Radiative decay branching ratio of the Hoyle

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Introduction

The triple-alpha process is a crucial reaction in nuclear astrophysics. It consists of two consecutive steps: a) $\alpha + \alpha \rightarrow {}^{8}$Be(g.s.), and b) ^{8}Be + $\alpha \rightarrow \gamma + {}^{12}$C, ultimately leading to the formation of carbon. The second reaction occurs via a 0^+ state in ^{12}C at an excitation energy of 7.65 MeV (Hoyle state) – just above the α-decay threshold. The rate of the triple-alpha process is determined by the product of the α-decay width (Γ_α) and the radiative width (Γ_{rad}) divided by their sum ($\Gamma_\alpha + \Gamma_{rad}$), which reduces to Γ_{rad} due to the significantly larger value of Γ_α compared to Γ_{rad}. A method of determining the value of Γ_{rad} involves measuring the branching ratio for electromagnetic decay (Γ_{rad}/Γ) and utilizing the established partial width Γ_π(E0) for electron-positron pair production, i.e., $\Gamma_{\rm rad} = \frac{\Gamma_{\rm rad}}{\Gamma} \times \frac{\Gamma}{\Gamma_\pi({\rm E0})} \times \Gamma_\pi({\rm E0})$.

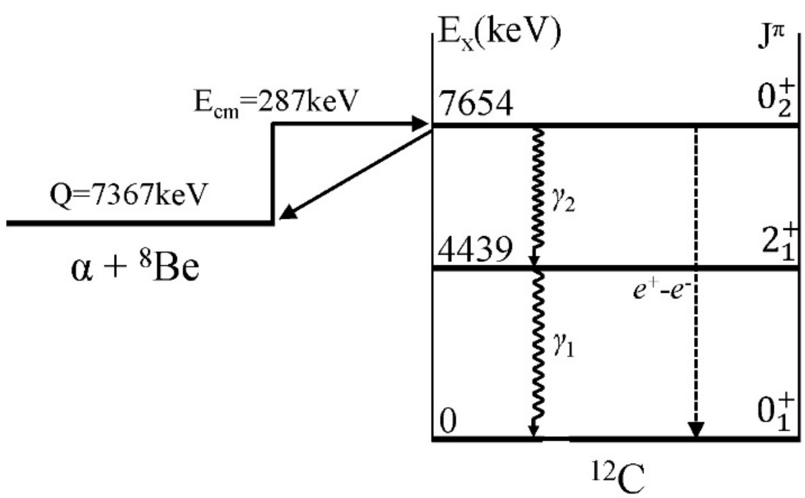

Fig. 1. Decay modes of Hoyle state.

A recent study by Kibedi *et al.* [1] reports a deviation of more than 3σ from the currently adopted value for Γ_{rad}/Γ, as reported in the reference by Freer *et al.* [2]. The values are summarized in Table I. *The goal of this project is to make an independent measurement of the Γ_{rad}/Γ branching ratio to resolve the discrepancy.*

Table 1. Summary of measurements of radiative branching ratio, pair-production branching ratio, and pair-production width of the Hoyle state.

Parameter	Adopted [1]	Recent
$\Gamma_{\mathrm{rad}}/\Gamma$	$4.03(10) \times 10^{-4}$	$6.2(6) \times 10^{-4}$ [2]
$\Gamma_{\pi}(\mathrm{E0})/\Gamma$	$6.7(6) \times 10^{-6}$	$7.6(4) \times 10^{-6}$ [3]
$\Gamma_{\pi}(\mathrm{E0})$	$62.3(2)\mu\mathrm{eV}$	-
Γ_{rad}	3.8×10^{-3} eV	$5.1(6) \times 10^{-3}$ eV [2]

Experiment

The experiment was conducted at the Cyclotron Institute using the K150 cyclotron in September 2021. Fig. 2 illustrates the experimental setup, while Fig. 3 depicts the DAQ system. We utilized the charged-particle coincidence method for this measurement. The Hoyle state was populated through the reaction ^{12}C(α, α')^{12}C*. The α' particles, which were elastically scattered, were detected by a ΔE-E silicon telescope positioned at an angle of 81° relative to the beam axis. The ^{12}C(g.s.) ions, produced as a result of the electromagnetic decay of the Hoyle state, were detected by the MDM-TexPPAC system at an angle of 35.3°. The spectrometer covers an angle of 4° in both the vertical and horizontal directions. The idea of these measurements is simple as the radiative decay branching ratio is given by the ratio of the number of ^{12}C ions produced in the decay of the Hoyle state and measured in the TexPPAC system to the total number of the Hoyle states populated. The challenge is to obtain the desired accuracy in view of the small branching ratio of less than 0.1%.

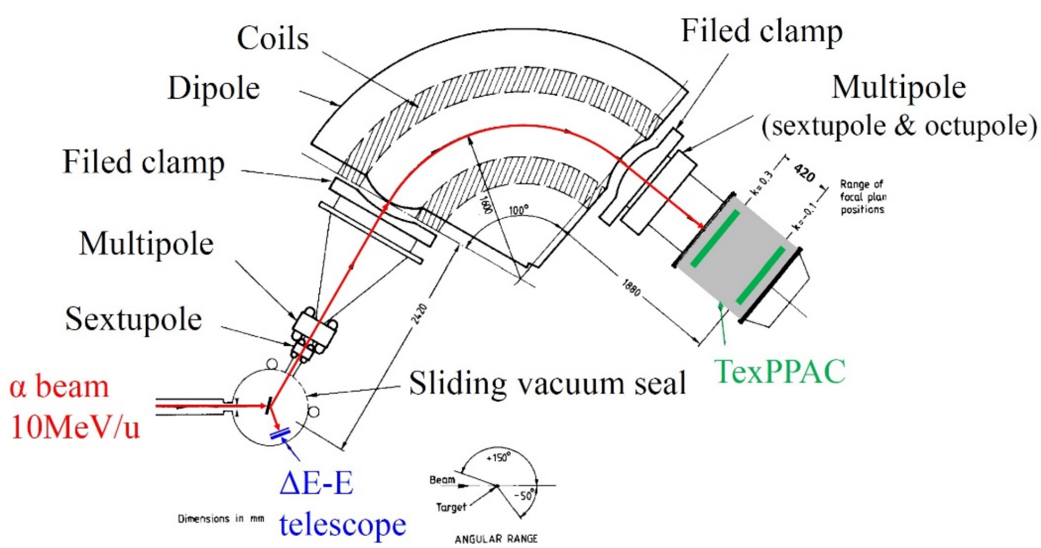

Fig. 2. Schematic of experimental setup.

The identification of the ^{12}C ions is performed in MDM spectrometer using magnetic rigidity $B\rho = \frac{mv}{q} = \frac{m}{q}\sqrt{2\frac{E_k}{m}}$. However, both $^{4}He^{2+}$ and $^{12}C^{6+}$ share the same m/q ratio. Consequently, fully stripped helium and ^{12}C ions have the same rigidity if they have the same energy per nucleon. Figure 3 displays the Geant4 simulation depicting the energies of the ^{4}He from the alpha-decay of the Hoyle state (dominant decay mode) and ^{12}C ions as they enter the slit box (MDM spectrometer entrance). To reduce the transmission of unwanted ^{4}He, the spectrometer was configured for $^{12}C^{5+}$ ions, thereby allowing only a small number of $^{4}He^{2+}$ ions, which travel 1.2 times faster than $^{12}C^{5+}$ ions, to pass through. By measuring the time of flight (ToF), we can further distinguish the transmitted $^{4}He^{2+}$ ions from the $^{12}C^{5+}$ ions, eliminating any chance for misidentification of ^{12}C.

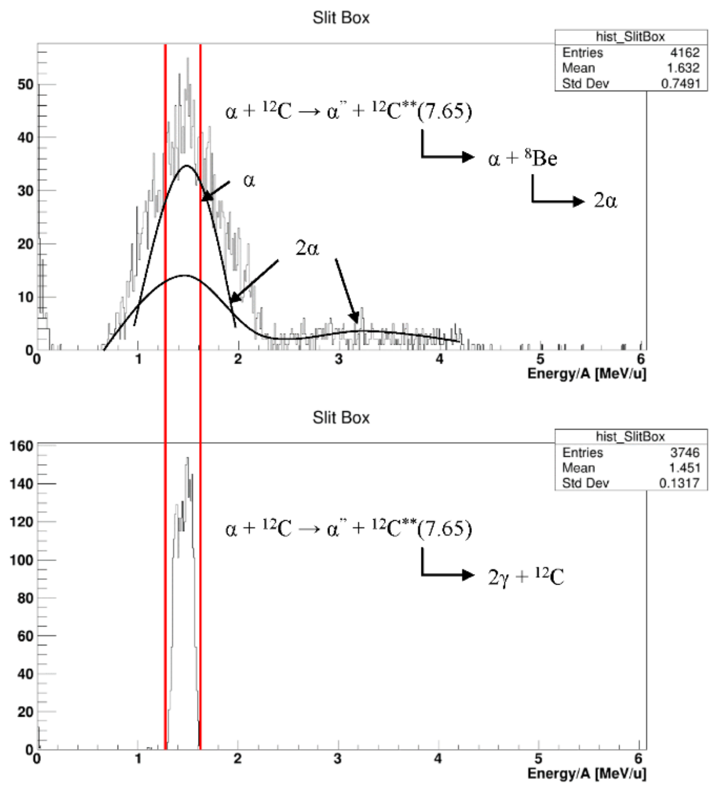

Fig. 3. Energy distribution of $^{12}C(\mathbf{0_2^+})$ decay products that enter MDM spectrometer.

Analysis of the experimental results

The first step in the analysis is to determine the charge state fractions for the ^{12}C ions. The ^{12}C ions emitted from the target exhibit charge states ranging from 1^+ to 6^+. In order to ascertain the distribution of charge states, we performed elastic scattering measurements by tuning the MDM spectrometer to detect ^{12}C

in each charge state individually. The outcome is presented in Figure 4 for the ^{12}C energy after the target at 1.5 MeV/u. Notably, it can be observed that $^{12}C^{5+}$ holds the highest fraction, with $F_{5+} = 0.495 \pm 0.026$.

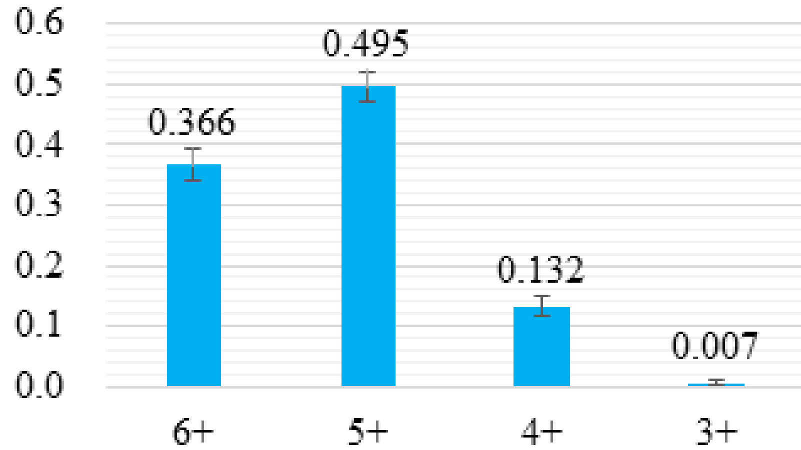

Fig. 4. Charge state distribution of ^{12}C out of 200 μm/cm^2 ^{12}C target at energy 1.5 MeV/u.

Particles detected by the TexPPACs travel a distance of more than 7 meters, whereas the particles detected by the silicon detectors only covered a distance of 17 cm. The ToF for the first type of particles (T_1) is on the order of 300 ns, while the ToF for the second type (T_{Si}) is approximately 10 ns. Fig. 5 exhibits

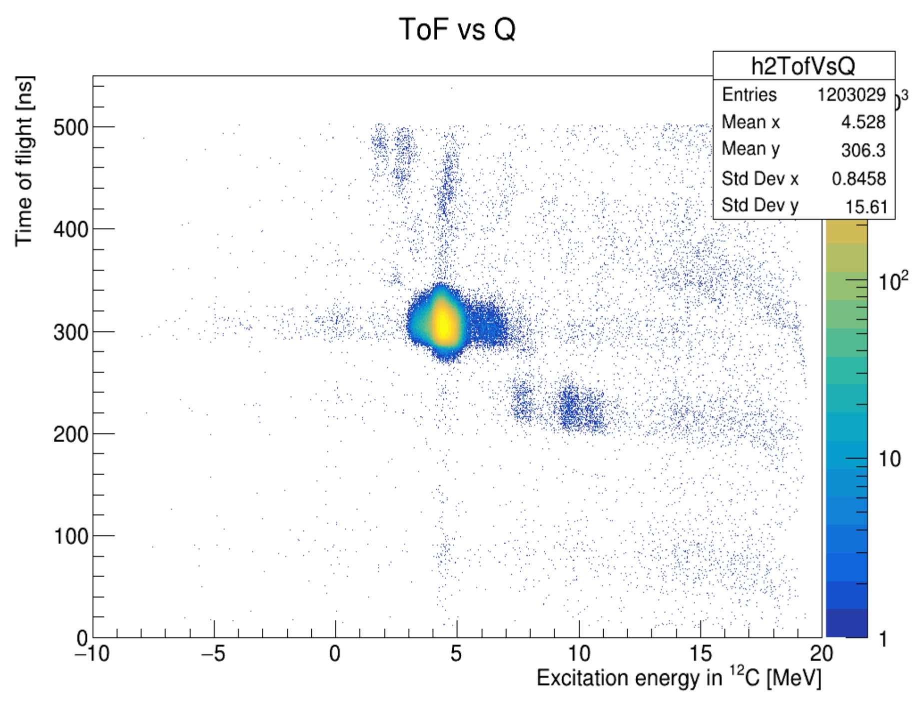

Fig. 5. ToF difference between TexPPAC1 and E detector. The boxes show the clusters of $^{12}C^{5+}$ ions and $^{4}He^{2+}$ respectively.

the plot of T_1-T_{Si} against the excitation energy in ^{12}C. The clusters observed in the upper and lower regions correspond to events involving $^{12}C^{5+}$ and $^{4}He^{2+}$ respectively. As previously discussed, the α-particles are faster compared to the ^{12}C ions due to their 1.2 times higher velocity. This characteristic enables effective discrimination between α particles and ^{12}C.

Figs 6(a) and 6(b) display the excitation-energy spectra of both singles and coincidence events centered around the Hoyle state measured by DSSD detector telescope. In the coincidence spectrum, a small peak associated with the Hoyle state was observed on the higher energy side of a larger peak, which is most likely due to the $^{16}O(\alpha,\alpha')^{16}O^{*}\rightarrow{}^{12}C+\alpha$ reaction originating on the oxygen impurities of the isotopically enriched ^{12}C target used for this experiment.

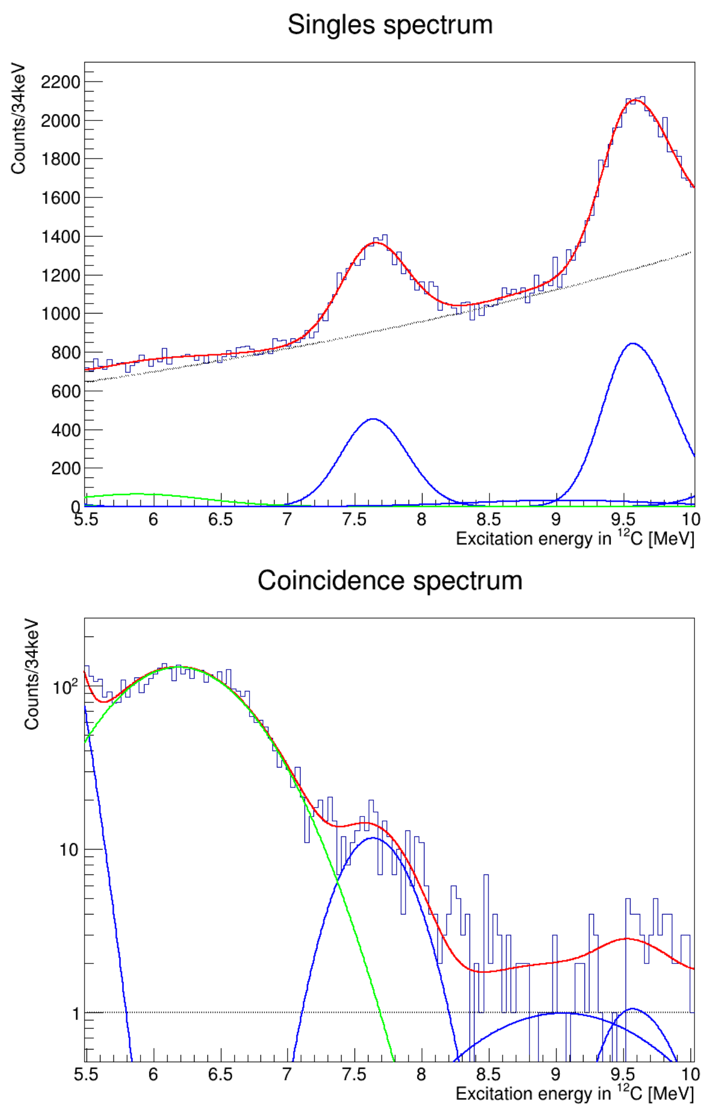

Fig. 6. Excitation-energy spectrum of ^{12}C around the Hoyle state for (a) the singles events and (b) the coincidence events in the inelastic α-scattering.

To determine the yields of singles and coincidence events, both spectra were fitted using Gaussian functions for the 0_2^+ and 3_1^- states, as well as other peaks, while a smooth function was employed for the continuum. The centroids and widths of the Gaussian functions were adjusted to reproduce the singles spectrum, and the same parameters were utilized for the coincidence spectrum. Two different functions were tested to fit the continuum: an exponential function and a semi-phenomenological function obtained from [5] with an added constant offset. The measured spectra were then subtracted by the fit functions for the continuum, and the remaining spectra were integrated to obtain the yields of the Hoyle state. This approach was employed to mitigate errors resulting from discrepancies between the Gaussian fit function and the actual measured peak shape.

The reduced χ^2 values for the fits using the semi-phenomenological function and the exponential function were found to be 1.93 and 1.23, respectively. Given that the exponential function yielded a better reduced χ^2 value, the yield obtained from this fit was adopted as the most probable value. The difference between the two yields was considered as the systematic uncertainty arising from the ambiguity of the continuum function. Consequently, the present $\frac{\Gamma_{\mathrm{rad}}}{\Gamma}$ of the Hoyle state in ^{12}C was determined to be $\frac{\Gamma_{\mathrm{rad}}}{\Gamma} \times 10^4 = 5.5 \pm 0.6\ (stat.) \pm 0.2\ (syst.)$.

Conclusion

The Hoyle state radiative branching ratio established in this work is consistent with the most recent results by Kibedi *et al.*, [1] within the experimental uncertainties and is 2.5σ above the previous recommended values. Statistical uncertainty dominates our measurements, and it would be desirable to repeat this or a similar experiment with better statistics (by at least a factor of four) before the final verdict can be made.

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