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New experimental results for the triple-alpha reaction

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The triple-alpha reaction is one of the key reactions in nuclear astrophysics. The reaction rate is primarily needed at temperatures of some 10^8K typical for Helium burning in red giant stars, but the rate at very low and very high temperatures is also needed for various specialized applications. Here we discuss new experimental results relevant for determining the rate of the 3α reaction. First, we present a new improved upper limit for direct α-decay of the Hoyle state, which effectively removes this issue from the error budget of the reaction rate at Helium burning temperatures. We use the reaction ^{11}B(^{3}He,d)3α to populate the Hoyle state, and measure its decay in complete kinematics. Second, we present a new method for studying broad resonances in ^{12}C. We populate a resonance above the region of interest and select γ-decays of this resonance to lower lying resonances. The γ-decay is identified by measuring the final state in complete kinematics, which makes it possible to identify γ-decay to broad resonances, which is otherwise very difficult due to either background from overlapping states with different spin-parity, or due to the response of conventional gamma-detectors. By choosing the first resonance appropriately one can enhance the selectivity for each state of interest by using the selection rules of γ-decay. Our first case using this method is a search for the first 2^+ resonance in ^{12}C, which has been the object of countless studies throughout the years. We will present clear evidence for a 2^+ resonance near 11-12 MeV and tentative evidence also for a resonance at 9-10 MeV. These resonances will enhance the 3α-reaction rate at elevated temperatures.

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1. Introduction

In the present paper, the 3α-reaction is discussed in three temperature regimes starting with medium temperatures relevant for quiescent burning in red giant stars in Section 2, very low temperatures in section 3 and very high temperatures in section 4.

2. 3α-reaction at Helium burning temperatures

For quiescent Helium burning in red-giant stars the $\alpha(\alpha\alpha,\gamma)^{12}$C reaction is dominated by the 7.65 MeV 0^+ resonance in ^{12}C, which is populated when two α-particles first form the short lived ground state resonance in ^{8}Be, which subsequently captures a third α-particle. Although this reaction cannot be directly measured it is believed to be relatively well determined in the temperature regime $\simeq 10^8$K because the reaction rate is determined by the properties of the 7.65 MeV resonance, namely, its energy, width and decay properties, see [1] for recent discussions.

Until recently the 3α reaction rate was believed to have an uncertainty of $\simeq$12% dominated by the 0^+ to 0^+ pair-decay width of the 7.65 MeV resonance. However, in a recent experiment at Catania, Raduta *et al.* used a ^{12}C beam on a Calcium target to measure the α-decay of this resonance [2], and extracted a 17(5)% direct decay branch of the 7.65 MeV state bypassing the intermediate ^{8}Be. This branch had previously been assumed to be negligible, and its existence would infer a corresponding reduction in the 3α-rate larger than the currently estimated error. Sequential decay means decay via the ground state of ^{8}Be (lifetime $\simeq 10^{-16}$s). A recent attempt at calculating the direct decay branch in a cluster model calculation gave a small branch of 4 % [3, 4], much smaller than the measured value of Raduta *et al.*

In 2012, the result of Raduta *et al.* has been cast into doubt by two new measurements, which have placed an upper limit on the direct decay at the level of 0.1% [5, 6]. In the most precise of these works [5], the 7.65 MeV resonance was populated in the ^{11}B(^{3}He,d)^{12}C* reaction, and the three α-particles from the decay of the resonance detected in complete kinematics. By using the method of kinematic fitting the final state could be accurately characterized to be completely dominated by sequential decays via the ground state of ^{8}Be. Manfredi *et al.* [6] used multi-nucleon transfer reactions from a ^{10}C beam on either Be or C targets to deduce a slightly less stringent upper limit for non-sequential decay.

With the sequential decay of the 7.65 MeV resonance firmly established by two independent measurements, the dominating contribution to the error on the reaction rate calculation is again the pair-decay branching ratio. There are several groups pursuing a more accurate determination of this quantity, see e.g. [7, 8]. See also the contribution of T. Kibedi to these proceedings [9]. In this context, it it also relevant to mention that there are two measurements of the E0 pair decay width by Crannell *et al.* [10] and by Chernykh *et al.* [11] with similar precision, which however deviate by five standard deviations. This quantity is measured using inelastic electron scattering, and the most recent of these works [11] combined new data at low momentum transfer with the existing world data to extract what seems like a more reliable value.

3. 3α-reaction at low temperatures

There has recently been considerable activity related to the calculation of the reaction rate of the triple-α process for temperatures well below the 0.1 GK range typical for Helium burning in the the cores of red giant stars. This was initiated by a calculation by Ogata *et al.* using a continuum discretized coupled channels (CDCC) approach [12]. This calculation predicted a 3α rate at low temperatures, which was larger than standard rates found in tabulations such as NACRE [13] by 20 orders of magnitudes at 0.02 GK. This is the dedicated subject of the contribution of Brown *et al.* to these contributions [14].

The response to this result has been in two directions. First, astrophysical modellers have implemented the new rate in model calculations of stellar evolution and found strong disagreements with a range of observations: The new rate causes a surpression of the Helium flash for low mass stars on the asymptotic giant branch phase [15, 16], it changes the ignition conditions for binary systems with a white dwarf accreting Helium, which affects type Ia supernovae [17], and the new rate reduces the burst luminosities of type-I x-ray bursts at least a factor 10 below observations [18, 19]. Second, several other groups have performed new calculations of the low temperature reaction rate: Garrido *et al.* [20] start from calculations of the photodissociation cross-sections of ^{12}C and deduce from it that while the 3α rate can be several orders of magnitude larger than the NACRE rate, it is unlikely to be as high as calculated by Ogata *et al.* Nguyen *et al.* [21, 22] use a combination of an R-matrix expansion and a hyperspherical harmonics basis and find a 3α rate larger than Garrido *et al.*, but still much smaler than Ogata *et al.* The results of both Garrido *et al.* and Nguyen *et al.* are in perfect agreement with observations.

A new computational approach has recently been put forward as an alternative method for calculating the 3α-rate [23]. In this method a wave-function is calculated along an imaginary time axis, which is related to the temperature. It is possible that this approach will be able to shed light on which aspect of the CDCC calculation causes the rate to become so large.

Tamii *et al.* [24] have suggested an interesting method for how to test the different computational methods for calculating the low-temperature 3α-rate by direct empirical tests to complement the astrophysical observational tests. The idea consists in measuring the intensity of α-decays of the part of the ^{12}C continuum between the 3α-threshold and the 7.65 MeV resonance. It will be interesting to follow if this approach can be used to gain further constraints in the future.

4. 3α-reaction at high temperatures

There have been several sensitivity studies of the effect of the uncertainty of the 3α-reaction rate at high temperatures [25, 26, 27, 28, 29]. As an example, there has been focus on the production of ^{44}Ti in core collapse supernovae. γ-lines associated with ^{44}Ti decay have been detected by the INTEGRAL satellite from the supernova remnant Cassiopeia A [30], and explaining the mass fraction of ^{44}Ti produced could be a sensitive diagnostic of such events, however, this requires that the relevant production and destruction rates are sufficiently well known. Here, it turns out the 3α-process is among the most sensitive.

The uncertainty of the 3α reaction rate for temperatures above 10^9 K is related to the position of resonances inside the Gamow window at those elevated temperatures, in particular an elusive 2^+ resonance. In 1956 Haruhiko Morinaga conjectured that the 7.65MeV 0^+ state should be deformed and therefore sustain a band of rotational excited states with angular momentum J=2, 4, etc. [31]. Similar predictions have come from numerous later calculations all the way to the present, see

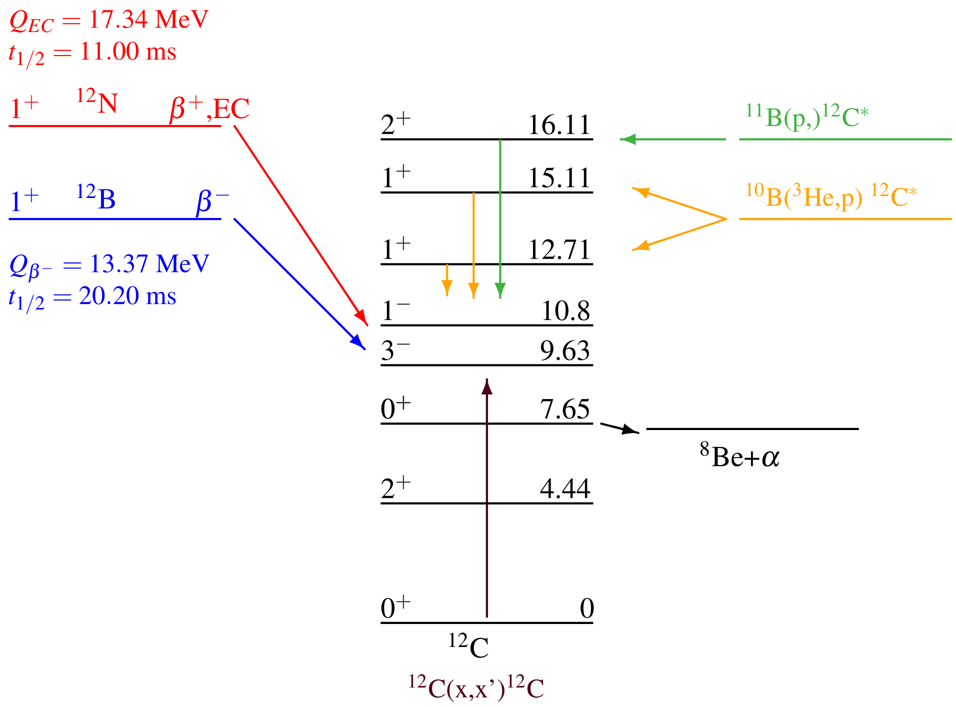

Figure 1: Level scheme of ^{12}C illustrating the methods of populating the states, which are discussed in the text.

e.g. the recent result from a nuclear lattice approach [32]. The influence of the 2^+ resonance on the 3α-rate can explored e.g. in the NACRE compilation [13], where a specific theoretically determined resonance is included, and also in [33], who explores the high temperature rate for a range of parameters of the 2^+ resonance.

Since the 1950s there have been many unsuccessful attempts to experimentally locate this 2^+ resonance. In the past three years three papers have come out which point to a 2^+ resonance close to where it was originally predicted at 9-10 MeV [34, 35, 36], see also [39]. The data from [34] and [35] have recently been jointly analysed to gain further support for the identification of the 2^+ resonance [37]. There is also tentative evidence for the next rotational state with J=4 [38]. But, as will be discussed below, other experiments find no evidence for these states, and hence the situation remains somewhat unclear.

Morinaga's resonance is expected in a region of overlapping 0^+, 1^-, 3^- resonances. The problem is that in most experiments trying to study this problem, these other resonances are dominating the experimental spectra. The three recent papers mentioned above solve this problem by letting a high-energy beam of α-particles or protons scatter on a target of ^{12}C. They then determine which resonance is populated by very accurate measurement of the energy and angle of the scattered particle: for the smallest angles J=0 dominates, J=2 for somewhat larger angles, and so on. In this way they argue for a small contribution of a 2^+ state underneath dominating contributions from the 0^+, 1^-, 3^- states.

Another way to achieve selectivity is to use quantum mechanical selection rules to restrict the transitions between the initial and final states. Using radioactive beams techniques, a series of experiments aimed at pursuing this idea have populated the resonances in ^{12}C in the β-decays of the two isotopes ^{12}N and ^{12}B, see e.g. [40, 41]. In these decays only 0^+, 1^+, and 2^+ states can be populated in ^{12}C due to the selection rules of β-decay (allowed transitions). The approach is challenging because in order to determine the spectrum of (unbound) final states populated in the decay one must measure and add the energies of the three emitted α-particles, which requires a very efficient detection system, and in addition, the half-lives of ^{12}N and ^{12}B are as short as 11 ms and 20 ms respectively, and the branching ratios to the interesting unbound states are as low as 10^{-4} to 10^{-2}.

The advantage of this approach is clearly in removing the unwanted 3^- and 1^- states. The spectra measured from these β-decays can be understood as coming from several broad and interfering 0^+ and 2^+ resonances [42]. However, the detailed analysis of the data cannot easily be reconciled with the 2^+ resonance found by the scattering experiments [34, 35, 36]. Instead R-matrix fits to the β-decay data favour a 2^+ resonance close to 11 MeV in ^{12}C. However, a recent measurement of the ^{11}B(^{3}He,d)^{12}C reaction found no evidence for a 11 MeV resonance in ^{12}C [43].

Figure 4 shows the methods aimed at studying the resonances in ^{12}C discussed so far: scattering off the ground state, and β-decay of ^{12}N and ^{12}B. Also illustrated is a new approach which will be briefly discuss in the following. The idea is to populate a selected higher lying resonance, and then observe its γ-decay. The initial state is chosen such that the spin-parity of the state and the selection rules of γ-decay selectively populate the state of interest. Our particular interest is in elucidating the relative contributions of broad 0^+ and 2^+ resonances above the 7.65 MeV resonance. Hence, if we populate 2^+ or 0^+ states at higher energy then their γ-decay will favour population of lower lying 2^+ resonances over 0^+ resonances. We do not identify these transitions by measuring the emitted γ-ray because the resonances we are looking for are very broad with widths of the order of an MeV. Instead we proceed as in the β-decay studies and identify the populated resonances by measuring their α-decay.

Our first measurement using this method focussed on the γ-decay of the 1^+ states at 12.7 MeV and 15.1 MeV populated in the reaction ^{10}B(^{3}He,p)^{12}C [46], see Figure 4. The latter is in an isospin triplet with the ground states of ^{12}N and ^{12}B, and because the M1 operator is similar to the Gamow-Teller operator this decay should give a pattern similar to what has been observed in the β-decay experiments. This expectation turns out to be fulfilled [46], and in a sense this case therefore also serves as a proof of principle that this approach for studying broad resonances is feasible.

The next case we have turned to is the 2^+ state at 16.11 MeV in ^{12}C which we populate in the reaction ^{11}B(p,^{12}C*). M1 decays should populate 1^+, 2^+ and 3^+ states, and therefore the 0^+ contribution should be suppressed. Unfortunately there is also an E1 contribution, which populates 1^-, 2^- and 3^- and therefore the problem of the background from the 3^- states, as experienced by the scattering experiments [34, 35, 36], is present. Preliminary results from this approach are shown in Figure 2. The direct α-decay of the 16.11 MeV state is seen from the intense peak at the high energy end of the spectrum. In of the order one out of 10^5 events a γ-ray is emitted to lower lying unbound states, which is seen as events with less energy than the direct α-decay events. Population in this way of the known 3^- (9.63MeV), 1^- (10.8MeV) and 1^+ (12.7MeV) states is directly evident. Apart from the known states we also see evidence for broad natural parity states indicated by the circles in Figure 2. Due to the selection rules of γ-decay the most likely

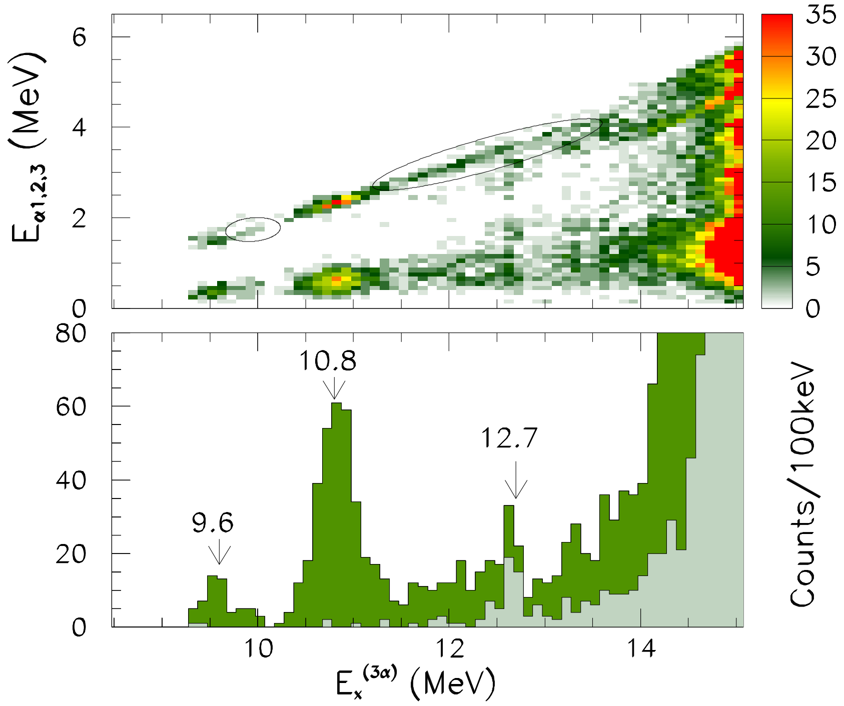

Figure 2: In the lower part of the plot is shown the sum energy of three α-particles from the reaction ^{11}B(p,3α) measured at the 2^+ resonance at 16.11 MeV in ^{12}C. One out of 10^5 of the decays of this state proceed by γ-decay to lower lying unbound states in ^{12}C, which can be identified by the 3α sum-energy being reduced by the energy of the emitted γ-ray. In the upper part of the plot is shown the distribution of the individual energies for each 3α event. The diagonal running from the lower left corner to the upper right corner signifies sequential 3α decays via the ground state of ^{8}Be, which can only originate from natural parity states. There is evidence for population of the known 3^- (9.63MeV), 1^- (10.8MeV) and 1^+ (12.7MeV) states as well as very short lived (broad) natural parity states marked by circles.

assignment for these states is 2^+.

Another approach based on selection rules is to use the reaction ^{12}C(γ,3α). This approach is pursued by Gai *et al.* at the HIgS facility [44, 45]. The first results indicate a 2^+ resonance close to that found by the scattering experiments. This approach has the great benefit of also adding information about the radiative width of the 2^+ resonance, which will be needed for the evaluation of the effect of this resonance on the 3α-reaction rate.

5. Questions

A question was asked by Lothar Buchmann as to how one could determine the radiative width of the 2^+ resonance, which may influence and dominate the reaction rate at high temperatures. One option would be the approach mentioned above using the reaction ^{12}C(γ,3α) [44, 45]. This will provide the width for transitions to the ground state. For possible small contributions via the bound 4.44 MeV 2^+ state one would have to populate the 2^+ resonance in some suitable reaction, and measure the 4.44 MeV γ-ray in coincidence. There could also be transitions to unbound states, must importantly to the Hoyle state, which would be important to measure in order to explore the rotational nature of these two states. For this purpose the method discussed above for indirectly detecting γ-transitions using complete kinematics reactions would be useful.

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