α-decay of excited states in ^{12}C

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Introduction

The Hoyle state of ^{12}C ($J^{\pi} = 0^+$, E = 7.65 MeV) is essential for the synthesis of nuclei heavier than carbon. Most often this state decays via sequential α-decay **($^{12}C \rightarrow {}^{8}Be + \alpha \rightarrow 3\alpha$).** Recently it was proposed that 7.5 ± 4.0% of Hoyle state decays occur via the equal-energy emission of three α-particles **($^{12}C \rightarrow 3\alpha$)** [1]**.** If true, this decay branch could be evidence that the wave function of the Hoyle state can be described as an alpha-particle condensate.

This experiment: a) showed that the 9.64 MeV excited state in ^{12}C decays almost exclusively through $^{8}Be_{g.s.}$ and b) set upper limits for Hoyle state decay branches corresponding to equal-energy α-particle breakup and a process uniformly spanning three-body phase space at 0.45% and 3.9%, respectively. These findings are discussed in [2].

Experiment

The experiment was performed using the K500 Cyclotron at the Texas A&M Cyclotron Institute in 2008. The 200 pnA primary beam of *E/A* = 15.0 MeV ^{10}B impinged on a 2.0 atm hydrogen gas cell to produce a secondary beam of ^{10}C at *E/A* = 10.7 MeV via the $^{10}B(p,n)^{10}C$. The **Momentum Achromat Recoil Separator (MARS, see Fig. 1)** was used to separate the ^{10}C from other reaction products. The secondary beam then bombarded both a 14.1 mg/cm² Be target and a 13.4 mg/cm² C target.

The charged particles produced in the nuclear reaction were detected in 4 *E-ΔE* telescopes (**Fig. 2)** that are part of the High Resolution Array (HiRA) detector. Each of these telescopes consisted of a 64 um thick single-sided silicon-strip detector (with 32 strips in one direction) followed by a 1.5-mm thick double-sided silicon stopping detector (with 32 strips on each side, with the strips from one side orthogonal to the strips on the other side). These detectors provide position, energy, and particle-identification information for each of the charged particles. Detector signal processing was done with HINP16C chip electronics developed over the past decade in a WU-SIUE collaboration.

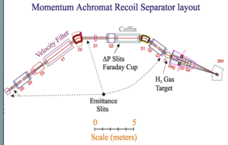


Fig. 1: Layout of the Momentum Achromat Recoil Separator (MARS).

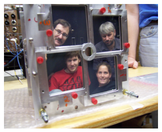


Fig. 2: Four elements of the Si telescope detector array

Excitation Spectra

Decays can be reconstructed by using the position and energy information of the decay products, (see **Figs. 3 and 4**). By gating the resulting excitation spectra, (see **Fig. 5**) the decays of individual states could be studied. **Both the Hoyle state and the 9.64 MeV state of ^{12}C were found to decay predominately through $^{8}Be_{g.s.}$**. However, R-matrix theory predicts that only 98.1% of decays from the 9.64 MeV state passing through $^{8}Be_{g.s.}$ populate the peak clearly identified with this state (gate V1 in **Fig. 6**). The rest are included in a small and broad satellite peak at energies slightly above resonance. This "ghost peak" is due to the sharply increasing penetrability temporarily dominating the density of states term used in Fermi's Golden Rule. Experimentally, 98.3 ± 0.13% of the decays were found to pass through gate V1, and gating the data in the ^{8}Be excitation spectra on the 9.64 MeV ^{12}C state reproduced the ghost peak, see **Fig. 6**.

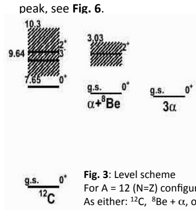
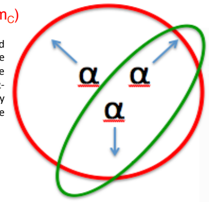


Fig. 3: Level scheme
For A = 12 (N=Z) configurations
As either: ^{12}C, $^{8}Be + \alpha$, or 3α.

$$Ex(^{12}C) = E_{rel} - (3m_{\alpha} - m_C)$$

Fig. 4: Excitation energies were obtained for ^{12}C and ^{8}Be by subtracting the Q value from the center of mass energy of the detected α-particles. For ^{8}Be, the two α-particles with the lowest relative energy between them were used to calculate the excitation energy.

$$Ex(^{8}Be) = E_{rel} - (2m_{\alpha} - m_C)$$



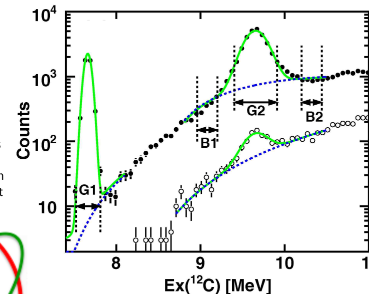


Fig. 5: The excitation energy (Ex) spectrum of ^{12}C reconstructed from triple-α events. Solid circles correspond to the data, and open circles correspond to the data gated on $^{8}Be_{g.s.}$ (gate V1 in Fig. 6). The fits (solid green curves) for each peak sit upon assumed background (blue dotted line). When gated, the counts for the Hoyle state peak disappear and those for the higher energy state are decreased by over an order of magnitude. This means that both states decay predominately through $^{8}Be_{g.s.}$.

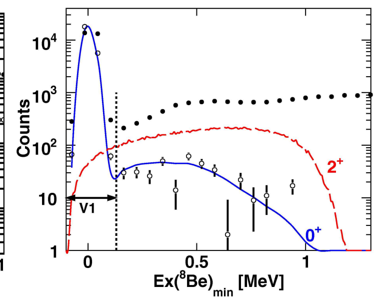


Fig. 6: The excitation spectrum (Ex) of ^{8}Be from the lowest relative energy alpha pair from triple-α events. Shown with the data (solid circles) are the R-matrix expected line shapes for the decay of the 9.64 MeV state in ^{12}C through the ground state (blue solid line) and the $J^{\pi} = 2^+$, 3.03 MeV state (red dashed line) of ^{8}Be. The clear circles, which correspond to data gated on the 9.64 MeV state in ^{12}C (G2 in Fig. 5) mainly correlate with the lines shape expected for decay through the $^{8}Be_{g.s.}$ (0^+).

Monte Carlo Simulations

Monte Carlo simulations were performed to model the response of the detection hardware to each possible decay mode (sequential, equal-energy, and uniform phase-space). Then, linear combinations of physical observables from these theoretical simulations were optimized to best fit the data via a χ-squared analysis.

The root-mean-squared energy deviations from the average center-of-mass energy (E_{RMS}) for the equal-energy and sequential decay simulations (as well as for a combination of the two) are shown with the experimentally measured E_{RMS} spectra in **Fig. 7**. The lack of experimental counts at small values of E_{RMS} enables precise discrimination between decay mechanisms. Using χ-squared analysis, **an equal-energy mixing fraction of greater than 0.45% is excluded at the 99.75% confidence level.** This result is consistent with no contribution from the equal-energy process.

The minimum possible excitation energy for ^{8}Be ($Ex(^{8}Be)_{min}$) was used to investigate the frequency with which the Hoyle state decays via a process that uniformly spans three-body phase space (**Fig. 8**). Via χ-squared analysis**, a uniform three-body mixing fraction greater than 3.9% was excluded at the 99.75% confidence level.**

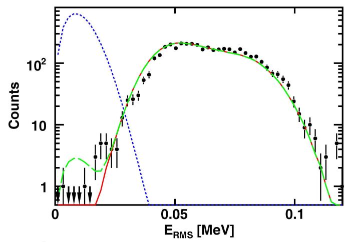


Fig. 7: E_{RMS} spectra from triple-α events corresponding to the Hoyle state (solid circles), simulations producing equal-energy α-particles (blue dotted line), sequential decay through $^{8}Be_{g.s}$. (red solid line), and a combination of these two simulations (dashed green line) consisting of 0.45% equal-energy and the rest sequential decay. The mixed curve corresponds to an upper limit for the contribution of the equal-energy decay process at a confidence level of 99.75%. The lack of counts for small values of E_{RMS} is due to the experimental response filter greatly decreasing the probability that the three α-particles are detected at the same energy.

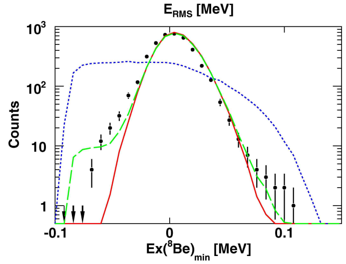


Fig. 8: ^{8}Be excitation ($Ex(^{8}Be)_{min}$) spectra from triple-α events corresponding to the Hoyle state (solid circles), the sequential decay simulation (red solid line), the uniform three-body decay simulation (blue dotted line), and a combination of these two simulations (dashed green line) consisting of a 3.9% uniform three-body decay and the rest sequential decay. The mixed curve corresponds to an upper limit for the contribution of the uniform three-body decay process at a confidence level of 99.75%.

Conclusions

Analysis of our high-resolution data indicates that the α-particle decays of ^{12}C excited states at 7.65 MeV (Hoyle) and 9.64 MeV decay exclusively through $^{8}Be_{g.s.}$. An upper limit of 0.45% (much lower than previously claimed in [1]) was placed on an equal-energy α-particle decay branch. Furthermore, an upper limit of 3.9% was set on a contribution from a decay branch that uniformly samples three-body phase space. This result suggests that the Hoyle state is not an α-particle condensate. Future work on other α-cluster states will be done using the HiRA array at the National Superconducting Cyclotron Laboratory at Michigan State University.

Acknowledgements:

This work was supported by the US Department of Energy, Division of Nuclear Physics with grants DE-FG02-87ER-40316, DE-FG02-93ER40773), and DE-FG02-04ER41320. I would also like to thank Lee Sobotka and Robert Charity for their guidance and insight.

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[1] Ad. R. Raduta et al., Phys. Lett. B **705**, 65 (2011).
[2] J. Manfredi et al., PRC **85,** 037603 (2012).