Physics Letters B 817 (2021) 136283

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First experimental determination of the radiative-decay probability of the 3_1^- state in ^{12}C for estimating the triple alpha reaction rate in high temperature environments

M. Tsumura [a,*,1], T. Kawabata [b], Y. Takahashi [a], S. Adachi [b], H. Akimune [c], S. Ashikaga [a], T. Baba [a], Y. Fujikawa [a], H. Fujimura [d], H. Fujioka [e], T. Furuno [b], T. Hashimoto [f], T. Harada [g], M. Ichikawa [a], K. Inaba [a], Y. Ishii [a], N. Itagaki [h], M. Itoh [i], C. Iwamoto [j], N. Kobayashi [k], A. Koshikawa [a,2], S. Kubono [g,l], Y. Maeda [m], Y. Matsuda [i,3], S. Matsumoto [a], K. Miki [n], T. Morimoto [a], M. Murata [k], T. Nanamura [a], I. Ou [o], S. Sakaguchi [p], A. Sakaue [g,4], M. Sferrazza [q], K.N. Suzuki [a], T. Takeda [a], A. Tamii [k], K. Watanabe [a], Y.N. Watanabe [r], H.P. Yoshida [k], J. Zenihiro [a]

[a] *Department of Physics, Kyoto University, Kitashirakawa-Oiwake, Sakyo, Kyoto 606-8502, Japan*
[b] *Department of Physics, Osaka University, Machikaneyama, Toyonaka, Osaka 560-0043, Japan*
[c] *Department of Physics, Konan University, Okamoto, Higashi-nada, Kobe, Hyogo 658-8501, Japan*
[d] *School of Medicine, Wakayama Medical University, Kimiidera, Wakayama 641-8509, Japan*
[e] *Department of Physics, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo 152-8550, Japan*
[f] *Rare Isotope Science Project, Institute for Basic Science, Somunsanseong-gil, Yuseong-gu, Daejeon 34000, Republic of Korea*
[g] *Nishina Center for Accelerator-Based Science, RIKEN, Hirosawa, Wako, Saitama 351-0198, Japan*
[h] *Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa-Oiwake, Sakyo, Kyoto 606-8502, Japan*
[i] *Cyclotron and Radioisotope Center, Tohoku University, Aoba, Aramaki, Aoba, Sendai, Miyagi 980-8578, Japan*
[j] *RIKEN Center for Advanced Photonics, RIKEN, Hirosawa, Wako, Saitama 351-0198, Japan*
[k] *Research Center for Nuclear Physics, Osaka University, Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[l] *Center for Nuclear Study, Graduate School of Science, The University of Tokyo, Hirosawa, Wako, Saitama 351-0198, Japan*
[m] *Faculty of Engineering, University of Miyazaki, Gakuen-kibanadai-nishi, Miyazaki 889-2192, Japan*
[n] *Department of Physics, Tohoku University, Aoba, Aramaki, Aoba, Sendai, Miyagi 980-8578, Japan*
[o] *Department of Physics, Okayama University, Tsushimanaka, Kita, Okayama 700-8530, Japan*
[p] *Department of Physics, Kyushu University, Motooka, Nishi, Fukuoka 819-0395, Japan*
[q] *Départment de Physique, Université Libre de Bruxelles, Bruxelles 1050, Belgium*
[r] *Department of Physics, The University of Tokyo, Hongo, Bunkyo, Tokyo 113-0033, Japan*

ARTICLE INFO

Article history:
Received 29 October 2020
Received in revised form 8 April 2021
Accepted 8 April 2021
Available online 16 April 2021
Editor: B. Blank

Keywords:
Triple alpha reaction
Nucleosynthesis
Radiative-decay probability

ABSTRACT

The triple alpha reaction is one of the most important reactions in the nuclear astrophysics. However, its reaction rate in high temperature environments at $T_9 > 2$ was still uncertain. One of the major origins of the uncertainty was that the radiative-decay probability of the 3_1^- state in ^{12}C was unknown. In the present work, we have determined the radiative-decay probability of the 3_1^- state to be $1.3^{+1.2}_{-1.1} \times 10^{-6}$ by measuring the ^{1}H(^{12}C,^{12}Cp) reaction for the first time, and derived the triple alpha reaction rate in high temperature environments from the measured radiative-decay probability. The present result suggests that the 3_1^- state noticeably enhances the triple alpha reaction rate although the contribution from the 3_1^- state had been assumed to be small.

* Corresponding author.
E-mail addresses: tsumura@rcnp.osaka-u.ac.jp (M. Tsumura), kawabata@phys.sci.osaka-u.ac.jp (T. Kawabata).
1 Present address: Kobe Air Traffic Control Center, Ministry of Land, Infrastructure, Transport and Tourism, Ibukidai-Higashi, Nishi, Kobe, Hyogo 651-2242, Japan.
2 Present address: Graduate School of Information Sciences, Tohoku University, Aoba, Aramaki, Aoba, Sendai, Miyagi 980-8579, Japan.
3 Present address: Department of Physics, Konan University, Okamoto, Higashi-nada, Kobe, Hyogo 658-8501, Japan.
4 Present address: Center for Nuclear Study, Graduate School of Science, The University of Tokyo, Hirosawa, Wako, Saitama 351-0198, Japan.

https://doi.org/10.1016/j.physletb.2021.136283

When our universe began about 13.8 billion years ago, no elements existed there. All of the elements were synthesized in the history of the universe by nuclear reactions.

Helium, the second abundant element in the universe, was synthesized by a series of proton/neutron capture or transfer reactions during the big bang nucleosynthesis (BBN) in 3–20 minutes after the beginning of the universe. Since there is no bound state in the $A=5$ isobar, this proton and neutron capture chain suspended at $A=4$. ^{8}Be nuclei were produced in ^{4}He + ^{4}He collisions, but they decayed back to two ^{4}He nuclei with very short lifetimes. Therefore, it is considered in the standard BBN model that heavy elements with $A>4$ were rarely synthesized, and their abundances were less than 10^{-9} in the early universe.

Heavier elements than He were mainly synthesized in stars. Stars synthesize ^{4}He in proton-proton chain reactions or the CNO cycle during they remain on the main sequence. ^{4}He becomes abundant in cores of stars when stars exhaust hydrogen and leave from the main sequence. However it is not trivial how heavy elements are synthesized from ^{4}He in stars unless the bottlenecks at $A=5$ and 8 are solved. This was a serious puzzle in physics until 1950s.

It is widely known that this puzzle was solved by Salpeter and Hoyle [1,2]. Salpeter proposed that ^{12}C should be synthesized by the triple alpha (3α) reaction in dense and hot environments in stars [3], and Hoyle predicted that a 3α resonance should exist at slightly above the 3α decay threshold in ^{12}C to explain the cosmic abundance ratio of He:C:O in a scenario with the 3α reaction [4]. This predicted 3α resonance was experimentally established by Dunbar et al. [5]. This state is now called the Hoyle state [6,7].

In the 3α reaction, an α particle is captured by ^{8}Be which is a 2α resonance, and consequently an excited state in ^{12}C is populated as a 3α resonance. At normal stellar temperatures $T_9 \sim 0.1$ (T_9 is the temperature in units of 10^9 K.), this process proceeds mainly via the Hoyle state at $E_x = 7.654$ MeV, but high-lying 3α resonances such as 3_1^- at $E_x = 9.64$ MeV and 2_2^+ at $E_x = 9.87$ MeV play a significant role at higher temperatures [8]. Most of these 3α resonances decay back to three α particles, but an extremely little fraction of them is de-excited to the ground state in ^{12}C by radiative decay. The 3α reaction rate, therefore, strongly depends on the radiative-decay probabilities $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ of the 3α resonances, which are given by the ratios of the radiative-decay widths $\Gamma_{\rm rad}$ to the total widths $\Gamma_{\rm tot}$. $\Gamma_{\rm rad}$ is the sum of the γ-decay width Γ_γ and the pair-production decay width $\Gamma_{e^+e^-}$.

The 3α reaction is the doorway reaction that bypasses the $A=5$ and 8 bottlenecks and allows the production of heavier elements, and thus it is one of the most important nuclear reactions in the nucleosynthesis. For example, the 3α reaction has a great impact on abundances of proton-rich isotopes of medium heavy elements (p-nuclei). The astrophysical origin of the p-nuclei is still under debate. The νp-process during the supernova explosions is a promising solution to explain their abundances [9–12], but it has not been fully understood. Wanajo theoretically examined the νp-process and found that a small variation of the 3α reaction rate at $T_9 > 2$ drastically changes abundances of the p-nuclei [13]. The high-lying 3α resonances enhance the 3α reaction to increase medium mass nuclei with $A=60$–80, and these nuclei act as proton poisons to slow down the νp process at $A>80$. If the 3α reaction rate would increase several times, the production of the p-nuclei with $A>80$ would be suppressed by several orders of magnitude. The importance of the 3α reaction rate is also discussed in high-density environments [14,15].

In nuclear astrophysical calculations, the 3α reaction rate estimated in the NACRE compilation [16] has been widely used. However, the estimated 3α reaction rate at $T_9 > 2$ was quite uncertain because the radiative-decay widths of the 3_1^- and 2_2^+ states were experimentally unknown when the NACRE compilation was established.

The 2_2^+ state was naturally predicted as an excited state of the relative motion of the α particles in the Hoyle state by α cluster-model (ACM) calculations [17–20], but its existence was experimentally controversial for a long time. Fynbo et al. reported that the 2_2^+ state was not observed in the β decay of ^{12}N and ^{12}B, and claimed its contribution to the 3α reaction is negligible [21]. Later, Itoh et al. found the 2_2^+ state [22], and Zimmerman et al. experimentally determined its energy, the direct-decay width to the ground state $\Gamma(E2; 2_2^+ \to \text{g.s.})$, and the total width $\Gamma_{\rm tot}$ [23]. Although the sequential-decay width via the 2_1^+ state at $E_x = 4.440$ MeV $\Gamma(E2; 2_2^+ \to 2_1^+)$ is still unknown, its contribution to the 3α rate should be suppressed by a factor of about 20 ($\sim [9.87/(9.87-4.44)]^5$) compared to that from the direct decay because the $E2$-decay width is proportional to the 5th power of the decay energy.

Contrary to the 2_2^+ state, the contribution of the 3_1^- state is still very uncertain. The 3_1^- state also decays to the ground state by either a direct decay or a sequential decay via the 2_1^+ state. The direct decay is an $E3$ transition, and its width is already known as 0.31 ± 0.04 meV from the (e,e') measurement [24]. Since $\Gamma_{\rm tot}$ of the 3_1^- state is 46 ± 3 keV [25], the direct-decay probability is $(6.7 \pm 1.0) \times 10^{-9}$. This is the lower limit of $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 3_1^- state. On the other hand, in the sequential decay, the $E1$, $M2$, and $E3$ transitions are in principle allowed. However, the $M2$ transition is significantly suppressed due to the isospin selection rule [26] since both the 3_1^- and 2_1^+ states are isoscalar states. The shell-model calculation with the SFO interaction [27] predicts the $M2$-decay width from the 3_1^- state to the 2_1^+ state is as small as 5 μeV. The isoscalar $E1$ transition is also strictly forbidden in the first order. However the $E1$ transition might have a larger width than the $E3$ and $M2$ transitions due to the two reasons. First, the isospin symmetry is slightly broken due to the Coulomb interaction. Second, $E1$ transitions are generally much stronger than $E3$ and $M2$ transitions. Actually, it was reported that a typical $E1$ transition rate between the isoscalar states around $A=12$ is $10^{-3.6}$ Weisskopf unit [28], which corresponds to $\Gamma_{\rm rad}$ = 15 meV in the $3_1^- \to 2_1^+$ transition. This is significantly larger than $\Gamma_{\rm rad}$ = 2 meV assumed in NACRE. Therefore, the 3α reaction rate via the 3_1^- state might be much larger than the estimation in NACRE.

A pioneering work to determine $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 3_1^- state was carried out by measuring α inelastic scattering from ^{12}C back in 1970s [29]. Once the 3α resonances in ^{12}C are excited, these states decay either to three α particles or to the ground state of ^{12}C by emitting γ rays or e^+e^- pairs. The radiative-decay events can be identified by detecting ^{12}C in the final state without detecting γ rays nor e^+e^- pairs. In Ref. [29], recoil ^{12}C nuclei after radiative decay were detected in coincidence with scattered α particles. However, small ^{13}C impurities in the isotopically enriched ^{12}C target caused serious backgrounds, and thus only the upper limit of $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 3_1^- state was reported as 8.2×10^{-7} at a confidence level of 95%.

In the present work, proton inelastic scattering from ^{12}C was measured in order to determine $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 3_1^- state. The measurement was carried out under the inverse kinematic condition in which a ^{12}C beam bombarded a hydrogen target. Scattered ^{12}C nuclei were detected in coincidence with recoil protons. Since no ^{13}C impurity was contained in the ^{12}C beam, the signal-to-noise ratio was much improved.

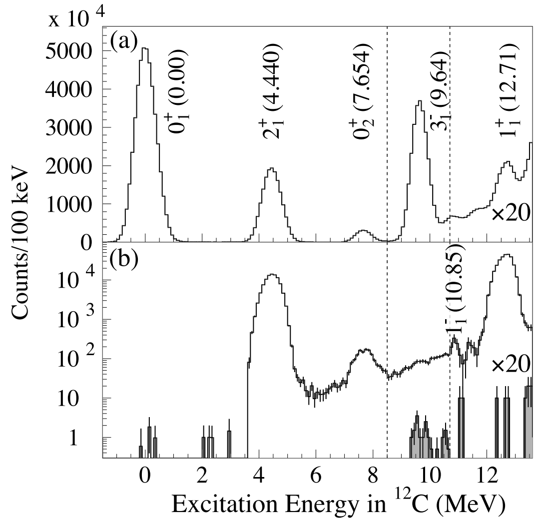

Fig. 1. Excitation-energy spectra of ^{12}C for (a) the singles events and (b) the coincidence events in the inelastic proton scattering. The gray histogram presents the accidental coincidence events. The vertical dashed lines at $E_x = 8.5$ and 10.7 MeV divide the spectra into the three excitation-energy regions measured by using different sensitive areas of Gion. The spectra at $E_x \geq$ 10.7 MeV are multiplied by a factor of 20.

The experiment was carried out at the cyclotron facility in Research Center for Nuclear Physics (RCNP), Osaka University. A $^{12}C^{5+}$ beam at 262 MeV bombarded a hydrogen target in the scattering chamber of the Grand Raiden (GR) spectrometer [30]. The unreacted beam was stopped in the Faraday cup downstream of a collimator plate for GR. A solid hydrogen target (SHT) system was newly developed to improve the hydrogen-to-contaminant ratio better than the gas target [31]. Pure hydrogen gas was fully converted to the parahydrogen whose thermal conductivity is about 10 times higher than the normal hydrogen [32]. The parahydrogen gas was filled into the target cell made of copper and cooled down to 9.6 K by a Gifford-McMahon refrigerator. A thin SHT with a thickness of 0.65 mm was made to keep the excitation-energy resolution in ^{12}C better than 0.65 MeV at the full width at half maximum. The entrance and exit windows of the target cell were 15 mm in diameter and sealed with 6-μm thick aramid films. Backgrounds due to the window films were successfully subtracted by an empty-cell measurement because the scattering events from target nuclei other than protons cause no peak structures in excitation-energy spectra.

Recoil protons were detected by using the GAGG [33] based light ion telescope (Gion) which was located at $\theta_{\text{lab}} = -41°$. Gion consisted of a double-sided Si strip detector (DSSD) and 24 GAGG scintillators. The particle identification was carried out with the ΔE-E correlation between the DSSD and the GAGG scintillators. The thickness of the DSSD was 650 μm, and the sensitive area was 48 mm in horizontal and 128 mm in vertical. The front and rear sides of the DSSD were divided into the 16 vertical strips and 32 horizontal strips, respectively. The GAGG crystals with a dimension of 18 mm × 18 mm × 25 mm were wrapped with enhanced specular reflector (ESR) films [34]. The thickness of the ESR film was 65 μm. The 24 GAGG crystals were mounted on avalanche photodiodes and stacked in 8 rows and 3 columns behind the DSSD. The distance between the target and Gion was 125 mm, and the 8 rows of the GAGG crystals were arranged to arch with respect to the target.

The GR spectrometer was located at θ_{lab} = 2.8° covering ±0.8° and ±30 mr in the horizontal and vertical directions. Scattered ^{12}C nuclei or decay α particles from excited states in ^{12}C were momentum-analyzed by GR and detected by the focal plane detectors. The focal plane detectors consisted of the two multiwire drift chambers (MWDCs) and two plastic scintillators (PS1 and PS2). They were tilted along the focal plane by 45° with respect to the central orbit of GR. Helium bags were installed between the detectors to suppress the multiple scattering by air. The MWDCs were operated using a detection gas of He (50%) + CH_4 (50%). The thicknesses of PS1 and PS2 were 1 mm and 10 mm so that ^{12}C nuclei stopped in PS1 but α particles penetrated it. By using an anti-coincidence technique between PS1 and PS2, trigger signals for ^{12}C events were generated. The GR spectrometer enabled us to precisely measure momenta, time of flights, and emission angles of scattered ^{12}C nuclei. It was crucial to reject background particles from different processes or different target nuclei. It was also useful to kinematically remove the accidental coincidence events as described later. This was a great advantage over the previous work [29] in which both of scattered α particles and recoil ^{12}C nuclei were detected by solid state detectors.

Fig. 1(a) shows the excitation-energy spectrum for the ^{12}C(p, p') reaction obtained with the SHT after the backgrounds due to the window films were subtracted. In the inverse kinematic measurement, spurious peaks are observed in excitation-energy spectra near the most backward angle where recoil protons can be emitted (critical angle) because $d\Omega_{\text{cm}}/d\Omega_{\text{lab}}$ diverges at the critical angle. Therefore, we eliminated events near the critical angle from the present analysis by reducing the effective area of Gion to 73%, 51%, and 3% for the three different excitation-energy regions at $E_x <$ 8.5 MeV, 8.5 MeV $\leq E_x <$ 10.7 MeV, and $E_x \geq$ 10.7 MeV, respectively.

The excitation-energy spectrum for the radiative-decay events was obtained from the coincidence events between protons and ^{12}C nuclei after subtracting the empty-cell spectrum. The backgrounds due to the window films were less than 10% of the coincidence events from the ^{12}C + p scattering around the 3_1^- state.

Accidental coincidence events, in which a ^{12}C nucleus and a proton from different events were detected at the same time, also caused serious backgrounds. In such events, two recoil protons must be emitted, therefore we set the angular acceptance of Gion to be large enough to detect both of these protons for rejecting most of the accidental coincidence events. In addition, the angular and energy correlations between the detected proton and ^{12}C were employed for further rejection of the accidental coincidence events.

The accidental coincidence events can be virtually generated by the event mixing analysis of singles events in GR and Gion. It was found that the accidental coincidence events were reduced by a factor of 100 thanks to the angular and energy correlations. The gray histogram

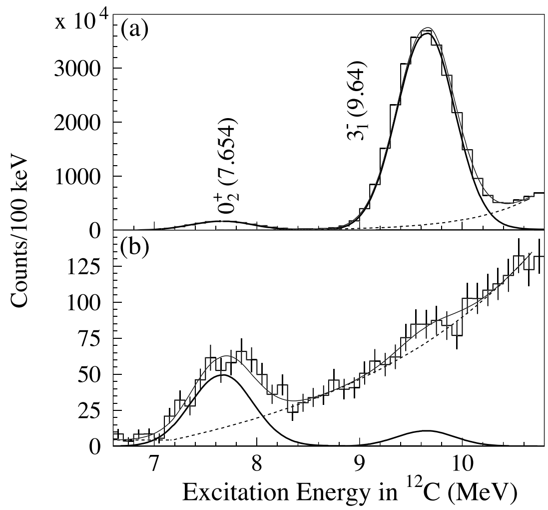

Fig. 2. Excitation-energy spectra of ^{12}C around the 3_1^- state for (a) the singles events and (b) the coincidence events in the inelastic proton scattering. The thick solid lines show the fit functions for the 0_2^+ and 3_1^- states while the dashed lines show that for the continuum. The thin solid lines present the sum of all the fit functions.

in Fig. 1(b) presents the excitation-energy spectrum for the remaining accidental coincidence events. The excitation-energy spectrum for the true coincidence events was obtained by subtracting these accidental coincidence events as presented by the open histogram.

The three prominent peaks due to the 2_1^+, 0_2^+, and 1_1^+ states were clearly observed in the coincidence spectrum. The two small bumps were also seen at $E_x \sim 10.85$ and 11.5 MeV. The bump at 10.85 MeV is close to the 1_1^- state which was observed in the inelastic electron scattering [35], whereas no state corresponding to another bump at $E_x \sim 11.5$ MeV is reported in Ref. [25]. It should be noted that the excitation-energy spectra at $E_x \geq 10.7$ MeV are scaled up by a factor of 20 and the statistical uncertainties around $E_x \sim 11$ MeV in Fig. 1(b) are very large. Therefore, we do not make further discussion about these two bumps here.

Figs. 2(a) and (b) show the excitation-energy spectra of the singles and coincidence events around the 3_1^- state, which were measured with 51% of the sensitive area of Gion optimized for $E_x = 8.5$–10.7 MeV. A small peak due to the 3_1^- state was observed on the continuum in the coincidence spectrum. The origin of this continuum is unclear. The broad 2_2^+ state lies near the 3_1^- state, but this state could not be observed in the present coincidence spectrum because its radiative-decay probability is considered to be an order of 10^{-8} [23]. One possible origin is the $^{12}\mathrm{C} + d \to ^{12}\mathrm{C} + p + n$ process. Because it is a three-body process, it might cause a continuous spectrum. However, we confirmed by a background measurement with a CD_2 target that the contribution from the deuteron break-up process is smaller than 10^{-8} when the SHT with the natural abundance is used. The accidental coincidence events are also unlikely to be the origin because the peak-to-continuum ratio in the coincidence spectrum would be the same with that in the singles spectrum if the accidental coincidence events caused the continuum.

Both of the singles and coincidence spectra were fitted by the two gaussian functions for the 3_1^- and 0_2^+ states and a smooth function for the continuum in order to obtain the yields of the singles and coincidence events. The centroids and widths of the gaussian functions were determined to reproduce the singles spectrum, and the same values were used for the coincidence spectrum. The two different functions were tried to fit the continuum. One is an exponential function, and the other is the semi-phenomenological function taken from Ref. [36] and added by a constant offset. The measured spectra were subtracted by the fit functions for the 0_2^+ state and the continuum, and the remaining spectra were integrated to obtain the yields of the 3_1^- state. This trick was introduced to avoid errors due to the disagreement in the shapes between the gaussian fit function and the measured peak.

The obtained yields in the coincidence spectrum were 71 and 116 with the semi-phenomenological function and the exponential function, respectively, and the reduced χ^2 values for the two fits were 0.69 and 1.05. Since the semi-phenomenological function gave the better reduced χ^2 value than the exponential function, the yield obtained with the semi-phenomenological function was adopted as the most probable value. The difference between the two yields was assumed to be the systematic uncertainty due to the ambiguity of the continuum function. Because the adopted yield is smaller than the other yield, we added this systematic uncertainty to the upper side. In order to estimate the systematic uncertainty on the lower side, we employed a liner function to fit the continuum. It is reasonable to assume that the continuum is described by a convex-downward function around the 3_1^- state because it is almost zero below the 3α-decay threshold at $E_x = 7.27$ MeV and seems to rise from the threshold smoothly. Therefore, the linear function is expected to simulate an extreme case to give the upper limit of the continuum. However, the linear function is physically unrealistic around the 0_2^+ state because this function becomes negative. In the present analysis, we used the linear function only for the error estimation and fitted it with the gaussian function to the spectrum at $E_x = 8.8$–10.5 MeV around the 3_1^- state. The obtained yield for the 3_1^- state in the coincidence spectrum was 31, and thus we estimated the systematic uncertainty on the lower side to be the difference between 71 and 31.

The statistical uncertainty of the yield as the 68% confidence interval was determined from the interval with $\chi^2 - \chi^2_{\mathrm{min}} \leq 1$ according to the standard procedure. The statistical uncertainty for the yield of the 3_1^- state in the coincidence spectrum was ± 42, and thus the statistical peak significance was 91%. Finally, the singles and coincidence yields of the 3_1^- state were obtained as listed with their uncertainties in Table 1. The uncertainties were determined by the quadratic sums of the statistical and systematic uncertainties.

Similarly, the yields of the 0_2^+ and 1_1^+ states were also obtained by analyzing the excitation-energy spectra measured with 73% and 3% of the sensitive area of Gion optimized for $E_x < 8.5$ MeV and $E_x \geq 10.7$ MeV, respectively.

Table 1
Summary of the experimental information for the 0_2^+, 3_1^-, and 1_1^+ states in ^{12}C.

	0_2^+	3_1^-	1_1^+
Yield of singles events	$(2.06 \pm 0.03) \times 10^7$	$(2.47 \pm 0.01) \times 10^8$	$(3.05^{+0.72}_{-0.76}) \times 10^6$
Yield of coincidence events	957 ± 79	71^{+62}_{-58}	$(1.43 \pm 0.01) \times 10^4$
Geometrical and event-selection efficiency $\epsilon_g \times \epsilon_s$	$(0.317 \times 0.344) \pm 0.019$	$(0.703 \times 0.306) \pm 0.036$	$(0.988 \times 0.182) \pm 0.023$
$\Gamma_{\rm rad}/\Gamma_{\rm tot}$ (present)	$(4.3 \pm 0.8) \times 10^{-4}$	$1.3^{+1.2}_{-1.1} \times 10^{-6}$	$(2.6 \pm 0.7) \times 10^{-2}$
$\Gamma_{\rm rad}/\Gamma_{\rm tot}$ (previous) [25]	$(4.16 \pm 0.11) \times 10^{-4}$	$< 8.2 \times 10^{-7}$(95%C.L.)	$(2.21 \pm 0.07) \times 10^{-2}$
$\Gamma_{\rm tot}$ (eV) [25]	9.3 ± 0.9	$(46 \pm 3) \times 10^3$	0.40 ± 0.05

The radiative-decay probability is given by

$$\frac{\Gamma_{\rm rad}}{\Gamma_{\rm tot}} = \frac{(\text{Yield of coincidence events})}{(\text{Yield of singles events})} \frac{1}{\epsilon_g \epsilon_s}.$$

ϵ_g is the geometrical efficiency for the coincidence measurement, and ϵ_s is the event-selection efficiency in the accidental-event rejection with the angular and energy correlations. These efficiencies were estimated by the Monte Carlo calculation as listed in Table 1. Their uncertainties mainly stem from the non-uniformity of the target thickness. Finally, $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 0_2^+, 3_1^-, and 1_1^+ states were obtained as listed in Table 1. The present $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ values for the 0_2^+ and 1_1^+ states are consistent with the literature values [25], and this warrants the reliability of the present analysis. Very recently, a new result for the radiative-decay probability for the 0_2^+ state was reported to be $(6.2 \pm 0.6) \times 10^{-4}$ [37], which was much larger than the literature value [25]. Most of the previous results [38–44] except one from Ref. [45] are consistent with Ref. [25] within their uncertainties but not with the new result from Ref. [37]. The present result also supports Ref. [25], therefore we adopted the radiative-decay probability of the 0_2^+ state from Ref. [25] in the present analysis.

The radiative-decay probability of the 3_1^- state was determined to be $\Gamma_{\rm rad}/\Gamma_{\rm tot} = 1.3^{+1.2}_{-1.1} \times 10^{-6}$. Unfortunately, the present data cannot reject the null result for the radiative decay of the 3_1^- state at the fully high statistical confidence level, but its most probable value is larger than the previous upper limit [29].

A possible reason for the overestimation is a wrong particle identification by the focal plane detector of GR. Because the magnetic rigidities of the decay α particles emitted from the 3_1^- state are almost same as that of ^{12}C, a sizable fraction of the decay α particles reached the focal plane as well as ^{12}C. If such α particles had been misidentified as ^{12}C, this event would have been recognized as a radiative-decay event. However, this scenario is not plausible. We have estimated the probability of misidentifying the α particle as ^{12}C is lower than 10^{-7} from the data analysis and the Monte Carlo calculation.

In conventional ACMs, predicted wave functions are purely isoscalar because all of nuclear states are described on the basis of relative motions of isoscalar α particles. Therefore, the $E1$ decay from the 3_1^- state to the 2_1^+ state is extremely suppressed. The $\mathcal{D}_{3h}$ symmetry, which was proposed to be well conserved in ^{12}C [47], also prohibits the $E1$ transition between the 3_1^- and 2_1^+ states. Under the $\mathcal{D}_{3h}$ symmetry, the 3_1^- state has a $K = 3$ quantum number while the 2_1^+ state is described as a member of the ground-state $K = 0$ rotational band. The $\Delta K = 2$ transition is strictly forbidden in the $E1$ transition. Therefore, the large $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ value, although its uncertainty is quite large, suggests that the $\mathcal{D}_{3h}$ symmetry breaking should be considered as well as the isospin symmetry breaking.

We calculated the 3α reaction rates with the formula given in Ref. [16]. The mathematical formula and resonance parameters are given in the supplementary material. The resonance parameters used in the calculation were taken from Ref. [25] except $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 3_1^- and 2_2^+ states. The direct-decay probability of the 2_2^+ state to the ground state was reported to be $7.5(1.7) \times 10^{-8}$ in Ref. [23], but the sequential-decay probability via the 2_1^+ state is still unknown. Therefore, we estimated the sequential-decay probability with the 3α resonating-group method (RGM) [18]. The RGM calculation gives the larger $E2$-decay widths of $\Gamma^{\rm RGM}(E2; 2_2^+ \to \text{g.s.}) = 2.0 \times 10^2$ meV and $\Gamma^{\rm RGM}(E2; 2_1^+ \to \text{g.s.}) = 64$ meV than their experimental values of $\Gamma^{\rm exp}(E2; 2_2^+ \to \text{g.s.}) = 60 \pm 10$ meV and $\Gamma^{\rm exp}(E2; 2_1^+ \to \text{g.s.}) = 10.8 \pm 0.06$ meV. In the present analysis, we renormalized the theoretical sequential $E2$-decay width of $\Gamma^{\rm RGM}(E2; 2_2^+ \to 2_1^+) = 24$ meV by the experiment-to-RGM ratio for the direct decay $\Gamma^{\rm exp}(E2; 2_2^+ \to \text{g.s.})/\ \Gamma^{\rm RGM}(E2; 2_2^+ \to \text{g.s.})$, and adopted $\Gamma(E2; 2_2^+ \to 2_1^+) = 7.2$ meV as the most probable value. We assumed its error distribution to be uniform between -7.2 meV and $+28.2$ meV, *i.e.* the uniform probability distribution of $\Gamma(E2; 2_2^+ \to 2_1^+)$ between 0 and 36 meV to estimate the uncertainty of the 3α reaction rate.

Fig. 3 presents the calculated 3α reaction rates $r_{3\alpha}$ divided by the 3α rate in NACRE $r_{3\alpha(\rm NACRE)}$. The error bands associated with the calculated 3α rates present their confidence interval at 68%, and the light gray band shows the uncertainty in NACRE. The 3α rate in NACRE was quite uncertain in the high temperature region at $T_9 > 2$ due to the poor experimental information on the 3_1^- and 2_2^+ states. According to the suggestion in Ref. [21], when only the 0_2^+ state and the direct radiative decay of the 3_1^- state are taken into account, the 3α rate presented by the red dotted line becomes much smaller than that in NACRE at high T_9 and close to the old 3α rate by Caughlan and Fowler [46] shown by the black dashed-dotted line. This is reasonable because the both calculations take into account the 0_2^+ and 3_1^- states but ignore the 2_2^+ state. The different behavior at $T_9 > 6$ is due to the difference in the assumed radiative-decay width of the 3_1^- state. By including the 2_2^+ state as reported in Refs. [22,23], the 3α rate restores but it is still smaller than NACRE as shown by the blue dashed line because $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 2_2^+ state is much smaller than the assumption in NACRE. In the present work, we have suggested that $\Gamma_{\rm rad}/\Gamma_{\rm tot}$ for the 3_1^- state is significantly larger than the assumption in NACRE for the first time. The 3α rate obtained by taking into account all the contributions from the 0_2^+, 3_1^-, and 2_2^+ states further restores as plotted by the black thick solid line. The reduction of the 3α rate due to the 2_2^+ state is compensated by the enhancement due to the 3_1^- state. After all, the new rate is consistent with NACRE within a large uncertainty which was inevitable before, but its uncertainty is now reduced at high temperatures. The approximate formula of the new 3α rates at $T_9 = 0.01$–10 is given in Appendix and the numerical values can be found in the supplementary material.

In summary, we measured the ^{1}H(^{12}C,^{12}Cp) reaction for estimating the contribution of the 3_1^- state in ^{12}C to the 3α reaction rate in high-temperature environments. We obtained the radiative-decay probability of the 3_1^- state to be $\Gamma_{\rm rad}/\Gamma_{\rm tot} = 1.3^{+1.2}_{-1.1} \times 10^{-6}$ although systematic and statistical uncertainties were considerably large. Unfortunately, we cannot rule out a radiative-decay probability close to

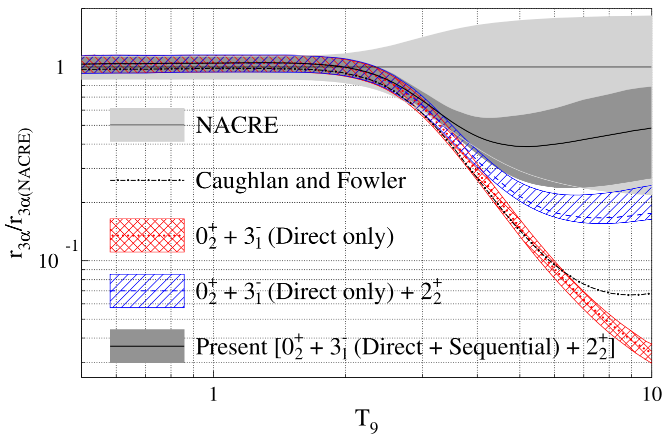

Fig. 3. Various 3α reaction rates with their uncertainties divided by that from NACRE [16] at $T_9 = 0.5$–10. The black dashed-dotted line shows the 3α rate taken from Ref. [46]. The red dotted line shows the 3α rate when the 0_2^+ state and the direct decay of the 3_1^- state are taken into account as suggested in Ref. [21]. The blue dashed line shows the same calculation with the dotted line but the contribution from the 2_2^+ state is also considered as suggested in Ref. [23]. The black thick solid line presents the new calculation including all the contributions from the 0_2^+, 3_1^-, and 2_2^+ states.

zero at the fully high confidence level, but the present result suggests that the 3_1^- state noticeably enhances the 3α reaction rate. Although it had been considered that the 3α reaction rate at $T_9 > 2$ is significantly smaller than the estimation in NACRE, the new rate comes back to that in NACRE within its uncertainty.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the RCNP cyclotron crews for the stable operation of the cyclotron facilities. The authors also thank Prof. S. Kurosawa from Tohoku University for his kind support in the development of Gion with the GAGG scintillators and Prof. Y. Funaki from Kanto Gakuin University for the fruitful discussion on the α cluster structure in ^{12}C. M. T. appreciates the support of Grant-in-Aid for JSPS Research Fellow JP14J01256. This research was supported by JSPS KAKENHI, Grants No. JP15H02091 and No. JP19H05604, and Fonds De La Recherche Scientifique - FNRS Grant Number 4.45.10.08.

Appendix A

The analytical expression of the revised triple alpha reaction rate $N_A^2\langle\sigma v\rangle^{\alpha\alpha\alpha}$ at $T_9 = 0.01$–10 in the unit of cm^6 mol^{-2} s^{-1} is approximately given in Eq. (1).

$$N_A^2\langle\sigma v\rangle^{\alpha\alpha\alpha} = N_A\langle\sigma v\rangle^{\alpha\alpha}_{\mathrm{gs}} \Big\{3.055\times10^{-10}T_9^{-2/3}\exp\left[-23.135T_9^{-1/3} - (T_9/0.4)^2\right](1 + 187.12T_9 + 4.294\times10^3T_9^2)$$
$$+4.909\times10^{-14}T_9^{-3/2}\exp(-3.35/T_9) + 9.551\times10^{-12}T_9^{-3/2}\exp(-26.84/T_9)\Big\}, \quad (1)$$

$$N_A\langle\sigma v\rangle^{\alpha\alpha}_{\mathrm{gs}} = 2.43\times10^9T_9^{-2/3}\exp\left[-13.49T_9^{-1/3} - (T_9/0.15)^2\right](1 + 74.5T_9) + 6.09\times10^5T_9^{-3/2}\exp(-1.054/T_9). \quad (2)$$

Eq. (2) for $N_A\langle\sigma v\rangle^{\alpha\alpha}_{\mathrm{gs}}$ taken from Ref. [16] has no physical meaning but it is convenient for the definition of Eq. (1).

Appendix B. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2021.136283.

References

[1] G. Shaviv, The Synthesis of the Elements: The Astrophysical Quest for Nucleosynthesis and What It Can Tell Us About the Universe, Springer, 2012, p. 341.
[2] H. Kragh, An anthropic myth: Fred Hoyle's carbon-12 resonance level, Arch. Hist. Exact Sci. 64 (2010) 721–751.
[3] E.E. Salpeter, Nuclear reactions in stars without hydrogen, Astrophys. J. 115 (1952) 326.
[4] F. Hoyle, D.N.F. Dunbar, W.A. Wenzel, W. Whaling, A state in C^{12} predicted from astrophysical evidence, Phys. Rev. 92 (1953) 1095.
[5] D.N.F. Dunbar, R.E. Pixley, W.A. Wenzel, W. Whaling, The 7.68-Mev state in ^{12}C, Phys. Rev. 92 (1953) 649–650.
[6] W. von Oertzen, Alpha-cluster condensations in nuclei and experimental approaches for their studies, in: C. Beck (Ed.), Clusters in Nuclei, in: Lecture Notes in Physics, vol. 818, Springer-Verlag Berlin Heidelberg, 2010, p. 109.
[7] T. Yamada, Y. Funaki, H. Horiuchi, G. Röpke, P. Schuck, A. Tohsaki, Nuclear alpha-particle condensates, in: C. Beck (Ed.), Clusters in Nuclei, in: Lecture Notes in Physics, vol. 848, Springer-Verlag Berlin Heidelberg, 2012, p. 229.
[8] W.A. Fowler, G.R. Caughlan, B.A. Zimmerman, Thermonuclear reaction rates, Annu. Rev. Astron. Astrophys. 5 (1967) 525–570.

[9] C. Fröhlich, P. Hauser, M. Liebendorfer, G. Martinez-Pinedo, F.-K. Thielemann, E. Bravo, N.T. Zinner, W.R. Hix, K. Langanke, A. Mezzacappa, K. Nomoto, Composition of the innermost core-collapse supernova ejecta, Astrophys. J. 637 (2006) 415–426.
[10] C. Fröhlich, G. Martinez-Pinedo, M. Liebendörfer, F.-K. Thielemann, E. Bravo, W.R. Hix, K. Langanke, N.T. Zinner, Neutrino-induced nucleosynthesis of a 64 nuclei: the νp process, Phys. Rev. Lett. 96 (2006) 142502.
[11] J. Pruet, R.D. Hoffman, S.E. Woosley, H.-T. Janka, R. Buras, Nucleosynthesis in early supernova winds. II. The role of neutrinos, Astrophys. J. 644 (2006) 1028–1039.
[12] S. Wanajo, The rp-process in neutrino-driven winds, Astrophys. J. 647 (2006) 1323–1340.
[13] S. Wanajo, H.-T. Janka, S. Kubono, Uncertainties in the νp -process: supernova dynamics versus nuclear physics, Astrophys. J. 729 (2011) 46.
[14] M. Beard, S.M. Austin, R. Cyburt, Enhancement of the triple alpha rate in a hot dense medium, Phys. Rev. Lett. 119 (2017) 112701.
[15] S. Jin, L.F. Roberts, S.M. Austin, H. Schatz, Enhanced triple-α reaction reduces proton-rich nucleosynthesis in supernovae, Nature 588 (2020) 57–60.
[16] C. Angulo, M. Arnould, M. Rayet, P. Descouvemont, D. Baye, C. Leclercq-Willain, A. Coc, S. Barhoumi, P. Aguer, C. Rolfs, R. Kunz, J. Hammer, A. Mayer, T. Paradellis, S. Kossionides, C. Chronidou, K. Spyrou, S. Degl'Innocenti, G. Fiorentini, B. Ricci, S. Zavatarelli, C. Providencia, H. Wolters, J. Soares, C. Grama, J. Rahighi, A. Shotter, M. Lamehi-Rachti, A compilation of charged-particle induced thermonuclear reaction rates, Nucl. Phys. A 656 (1999) 3–183.
[17] E. Uegaki, S. Okabe, Y. Abe, H. Tanaka, Structure of the excited states in ^{12}C. I, Prog. Theor. Phys. 57 (1977) 1262–1276.
[18] M. Kamimura, Transition densities between the 0_1^+, 2_1^+, 4_1^+, 0_2^+, 2_2^+, 1_1^- and 3_1^- states in ^{12}C derived from the three-alpha resonating-group wave functions, Nucl. Phys. A 351 (1981) 456–480.
[19] P. Descouvemont, D. Baye, Microscopic theory of the ^{8}Be$(\alpha,\gamma)^{12}$C reaction in a three-cluster model, Phys. Rev. C 36 (1987) 54–59.
[20] Y. Funaki, Hoyle band and α condensation in ^{12}C, Phys. Rev. C 92 (2015) 021302(R).
[21] H.O.U. Fynbo, C.A. Diget, U.C. Bergmann, M.J.G. Borge, J. Cederkäll, P. Dendooven, L.M. Fraile, S. Franchoo, V.N. Fedosseev, B.R. Fulton, W. Huang, J. Huikari, H.B. Jeppesen, A.S. Jokinen, P. Jones, B. Jonson, U. Köster, K. Langanke, M. Meister, T. Nilsson, G. Nyman, Y. Prezado, K. Riisager, S. Rinta-Antila, O. Tengblad, M. Turrion, Y. Wang, L. Weissman, K. Wilhelmsen, J. Äystö, T.I. Collaboration, Revised rates for the stellar triple-α process from measurement of ^{12}C nuclear resonances, Nature 433 (2005) 136–139.
[22] M. Itoh, H. Akimune, M. Fujiwara, U. Garg, N. Hashimoto, T. Kawabata, K. Kawase, S. Kishi, T. Murakami, K. Nakanishi, Y. Nakatsugawa, B.K. Nayak, S. Okumura, H. Sakaguchi, H. Takeda, S. Terashima, M. Uchida, Y. Yasuda, M. Yosoi, J. Zenihiro, Candidate for the 2^+ excited Hoyle state at E$_x$ ~10 MeV in ^{12}C, Phys. Rev. C 84 (2011) 054308.
[23] W.R. Zimmerman, M.W. Ahmed, B. Bromberger, S.C. Stave, A. Breskin, V. Dangendorf, T. Delbar, M. Gai, S.S. Henshaw, J.M. Mueller, C. Sun, K. Tittelmeier, H.R. Weller, Y.K. Wu, Unambiguous identification of the second 2^+ state in ^{12}C and the structure of the Hoyle state, Phys. Rev. Lett. 110 (2013) 152502.
[24] H. Crannell, T.A. Griffy, L.R. Suelzle, M.R. Yearian, A determination of the transition widths of some excited states in ^{12}C, Nucl. Phys. A 90 (1967) 152–158.
[25] J. Kelley, J. Purcell, C. Sheu, Energy levels of light nuclei A = 12, Nucl. Phys. A 968 (2017) 71–253.
[26] E.K. Warburton, Gamma transitions in self-conjugate nuclei, Phys. Rev. Lett. 1 (1958) 68.
[27] T. Suzuki, R. Fujimoto, T. Otsuka, Gamow-Teller transitions and magnetic properties of nuclei and shell evolution, Phys. Rev. C 67 (2003) 44302.
[28] P.M. Endt, Strengths of gamma-ray transitions in A = 5-44 nuclei, IV, At. Data Nucl. Data Tables 55 (1993) 171–197.
[29] D. Chamberlin, D. Bodansky, W. Jacobs, D. Oberg, Upper limit on the radiative width of the 9.64-MeV state of ^{12}C, Phys. Rev. C 10 (1974) 909–911.
[30] M. Fujiwara, H. Akimune, I. Daito, H. Fujimura, Y. Fujita, K. Hatanaka, H. Ikegami, I. Katayama, K. Nagayama, N. Matsuoka, S. Morinobu, T. Noro, M. Yoshimura, H. Sakaguchi, Y. Sakemi, A. Tamii, M. Yosoi, Magnetic spectrometer Grand Raiden, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 422 (1999) 484–488.
[31] Y. Matsuda, M. Tsumura, H. Sakaguchi, S. Terashima, J. Zenihiro, T. Kawabata, H. Otsu, D. Beaumel, Z. Tian, Y. Maeda, S. Gotanda, S. Kawakami, N. Aoi, T. Yamamoto, Solid hydrogen target for missing mass spectroscopy in inverse kinematics, J. Radioanal. Nucl. Chem. 305 (2015) 897–901.
[32] Y. Matsuda, H. Sakaguchi, J. Zenihiro, S. Ishimoto, S. Suzuki, H. Otsu, T. Ohnishi, H. Takeda, K. Ozeki, K. Tanaka, S. Terashima, Y. Maeda, T. Kobayashi, A. Koreeda, K. Kamei, Large, thin solid hydrogen target using para-H_2, Nucl. Instrum. Methods Phys. Res., Sect. A 643 (2011) 6–10.
[33] K. Kamada, Y. Shoji, V.V. Kochurikhin, S. Okumura, S. Yamamoto, A. Nagura, J.Y. Yeom, S. Kurosawa, Y. Yokota, Y. Ohashi, M. Nikl, A. Yoshikawa, Growth and scintillation properties of 3in. diameter Ce doped $Gd_3Ga_3Al_2O_{12}$ scintillation single crystal, J. Cryst. Growth 452 (2016) 81–84.
[34] M.O. Systems, Vikuiti™ Enhanced Specular Reflector (ESR), https://multimedia.3m.com/mws/media/7217990/vikuititm-enhanced-specular-reflector-esr.pdf, 2010.
[35] M.C.A. Campos, P. von Neumann-Cosel, F. Neumeyer, A. Richter, G. Schrieder, E. Spamer, B.A. Brown, R.J. Peterson, Isospin mixing in the electroexcitation of the $e_x =$ 10.84 mev, j^π; $t = 1^-$; 0 state in ^{12}c; at low momentum transfers, Phys. Lett. B 349 (1995) 433–437.
[36] A. Erell, J. Alster, J. Lichtenstadt, M.A. Moinester, J.D. Bowman, M.D. Cooper, F. Irom, H.S. Matis, E. Piasetzky, U. Sennhauser, Measurements on isovector giant resonances in pion charge exchange, Phys. Rev. C 34 (1986) 1822–1844.
[37] T. Kibédi, B. Alshahrani, A. Stuchbery, A. Larsen, A. Görgen, S. Siem, M. Guttormsen, F. Giacoppo, A. Morales, E. Sahin, G. Tveten, F.B. Garrote, L.C. Campo, T. Eriksen, M. Klintefjord, S. Maharramova, H.-T. Nyhus, T. Tornyi, T. Renstrom, W. Paulsen, Radiative width of the Hoyle state from gamma-ray spectroscopy, Phys. Rev. Lett. 125 (2020) 182701.
[38] D.E. Alburger, Gamma-ray decay of the 7.66-MeV level of C^{12}, Phys. Rev. 124 (1961) 193–198.
[39] I. Hall, N.W. Tanner, The radiative decay of the 7.66 MeV level of C^{12}, Nucl. Phys. 53 (1964) 673–684.
[40] D. Chamberlin, D. Bodansky, W. Jacobs, D. Oberg, Electromagnetic decay of the 7.65-MeV state of ^{12}C, Phys. Rev. C 9 (1974) 69–75.
[41] C.N. Davids, R.C. Pardo, A.W. Obst, Radiative deexcitation of the 7.655-MeV state of ^{12}C, Phys. Rev. C 11 (1975) 2063–2068.
[42] H.B. Mak, H.C. Evans, G.T. Ewan, A.B. McDonald, T.K. Alexander, Radiative decay of the second excited state of ^{12}C, Phys. Rev. C 12 (1975) 1158–1166.
[43] R.G. Markham, S.M. Austin, M.A.M. Shahabuddin, A measurement of $\gamma_{\rm rad}/\gamma$ for the 7.654 MeV state of ^{12}C and the rate of the stellar 3α reaction, Nucl. Phys. A 270 (1976) 489–500.
[44] A.W. Obst, W.J. Braithwaite, Measurement of the radiative branching ratio for the 7.65-MeV state in ^{12}C using the cascade gamma decays, Phys. Rev. C 13 (1976) 2033–2043.
[45] P.A. Seeger, R.W. Kavanagh, Electromagnetic decay of the second excited state of C^{12}, Nucl. Phys. 46 (1963) 577–597.
[46] G.R. Caughlan, W.A. Fowler, Thermonuclear reaction rates V, At. Data Nucl. Data Tables 40 (1988) 283–334.
[47] D.J. Marín-Lámbarri, R. Bijker, M. Freer, M. Gai, T. Kokalova, D.J. Parker, C. Wheldon, Evidence for triangular $\mathcal{D}_{3h}$ symmetry in ^{12}C, Phys. Rev. Lett. 113 (2014) 012502.