नाभिकीय अभिक्रिया

7

नाभिकीय खगोल-भौतिकी से संबंधित अध्ययन

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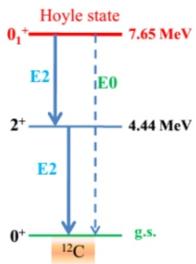

^{12}C की वास्तविक स्थिति में हॉयल अवस्था का रेडियोसक्रिय क्षय

सारांश

^{12}C की एक अनुनाद अवस्था को हॉयल अवस्था के नाम से जाना जाता है, जिसके माध्यम से 3α अभिक्रिया ^{12}C की आंकी गई प्रचुरता को दर्शाने के लिए ^{12}C के उत्पादन को ~ 10^8 गुना बढ़ा देती है और सितारों में कार्बन एवं ऑक्सीजन का अनुपात भारी तत्वों के संश्लेषण के लिए प्रासंगिक है। इस अध्ययन से पता चलता है कि ^{12}C की हॉयल अवस्था के 3 में प्रत्यक्ष क्षय के विभिन्न तरीकों की शाखन को विभाजित करना हॉयल अवस्था की प्रारंभिक संरचना से अत्यधिक प्रभावित है। एक बहुत ही गर्म (T_9 = 0.1 से 10) और सघन (10^6 gm/cm^3) तारकीय वातावरण में ^{12}C के हॉयल अवस्था के कण-प्रेरित व्युत्तेजन और उच्च अनुनाद (9.64 MeV, 3_1^- और 9.87 MeV, 2_2^+) ^{12}C उत्पादन दर हेतु वृद्धिकारक पाए गए हैं। संयोग से टूटने वाले कणों की सापेक्ष ऊर्जाओं के प्रयोगात्मक वितरण के विभिन्न संयोजनों की तुलना हॉयल अवस्था की विभिन्न क्षय प्रक्रियाओं को अलग करने के लिए अनुकरणीय माना जाता है।

Nuclear Reactions

7

Studies related to Nuclear Astrophysics

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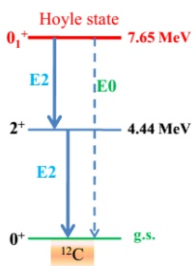

Radiative decay of the Hoyle state to the ground state of ^{12}C

ABSTRACT

A resonant state of ^{12}C, named Hoyle state, through which the 3α reaction increases the production of ^{12}C by ~10^8 times to explain the observed abundance of ^{12}C and the ratio of carbon to oxygen in stars relevant for synthesizing heavier elements. The study shows that the branching of different modes of direct decay of Hoyle state of ^{12}C into 3α is highly influenced by the initial structure of the Hoyle state. In a very hot(T_9 = 0.1 to 10) and dense (10^6 g/cm^3) stellar environment the particle-induced de-excitations of the Hoyle state and higher resonances (9.64 MeV, 3_1^- and 9.87 MeV, 2_2^+) of ^{12}C are found to enhance the ^{12}C production rate. Different combinations of experimental distribution of relative energies of the coincident breakup α particles are compared with simulations to disentangle different decay processes of the Hoyle state.

KEYWORDS: *Hoyle state,3α cluster structure, relative energy distribution, direct decay processes, nuclear astrophysics, ^{12}C abundance, up-scattering*

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Introduction

In recent years a lot of attention is drawn worldwide towards the study of the Hoyle state as well as ^{12}C production. Work on this area has been initiated recently in our laboratory. The BARC-TIFR Pelletron-Linac facility has been used for the related experiments. The results of some of the theoretical and experimental investigations are highlighted below.

Effect of Initial 3α Cluster Configurations in ^{12}C on the Direct Decay of its Hoyle State

We investigate the implications of initial 3α configurations in ^{12}C corresponding to different decay modes of its Hoyle state on the penetrability ratios. Considering the second 2^+ (10.03 MeV) state to be a collective excitation of the Hoyle state, the direct 3α decay width for the Hoyle state has been calculated using the ratio of the barrier penetration probability of the Hoyle state to the 2^+ state. The semi-classical Wentzel–Kramers–Brillouin (WKB) approximation has been employed to determine the penetrability ratio, resulting in an upper limit on the branching ratio of the direct decay of the Hoyle state in "equal phase-space" (DDφ) mode as $\Gamma_{3\alpha}/\Gamma < 3.1 \times 10^{-6}$. However, this limit for "linear chain" (DDL) decay is $\Gamma_{3\alpha}/\Gamma < 2.6 \times 10^{-7}$, which is one order of magnitude smaller than the DDφ decay and the limit for "equal energy" (DDE) decay is $\Gamma_{3\alpha}/\Gamma < 1.5 \times 10^{-5}$, which is greater than both DDφ and DDL decays. It implies that the limit on direct decay probability is strongly dependent on the initial configuration of the 3α cluster. A further probe using a bent-arm-like 3α initial configuration shows that the direct decay probability is maximum when the angle of the bent arm is ≈120^0, an important ingredient for understanding the Hoyle-state structure [1]

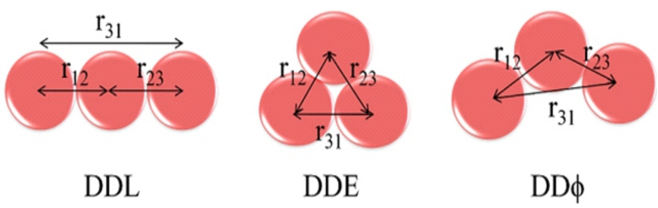

Fig.3: Initial 3α cluster configurations for direct decay modes in linear chain (DDL), equal energy (DDE), and equal phase space (DDφ).

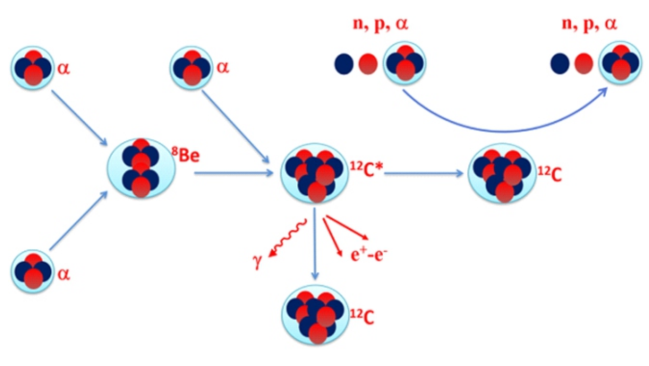

Fig.3: A cartoon of the particle-induced de-excitation process, that competes with the spontaneous radiative deexcitation (γ or e^+-e^- pair emission).

Light-particle-induced De-excitations of 3_1^- and 2_2^+ Resonances of ^{12}C in Extreme Stellar Conditions

The particle-induced de-excitations of the 9.64 MeV, 3_1^- and 9.87 MeV, 2_2^+ resonances of ^{12}C increase the ^{12}C production rate in a very hot and dense stellar environment. The enhancements in ^{12}C production in such environments were estimated for a particle (n, p, and α) density of 10^6 g/cm^3 in the temperature range of T_9 = 0.1 to 10. Enhancement due to neutron-induced de-excitation was found to be the maximum.

The net ^{12}C production rate due to the combined contributions from 7.65 (Hoyle state), 9.64, and 9.87 MeV states is much higher compared to the rate adopted by NACRE compilation. In case of a typical collapsing massive star with temperature dependent densities, for any of the 3_1^- or 2_2^+ resonances, the enhancement factor due to n, p, and α-induced de-excitations together can be as high as 600 [2].

Measurement of the Direct Decay Modes of the Hoyle State

We have carried out two experiments to measure the direct 3α decay branching ratio of the Hoyle state of ^{12}C to investigate recent theoretical prediction [1] which is considerably lower than the presently measured upper limit. Data analysis of the pilot measurement shows that using different analysis techniques such as, Dalitz plot technique, relative energy of ^8Be like α pair spectrum and RMS energy deviation spectrum together, contributions from different decay modes can be extracted with better precision. An improved experiment has been carried out using a larger beam time, bigger detector setup consisting of eight large area double sided silicon strip detectors (DSSD) and a beam energy closer to a different resonance in $^{12}C+^{12}C$ reaction. In addition to precision direct decay branching measurement we planned to confirm the observation of a state at 7.458 MeV, named as Effimov state, which lies very close to the Hoyle state [3].

Over the last decade, numerous experiments have been performed to quantify the direct decay component of the Hoyle-state which is supposed to throw new light on the structure. An upper limit of 0.019% was put by T. Rana et al. [4] which is

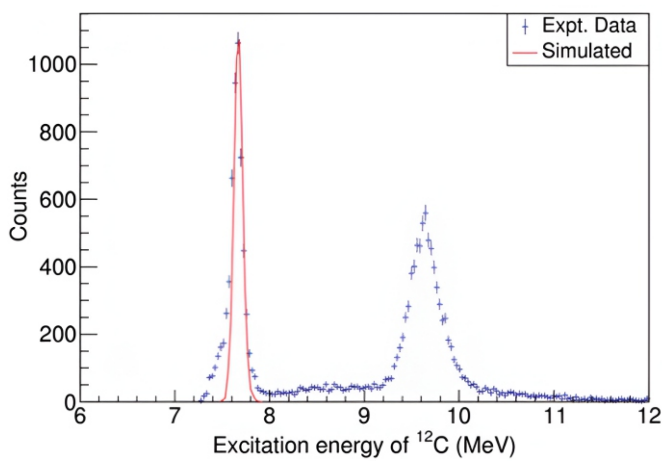

Fig.3: Excitation energy spectrum by reconstructing 3 simultaneous α particle momenta.

actually the upper limit of DDφ decay, for DDL decay they put an upper limit of 0.004% and for DDE decay the same is 0.012%. a comparison of the results obtained in some of the major experiments shows a clear trend that with increasing statistics, the upper limit of direct decay is decreasing. Recent calculations for the upper limit of direct decay [1,5] show the upper limit is even two orders of magnitude smaller than what has been found in the highest statistics experiment so far [4]. This indicates that we need even higher statistics to go further down the upper limit. It has been shown [1] that the resolution plays a major role while extracting the contributions from different decay modes. This was the motivation behind performing an even higher statistics experiment than Rana *et al.* [4] with even better angular resolution.

Here we report a new high-precision measurement of the DD branching ratio utilizing an optimized array of eight double-sided silicon strip detectors and advanced kinematic reconstruction techniques, yielding over 2.2×10^5 fully reconstructed Hoyle state events.

As can be seen from Fig.3, the Hoyle state at 7.65 MeV as well as 9.65 MeV 3^- state has been populated. For further analysis of the Hoyle state, the events under the 7.65 MeV peak are chosen. These events are a mixture of both the sequential and direct decay events. In order to disentangle these two kinds of events, we have used three sophisticated techniques: i) Dalitz plot analysis ii) Relative energy of ^{8}Be like α pair and iii) RMS energy deviation spectrum.

A comparison between simulated and experimental Dalitz plots reveals that sequential decay is dominant as expected. However, in order to quantify the individual direct decay components, we have to resort to other techniques.

The distribution of the lowest relative energy between any two α-particles in each 3α decay event of the Hoyle state is called "relative energy of ^{8}Be like α pair spectrum". So, all sequential decay (SD) events decaying through the ^{8}Be ground state will contribute to the peak at a relative energy of ~ 92 keV, the breakup energy of $^8Be_{g.s.}$, whereas for DDL it should peak around 95 keV and for DDE mode of decay, it should peak at $E_{rel} \approx$ 188 keV. So, this technique can differentiate between SD and DDE but not between SD and DDL. The relative energy distribution of the ^{8}Be like pairs in the experimental data is displayed in Fig.6 along with those obtained from simulation events for SD, DDE, DDL and DDφ processes in the same figure to show the nature of distribution for different types of decays. It is seen that the experimental distribution is dominated by the peak at around 92 keV signifying strong dominance of the SD process. The results of the simultaneous fit are shown in Fig.4.

The root mean square energy deviation, E_{rms} can be defined as, $E_{rms} = \sqrt{[<E_{rel}(ij)^2> - <E_{rel}(ij)>^2]}$, where, $E_{rel}(ij)$ are the relative energy between the α particles from the decay of the Hoyle state, and the average is over all possible pairs of the 3α events. Fig.5 displays the distribution of E_{rms} for the fully detected events along with the simulated spectra for different modes. It is clear from the relation for E_{rms} that DDE should contribute prominently in the neighbourhood of $E_{rms} \approx 0$ in the distribution, subject to finite broadening due to the total instrumental resolution. The results of the simultaneous fits show that the sequential decay constitutes the major contribution.

A new method of data analysis was employed including both the "folded Dalitz plot projections" and "normalized energy difference" methods, supplemented by Bayesian soft-assignment classification, to disentangle DD events from the overwhelming sequential decay background. We determined an upper limit of 0.018% for the DDϕ mode (and 0.002% for the DDE mode) at the 2σ confidence level, and a realistic branching ratio of approximately 0.0018% for Ddϕ using Bayesian inference. These results provide the most stringent experimental limits to date, closer to the recent theoretical predictions, and reinforce the dominance of sequential decay. This work has significant implications for nuclear structure models and the astrophysical rate of carbon production in stars.

Summary

Systematic measurements related to the famous Hoyle state of ^{12}C have been carried out to understand the structure

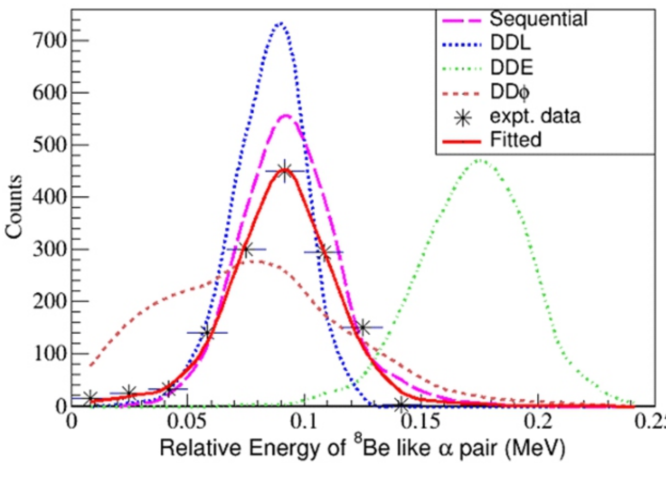

Fig.4: Simultaneous fit of different decay modes with experimental data for relative energy analysis to delineate individual direct decay contributions.

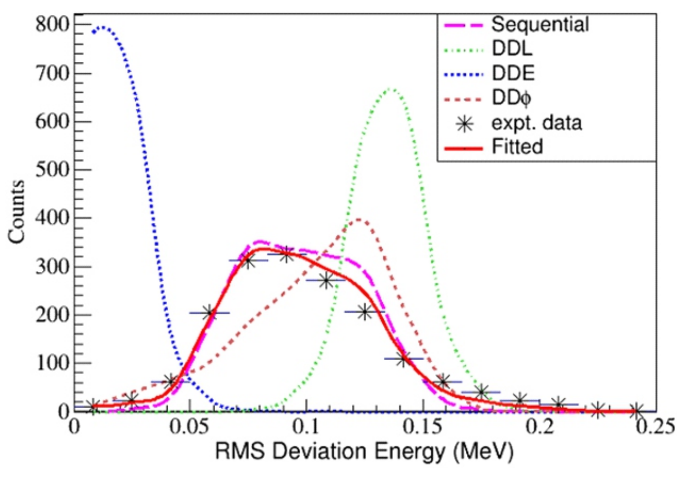

Fig.5: Simultaneous fit of different decay modes with experimental data for rms energy deviation analysis to determine individual contributions.

of this resonance state as well as the effect on the three alpha reaction rate due to the variation in the environmental condition. It was observed that the initial three-alpha cluster structure has a huge impact on the probability of different direct decay modes. In a highly dense and hot star, the production of ^{12}C was found to be enhanced due to the upscattering of protons, neutrons and alpha particles off ^{12}C proceeding through its different resonance states. A new upper limit on the existence of another resonance state called Effimov state, very close to the Hoyle state, has been obtained from a high precision 3-alpha breakup measurement. In the investigation of direct decay branching of the Hoyle state, an upper limit of about 0.0018% was obtained for the most dominant DDϕ mode using Bayesian inference. These results provide the most stringent experimental limits to date.

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