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Limits for the 3α branching ratio of the decay of the 7.65 MeV, 0^+ state in ^{12}C

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A study of the ^{12}C(^{12}C,3α)^{12}C reaction has been performed in order to determine the magnitude of the process by which the 7.65 MeV, 0_2^+ state in ^{12}C breaks up directly into three alpha particles, in contrast to the sequential decay through ^{8}Be. The strength of this decay channel has important implications for the production rate of ^{12}C in stellar nucleosynthesis. The present measurement indicates that the contribution of this decay process to the alpha width, Γ_α, of this state is less than 4%.

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One of the most important questions in the first studies of stellar nucleosynthesis concerned the production mechanism of ^{12}C to the abundance which is presently observed, since the formation of this element through hydrogen burning is blocked by the absence of stable elements of the masses $A = 5$ and 8. A solution to this problem was proposed by Salpeter and Öpik [1,2] who suggested that ^{12}C was formed through a two-stage process $\alpha(\alpha,{}^8\mathrm{Be})$, followed by the reaction $^8\mathrm{Be}(\alpha,\gamma)^{12}\mathrm{C}$. Such a two-stage mechanism is required since the direct formation ($\alpha+\alpha+\alpha \rightarrow {}^{12}\mathrm{C}$) is inhibited by the negligible probability that, at stellar densities and temperatures, three alpha particles simultaneously collide in the stellar medium. Although ^{8}Be is unstable against decay into two α particles, its lifetime of $\sim 10^{-16}$ s results in the formation of an equilibrium concentration of ^{8}Be nuclei, in which there exists one ground state ^{8}Be nucleus for every 10^9 ^{4}He nuclei. It is from this very small concentration of ^{8}Be nuclei that the synthesis of ^{12}C proceeds. This proposed reaction sequence did provide an increase in the production of ^{12}C; however, this was still not sufficient to account for the observed abundance. Hoyle [3] speculated that the reaction rate of the second stage of the ^{12}C formation may be enhanced if the reaction proceeded via an s-wave resonance in ^{12}C close to the formation threshold. This prediction was subsequently verified experimentally, when a resonance which possessed the required properties (E_x = 7.65 MeV and $J^\pi=0^+$) was discovered in studies of the $^{14}\mathrm{N}(d,\alpha)^{12}\mathrm{C}$ [3] reaction and the β decay of ^{12}B [4].

In the instance of the ^{12}C formation proceedings via such a resonance, the reaction rate can then be related to the properties of the resonance and the formation medium [5]

$$R \propto T^{-3/2}\frac{\Gamma_\alpha\Gamma_{\mathrm{rad}}}{\Gamma}\exp\left(\frac{-E_R}{kT}\right). \quad (1)$$

Here Γ is the total width, Γ_α is the α-particle width, and Γ_{rad} is the combined electromagnetic widths for the decay of the excited state to the ^{12}C ground state via sequential γ emission (Γ_γ) and internal pair conversion ($\Gamma_{e^+e^-}$). E_R is the energy of the resonance above the α decay threshold, and T is temperature. Significant effort has been devoted to the measurement of the excitation energy and the partial widths of the excited 0^+ state in order to precisely determine the production rate of ^{12}C. The reaction Q value for the process $^{12}\mathrm{C}(0^+)\rightarrow \alpha+{}^8\mathrm{Be}$, has now been determined (379.38±0.2 keV [6]) to the extent that its contribution to the uncertainty in the reaction rate is of the order of 1%. From a compilation of several experimental sources [7] $\Gamma_{\mathrm{rad}}/\Gamma$ has been determined to be $(4.12\pm0.11)\times10^{-4}$, indicating that $\Gamma_\alpha \simeq \Gamma$. The ratios Γ_γ/Γ and $\Gamma_{e^+e^-}/\Gamma$ have also been measured, and were found to be $(4.02\pm0.28)\times10^{-4}$ [8] and $(6.8\pm0.7)\times10^{-6}$ [9–11], respectively. Inelastic scattering measurements [12–15] have provided an absolute determination for $\Gamma_{e^+e^-}$ of 60.5±3.9 μeV, implying that $\Gamma_\gamma = 3.58\pm0.5$ meV and $\Gamma_\alpha = 8.90\pm1.08$ eV. Since the dominant contribution to the total width of the state is from Γ_α, the reaction rate is almost complete determined by Γ_{rad} [see Eq. (1)] which is known to an accuracy of 13%.

In the above description of the production rate of ^{12}C there is the implicit assumption that the only contribution to the width Γ_α is from the $^8\mathrm{Be}_{\mathrm{g.s.}}+\alpha$ reaction ($\Gamma_{\alpha\text{-}^8\mathrm{Be}}$). However, in principle, there exists a contribution from the direct 3α channel, where the ^{12}C nucleus spontaneously decays into three α particles, bypassing the ^{8}Be+α intermediate stage. Although such a process has no effect on the reaction rate when considering the decay of the 0_2^+ state, there are implications for the formation rate, $\Gamma_\alpha\Gamma_{\mathrm{rad}}$. Since the direct fusion of three α particles is effectively prohibited, a significant contribution to Γ_α from $\Gamma_{3\alpha}$ would reduce the reaction rate accordingly, since

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$$\frac{\Gamma_\alpha \Gamma_{\mathrm{rad}}}{\Gamma} = \frac{\Gamma_{\alpha\text{-}^8\mathrm{Be}}\Gamma_{\mathrm{rad}}}{\Gamma_{3\alpha}+\Gamma_{\alpha\text{-}^8\mathrm{Be}}+\Gamma_{\mathrm{rad}}}. \quad (2)$$

This result would modify not only the theoretical value of the abundance of ^{12}C, but directly affects the formation rates of the heavier elements whose production proceeds from ^{12}C. Consequently, it is important to determine the magnitude of $\Gamma_{3\alpha}$.

A calculation of the relative phase spaces for the spontaneous 3α and α+^{8}Be decay process would suggest that the 3α decay probability is a factor of 5×10^{-4} smaller than the sequential decay process. However, the ^{12}C(7.65 MeV, 0_2^+) state is believed to possess unusual propeties, for example, cluster models suggest that this state is formed from a linear chain of three α particles [16]. Further, electron inelastic scattering data also indicates that this state has an abnormally large charge radius [17]. These unusual properties may alter the decay modes as to enhance, in some manner, the 3α decay probability.

In this paper we present the first direct experimental determination of the magnitude of the contribution of $\Gamma_{3\alpha}$ to Γ_α.

A study of the ^{12}C(^{12}C,3α)^{12}C reaction was performed at the University of Pennsylvania tandem Van de Graaff accelerator. The ^{12}C beam was inelastically scattered from a 50 μg cm^{-2} ^{12}C target, at a beam energy of 58 MeV. The recoiling ^{12}C nucleus was detected in a E-ΔE telescope [19], covering laboratory scattering angles from 32.5° to 47.5°. This telescope consisted of a silicon stopping detector placed within a gas ionization chamber, and was used to positively identify the ^{12}C ions. The breakup of the ^{12}C(7.65 MeV, 0_2^+) state into three α particles was recorded using a 5×5 cm^2, 16×16 double sided silicon strip detector (DSSD) [19]. This detector had 16, 3.125 mm strips oriented horizontally on the front, and 16 similar strips running vertically on the back face. By comparing the energies from the strips on the front and back of the detector, it was possible to assign each of the three α particles to a pixel with dimensions 3.125×3.125 mm^2. The strip detector covered an angular range of 30° to 51°, and had an angular resolution, corrresponding to the pixel dimensions of $\sim 1.3°$.

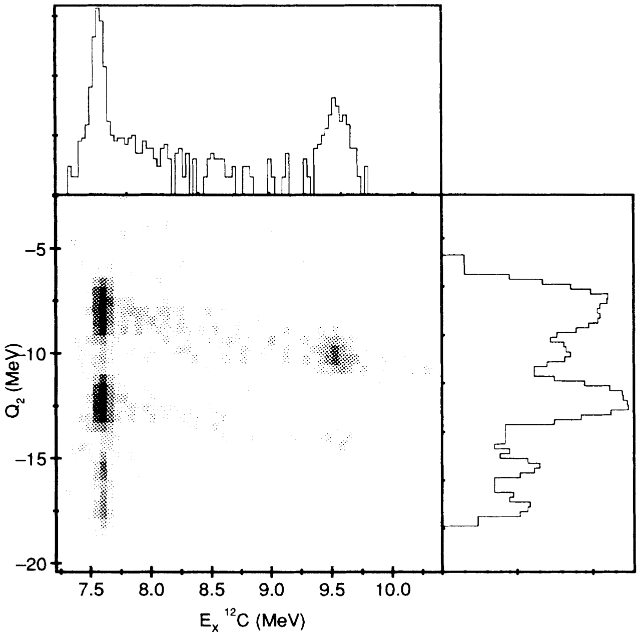

FIG. 1. The ^{12}C excitation energy plotted versus the two-body reaction Q value, both determined from the three detected α particles.

The reconstructed kinematics of the three α particles were used to infer the excitation energy of the parent nucleus and the excitation energy of the recoiling ^{12}C nucleus. This latter information was also determined from the kinematics of the ^{12}C ion detected in the E-ΔE telescope. These reaction parameters provided clean separation of all the reaction channels of interest (Fig. 1). Figure 1 shows that in this measurement, the breakup of the ^{12}C nucleus from the 0_2^+ (7.65 MeV) and 3^- (9.62 MeV) states were observed predominantly in coincidence with ^{12}C in either the ground or first excited state. The intensities of the various peaks in this spectrum are determined mainly by the experimental acceptance, and are not representative of the reaction yields. From the measurement of the energies and angles of the three alpha particles their relative energies in the center of mass frame of ^{12}C may be determined (Fig. 2). The relative energies are a reflection of the decay process by which each particle was produced; for example, if two alpha particles result from the decay of ^{8}Be then they will have a relative energy of 92 keV. The spectra in Fig. 2 correspond to the data falling under the ^{12}C(0_2^+)-^{12}C and ^{12}C(0_2^+)-^{12}C(2^+) peaks in Fig. 1. In Fig. 2 the relative energy index 1 refers to the most energetic α particle, 2 the second most energetic, and 3 the least. The relative energies of the three alpha particles are shown plotted against one another in Fig. 2(d). In the coordinate system employed in Fig. 2(d), if two of the three particles have a relative energy of 92 keV, the ^{8}Be breakup energy, then the data are forced to lie on a triangular locus. The intensity pattern around the locus is governed by the reaction kinematics and the experimental acceptance. The perpendicular distance from the side to the center of the triangle is determined by the amount of energy available to share between the particles, and is given by the relationship

$$E_{\mathrm{rel}}(12) + E_{\mathrm{rel}}(13) + E_{\mathrm{rel}}(23) = \frac{3(E_x - E_{\mathrm{thresh}})}{2} \quad (3)$$

which may be deduced from the laws of momentum conservation and the equation for the relative energies of any two of the three α particles [e.g., $E_{\mathrm{rel}}(12) = \mu(V_1 - V_2)^2/2$]. If none of the relative energies are constrained, i.e., the decay occurs directly, then it can be shown that the data are distributed over the area of a circle with radius $3(E_x - E_{\mathrm{thresh}})/4$. Through an integration of the yield distributed over the circle, the direct 3α contribution may be determined. However, there are detector effects which must be taken into account when evaluating this yield. The assignment of the angles to the three α particles is based upon the ability of the DSSD to

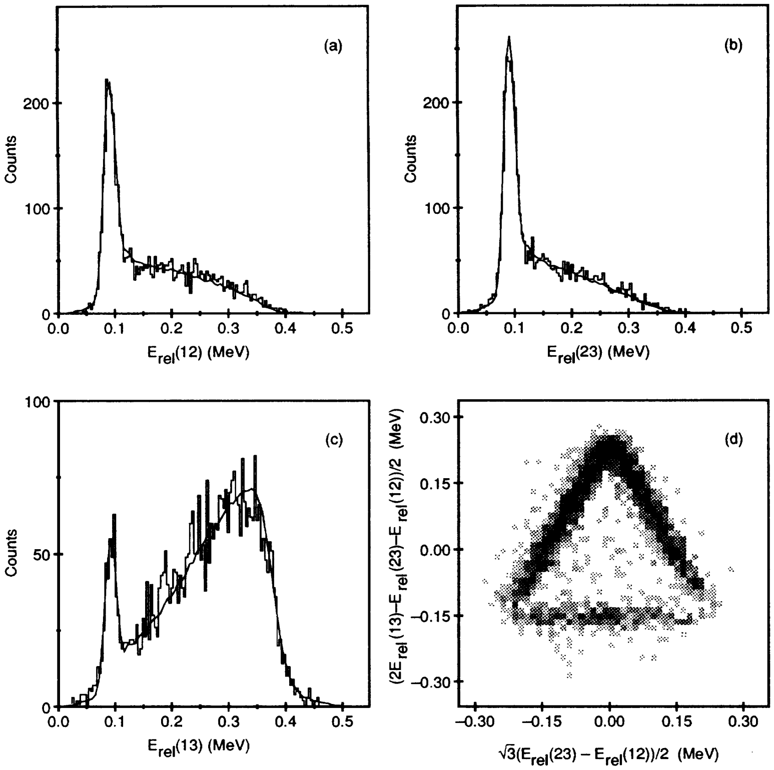

FIG. 2. Relative energy spectra for the three α particles (see text for labeling scheme). The histograms in (a), (b), and (c) are the data and the solid lines are the results of the Monte Carlo calculations. The three relative energies are plotted against each other in (d) showing the triangular locus corresponding to two of the α particles having a relative energy of 92 keV.

correlate the front and back energies [19]. If the energies of two or more of the particles cannot be resolved, due to the finite energy resolution of the detector, then there is a probability of misassigning the detector coordinates and thus inferring incorrect angles for the alpha particles. This results in the spreading of a fraction of the α-^{8}Be yield beyond the triangular locus. In order to study the effects of the detectors energy and angular resolutions on the observed distributions, a Monte Carlo simulation of the reaction and detection processes has been performed. The simulation includes the full experimental energy and angular resolutions, and the geometry of the strip detector including the rejection of events in which particles enter the same strip and also the possibility of switching angles of the particles. The energy response of the two faces of the detector, formed from the combined front and back strips, was deduced by producing a consistent description with the simulations of the three relative energy spectra (Fig. 2) and the reconstructed ^{12}C excitation energy spectrum. Through this empirical approach it is possible to fold into the calculations effects such as gain drifts, dead layers, and energy tails with the intrinsic detector resolution of 40 to 60 keV, without requiring any detailed knowledge of the detector response.

The background in these measurements is small owing to the selectvitiy of the detection system, however contributions from the reaction ^{12}C(^{12}C,^{16}O$\rightarrow \alpha+^{12}$C)^{8}Be, in which the three α particles do not correspond to an excited state in ^{12}C, appear as the locus passing between the 0_2^+ and 3^- peaks. The contribution from random ^{12}C, 3α uncorrelated coincidences is significantly smaller. An examination of the spectrum in Fig. 1 in the vicinity of the ^{12}C(0_2^+)-^{12}C and ^{12}C(0_2^+)-^{12}C(2^+) peaks indicate that the background contribution to the peaks in this spectrum is approximately 3%. This contributes predominantly to the sequential breakup yield since the contaminating reaction results in the produc-

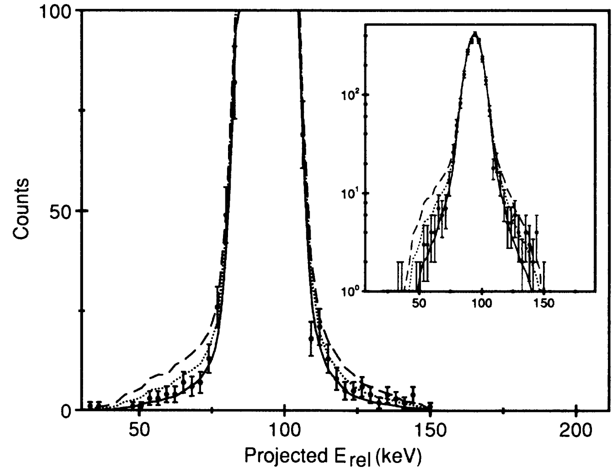

FIG. 3. The projected relative energy spectrum for the three α particles, labeled in terms of the ^{8}Be relative energy (see text for details). The full spectrum is shown in the inset and a blow up of the tails of the distribution is plotted in the main figure. The solid line is the result of the Monte Carlo calculations requiring no direct breakup contribution, the dotted and dashed lines are the same calculations but including 5% and 10% 3α contributions, respectively.

tion of a ^{8}Be nucleus.

In order to quantitatively compare the simulation with the experimental data, Fig. 2(d) has been converted into a one-dimensional figure. This was achieved by peforming three sequential reflections of the data about the three separate symmetry axes of the triangle such that the three sides of the ^{8}Be triangle are reduced to a single side of half the original length, which is then projected along the ^{8}Be locus into a one-dimensional spectrum. This transformation produces a peak corresponding to any two of the three particles having a relative energy of 92 keV, the direct 3α decay appears as an extended tail on the distribution (Fig. 3). The solid curve in Fig. 3 is the product of the Monte Carlo simulations. These calculations appear to reproduce many of the details of the projected relative energy distribution and the individual relative energy spectra (Fig. 2). As was discussed earlier, it is the magnitudes of the shoulders on the sides of the peak which are sensitive to the misassignments of the angles to the particles, particularly for low values of the projected relative energy, which corresponds to a larger portion of the direct breakup circle. These shoulders are well reproduced without requiring any 3α contribution to the decay process. The nature of the energy distributions for a 5% (dotted line) and 10% (dashed line) 3α decay component are also shown in Fig. 3; neither of these profiles reproduce the characteristics of the data.

Since the experimental distributions can be reproduced without requiring any contribution from a direct reaction process, this would indicate the $\Gamma_{3\alpha}$ is less than 1% of Γ_α. However, due to the statistical uncertainties of the data and also the degrees of freedom allowed in the simulations in the reproduction of the energy response of the detector, larger contributions cannot be ruled out. The simulation that excludes the direct decay process reproduces the data with $\chi^2 = 1.0$ per degree of freedom, which is at the 50% confidence level in the χ^2 distribution. With the inclusion of a 4% direct 3α decay contribution, the χ^2 is increased to 1.94 per degree of freedom. This lies beyond the 99.5% confidence level in the χ^2 distribution, indicating with high probability that a $\Gamma_{3\alpha}$ of this magnitude can be excluded.

A double sided strip detector has been used to measure the decay of the ^{12}C 7.65 MeV, 0_2^+ state into three α particles. The possibility of measuring the energies and angles of all the decay products with this detection system has permitted the study of the relative strengths of the two decay processes, $^{12}\mathrm{C}(0_2^+) \rightarrow 3\alpha$ and $^{12}\mathrm{C}(0_2^+) \rightarrow {}^8\mathrm{Be} + \alpha \rightarrow 3\alpha$. This measurement provides upper limits of 4% for the contribution of the direct process to Γ_α, which implies that the magnitude of Γ_{rad} is now the largest single uncertainty in the determination of the production rate of ^{12}C in stellar nucleosynthesis.

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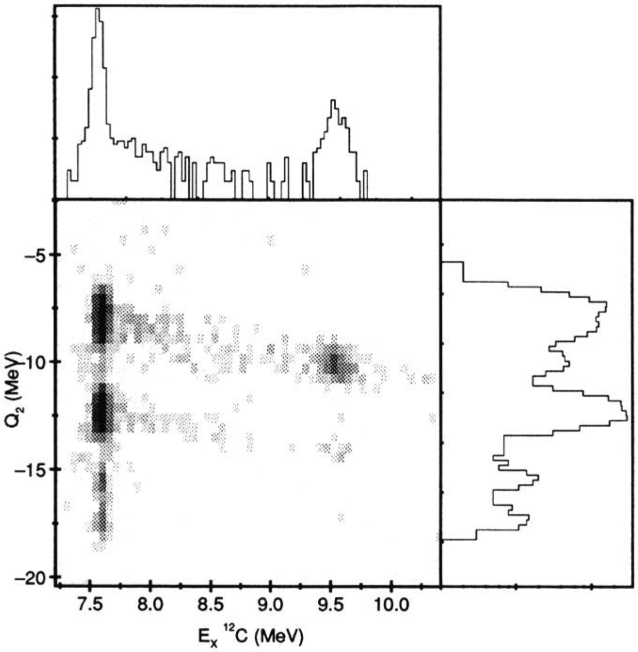

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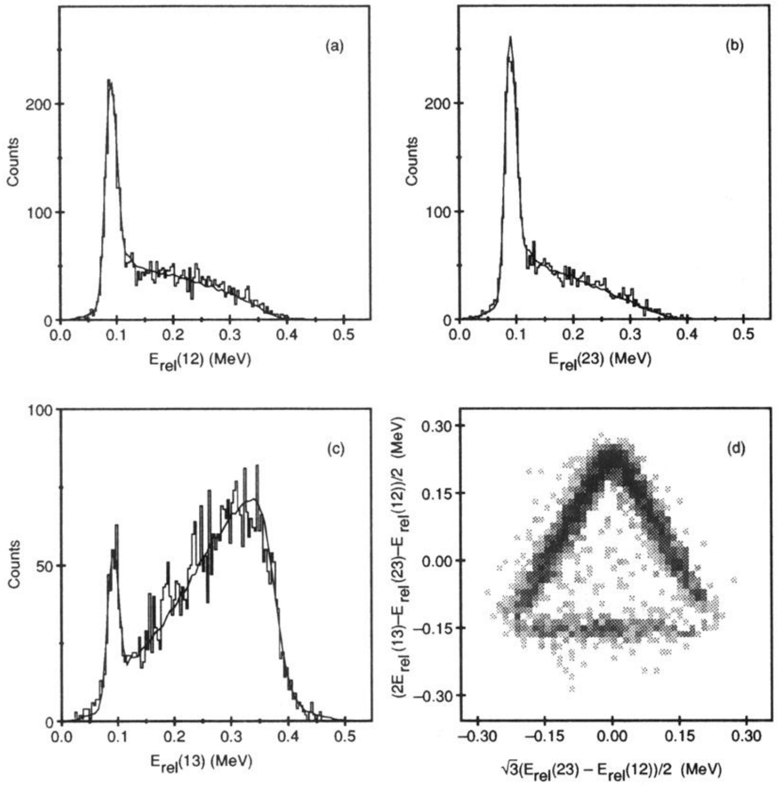

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