12}\text{C}) = 7.65$ MeV (Hoyle) and 9.64 MeV are clearly seen with over 4000 and 20,000 counts, respectively, and with the background for the former being a small fraction of a percent. The excitation of potential $^8$Be intermediates, $E^*(^8\text{Be})_{\text{min}}$, is calculated from the difference between the lowest $\alpha$-$\alpha$ relative energy (from the set of three in each triple-$\alpha$ event) and the 92-keV decay $Q$ value. The solid circles in

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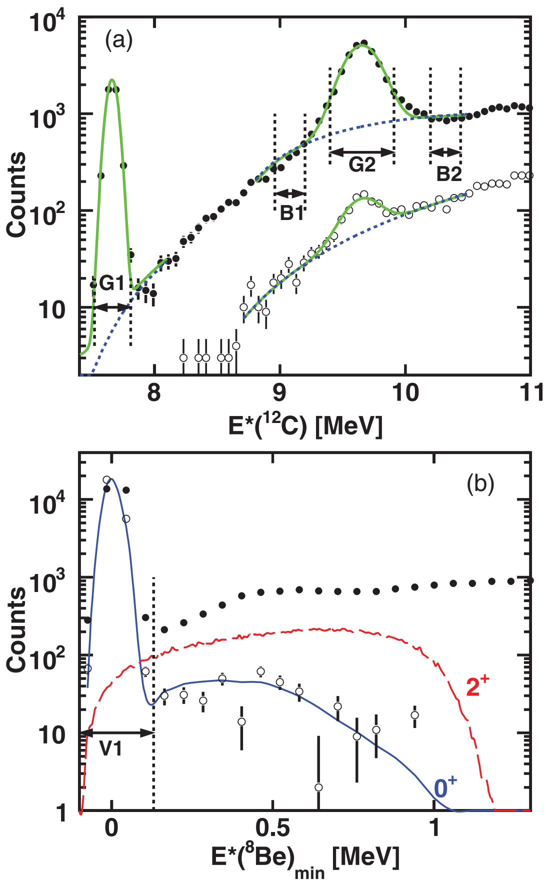


FIG. 1. (Color online) (a) $^{12}$C excitation spectra, $E^*(^{12}\mathrm{C})$, from three-$\alpha$ events, ungated (solid circles) and with $E^*(^8\mathrm{Be})_{\mathrm{min}} >$ 130 keV (open circles). Fits (solid curves) of the peak corresponding to ungated $^{12}$C at $E^* = 7.65$ MeV and the peaks for $^{12}$C at $E^* = 9.64$ MeV both ungated and gated are shown along with the assumed background (dotted lines). The gates used to select events populating the state in $^{12}$C at $E^* = 9.64$ MeV are indicated with vertical dashed lines. (b) $^8$Be excitation spectra deduced from the lowest relative-energy pair of $\alpha$ particles, $E^*(^8\mathrm{Be})_{\mathrm{min}}$, for all three-$\alpha$ events (solid circles) and gated on the state in $^{12}$C at $E^* = 9.64$ MeV (open circles). The latter has been normalized for display. The solid and dashed lines represent the $R$-matrix line shapes expected for $E^*(^8\mathrm{Be})_{\mathrm{min}}$ for the decay of the state in $^{12}$C at $E^* = 9.64$ MeV through $^8\mathrm{Be}_{g.s.}$ and the state in $^8$Be at $E^* = 3.03$ MeV, respectively.

Fig. 1(b) show the distribution of $E^*(^8\mathrm{Be})_{\mathrm{min}}$ for all triple-$\alpha$ events. The peak corresponding to $^8\mathrm{Be}_{g.s.}$ [$E^*(^8\mathrm{Be})_{\mathrm{min}} = 0$] dominates this spectrum. The spectrum shown with open circles in Fig. 1(a) is the result of the application of an event veto gate on the peak corresponding to $^8\mathrm{Be}_{g.s.}$ [V1 in Fig. 1(b)]. Note that the peak corresponding to the Hoyle state has disappeared entirely and the peak corresponding to the state in $^{12}$C at $E^* = 9.64$ MeV ($J^\pi = 3^-$) is reduced by over an order of magnitude, indicating that these states predominately decay through $^8\mathrm{Be}_{g.s.}$. Finally, application of a gate (with both foreground and background components) on the peak corresponding to the $^{12}$C state at $E^* = 9.64$ MeV (G2, B1, and B2) yields the background-subtracted spectrum of potential $^8$Be intermediates shown in Fig. 1(b) with open circles. This spectrum consists primarily of the $^8\mathrm{Be}_{g.s.}$ correlation with an additional weak and broad component peaking at $E^*(^8\mathrm{Be})_{\mathrm{min}} \sim 0.5$ MeV.

While almost all of the decay of the state in $^{12}$C at 9.64 MeV through $^8\mathrm{Be}_{g.s.}$ will access the peak in $E^*(^8\mathrm{Be})_{\mathrm{min}}$ clearly identified with this resonance (at zero excitation energy), there is enough energy in the overall decay that some tiny fraction of the decay *must* proceed through the "ghost peak" predicted from $R$-matrix theory [5]. This contribution, well known from both $^9\mathrm{Be}(p,d)^8\mathrm{Be}$ and $^9\mathrm{Be}(d,t)^8\mathrm{Be}$ reactions [6], results when the density of states (used in Fermi's golden rule) is dominated by the strongly increasing penetrability in the numerator of the density of states, temporarily (with increasing energy) overpowering the natural line shape and creating a small, broad satellite peak at energies slightly above the resonance energy. The full $R$-matrix expectations for the distributions of $E^*(^8\mathrm{Be})_{\mathrm{min}}$ for the decay of the state in $^{12}$C at $E^* = 9.64$ MeV through $^8\mathrm{Be}_{g.s.}$ and the excited $2^+$ in $^8$Be at $E^* = 3.03$ MeV are shown in Fig. 1(b) as solid and dashed lines, respectively. These calculations, modified by an experimental response filter, indicate that if the decay proceeds through $^8\mathrm{Be}_{g.s.}$ only 98.1% of the decay should be found with $E^*(^8\mathrm{Be})_{\mathrm{min}} < 130$ keV, gate V1 [Fig. 1(b)]. Experimentally, this gate captures $98.30\% \pm 0.13\%$ of the yield. Gating the reverse way, on the peak corresponding to the excited state in $^{12}$C at 9.64 MeV, and looking at the reconstructed $^8$Be spectrum [open circles in Fig. 1(b)] generates the expected $R$-matrix line shape (notably including the "ghost" contribution) for decay through $^8\mathrm{Be}_{g.s.}$. These results [finding all the strength one should expect in the narrow gate around $E^*(^8\mathrm{Be})_{\mathrm{min}} = 0$ and reproduction of the intermediate $^8$Be line shape] confirm that while in principle the excited state in $^{12}$C at $E^* = 9.64$ MeV could decay through the tail of the $^8$Be state at $E^* = 3.03$ MeV ($J^\pi = 2^+$), it does not.

Returning to the decay of the Hoyle state, we performed Monte Carlo simulations of three decay scenarios (sequentially through $^8\mathrm{Be}_{g.s.}$, uniform sampling of phase space [7], and equal-energy sharing among the $\alpha$ particles) to model the response of the detection hardware to these decay scenarios and thus allow quantitative comparisons to the data to be made. These simulations showed that the efficiency of the device is very similar for the three decay scenarios (11.5%, 10.8%, and 11.5%, respectively for the mechanisms listed above[1]).

The solid circular data points in Fig. 2 show the distribution of the root-mean-squared energy deviation, from the event average center-of-mass energy, $E_{\mathrm{RMS}}$, for the events produced by the decay of the Hoyle state [gate G1 in Fig. 1(a)]. $E_{\mathrm{RMS}} = \sqrt{\langle E_\alpha^2 \rangle - \langle E_\alpha \rangle^2}$, where $E_\alpha$ are the energies of the $\alpha$ particles in the $^{12}$C rest frame, the average is over the three $\alpha$'s in each event, and the second reference average

[1]The loss in efficiency results when one or more of the $\alpha$ particles goes down the central hole (i.e. misses the Si-strip detectors) or when two or more of the $\alpha$ particles share a common $x$ or $y$ strip. The similarity of the efficiencies indicates that there is no significant experimental bias, for or against, any of the decay mechanisms.

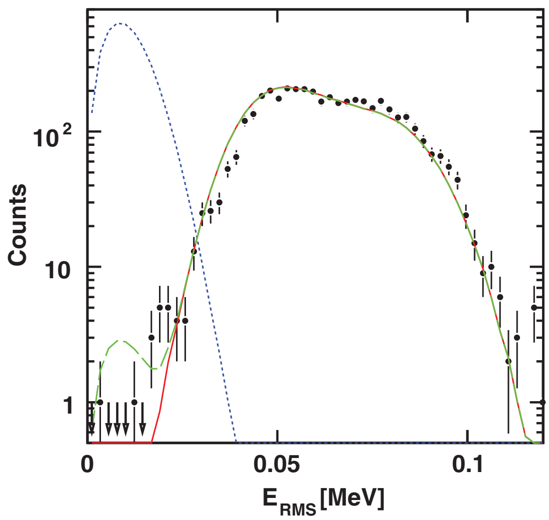


FIG. 2. (Color online) The distribution of the root-mean-square energy deviation of the three $\alpha$'s, $E_{\rm RMS}$, for those events consistent with formation of the Hoyle state is shown as solid circles. The lines correspond to the simulations of different decay scenarios: sequential decay through $^8\mathrm{Be}_{g.s.}$(solid), equal-energy decay (dotted), and a mixture of $f_{\rm eq} = 0.45\%$ of the equal-energy mechanism with the remainder the sequential process (dashed). The dashed curve represents the upper limit of the minor process at the 99.75% confidence limit.

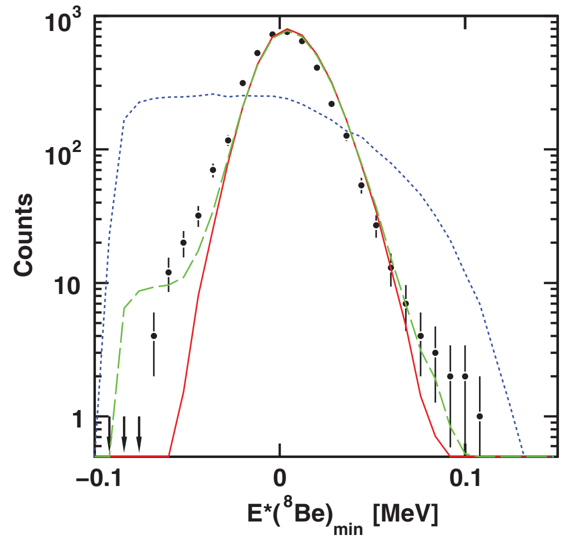


FIG. 3. (Color online) The distribution of the minimum possible excitation energy of $^8$Be, $E^*(^8\mathrm{Be})_{\rm min}$, for those events consistent with formation of the Hoyle state is shown as solid circles. The lines correspond to the simulations of different decay scenarios: sequential decay through $^8\mathrm{Be}_{g.s.}$ (solid), a process that uniformly samples phase space (dotted), and a mixture of $f_{\rm unif} = 3.9\%$ of the mechanism that uniformly samples phase space with the remainder the sequential process (dashed). The dashed curve represents the upper limit of the minor process at the 99.75% confidence limit.

is equal to $1/3$ of the $Q$ value for the decay of the Hoyle state into three $\alpha$ particles (127.4 keV). This variable is also employed in Ref. [1]; however, unlike the data used in that work, the data used in the present work permit a clean selection of events where the Hoyle state is formed. Also shown in Fig. 2 are the results of simulations filtered by the detector response of $E_{\rm RMS}$ for the following decay scenarios: sequential (solid line), equal energy (dotted), and a mixture of these with a fraction $f_{\rm eq} = 0.45\%$ of the equal-energy process (dashed). The absence of expected yield near $E_{\rm RMS} = 0$ for the equal-energy decay scenario (dotted line) is a consequence of the almost absence of probability that, after folding the simulated events with the experimental device response, all three $\alpha$ particles still have the same energy. The expectation is then that the equal-energy scenario generates small (but nonzero) values of $E_{\rm RMS}$, where the width of the distribution is determined by the instrument response and thus whether the primary mechanism produces equal or nearly equal energy (within the device resolution) $\alpha$ particles is irrelevant. The best fitted mix is $f_{\rm eq} = 0.079\% \pm 0.122\%$ (with an uncertainty of one standard deviation), a result consistent with zero. A contribution from such a process producing three equal-energy $\alpha$ particles exceeding 0.45% is excluded at the 99.75% confidence level. This ability to discriminate among the decay mechanisms is a consequence of the absence of counts at small values of $E_{\rm RMS}$. Other variables were also examined: $E^*(^8\mathrm{Be})_{\rm min}$ and the distance from the center of a Dalitz plot (a variant of which is shown in Fig. 2(d) of Ref. [2].) Fits of the distributions on these variables to sequential (through $^8\mathrm{Be}_{g.s.}$) decay with a contribution from an equal-energy emission process were also consistent with no contribution from the equal-energy process.

Figure 3 overlays the experimental distribution of $E^*(^8\mathrm{Be})_{\rm min}$, again for events consistent with Hoyle-state formation, with simulations of: the sequential-decay process through $^8\mathrm{Be}_{g.s.}$ (solid line), a process that uniformly samples phase space (dotted) and a mixture of these with a fraction $f_{\rm unif} = 3.9\%$ of the process that uniformly samples phase space (dashed). The best-fit value is $f_{\rm unif} = 1.3\% \pm 0.9\%$, where the one-standard-deviation uncertainty just allows for a small admixture of a direct three-body process. The fitted results can be recast to exclude contributions from a process that uniformly spans the three-body phase space above 3.9% at the 99.75% confidence level. Again this ability to discriminate the mechanisms comes from small values of the examined variable, this time $E^*(^8\mathrm{Be})_{\rm min}$. This result confirms, and is almost identical to, that presented by Freer *et al.* [2].

In summary, we find that our high-resolution data are consistent with the $\alpha$-particle decays of the excited states at 7.65 and 9.64 MeV in $^{12}$C decaying exclusively through $^8\mathrm{Be}_{g.s.}$.

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