Clarification of the Three-Body Decay of $^{12}$C (12.71 MeV)

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Using $\beta$ decays of a clean source of $^{12}$N produced at the IGISOL facility, we have measured the breakup of the $^{12}$C (12.71 MeV) state into three $\alpha$ particles with a segmented particle detector setup. The high quality of the data permits solving the question of the breakup mechanism of the 12.71 MeV state, a longstanding problem in few-body nuclear physics. Among existing models, a modified sequential model fits the data best, but systematic deviations indicate that a three-body description is needed.

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The breakup of a quantum system into three particles presents challenges that have still not been fully met, in particular, when long-range Coulomb forces are combined with short-range stronger forces as in nuclear and particle physics; see, e.g., the recent proceedings [1,2]. Experimentally, such studies are challenging since complete specification of the final state (complete kinematics) requires detection of the momenta of at least two of the three particles. The kinematics is not completely restricted by conservation laws as in the two-particle case. Instead the energy and angular distributions of the fragments reflect different possible breakup mechanisms.

In nuclear and particle physics, the distinction is often made between direct and sequential decay. In sequential decay, two of the particles form an intermediate state and the only correlation between the first emitted particle and the later ones are those due to conservation laws. In contrast, in direct decay there can be dynamic correlations between all particles. (This delineation focuses on a physical interpretation of the two decay modes since it is known that general reaction formalisms, e.g., the $R$ matrix [3,4], in principle can describe all processes.)

The excited states of $^{12}$C decaying into $3\alpha$ final states provide an ideal model case for tests of the breakup mechanism [5]. The normal parity states can decay sequentially via the narrow $0^+$ ground state of $^8$Be, whereas for the $1^+$ and $2^-$ states this decay mode is forbidden by parity conservation. This leaves only sequential decay via the broad $2^+$ excited state of $^8$Be or direct decay possible. In fact, due to the short lifetime of the $2^+$ state, this seems a very unlikely case for sequential decay. Theoretically, the system of three $\alpha$ particles is attractive since the $\alpha$ particle is a spin-0 boson with well-known interaction, the charges of all particles have the same sign, and no binary bound states exist.

The $\alpha$ spectrum from the $^8$Be at 12.71 MeV in $^{12}$C (formed in the reaction $^{13}$C($^3$He, $\alpha$)$^{12}$C) [6] has been analyzed both in terms of direct decay [5] and sequential decay taking into account Bose symmetry effects [6]. The same data has also been analyzed by Takahashi [7] in a three-body calculation taking into account the final state interactions with the Faddeev equations. Although none of these models succeeded in completely reproducing the data, this case is often mentioned in the literature as an example of a direct decay [8,9]. References [5–7] suggest that complete kinematics data covering the full phase space is needed for a better test of the models, and a clarification of this problem.

We have met this challenge by producing the 12.71 MeV state in the $\beta$ decay of $^{12}$N at the IGISOL facility of the Jyväskylä Accelerator Laboratory, Finland. An important advantage in using $\beta$ decay is that the initial state is produced unpolarized, whereas in [6] the polarization had to be determined in a separate measurement. The activity was produced with the $^{12}$C($p, n$)$^{12}$N reaction with the 10 $\mu$A proton beam from the cyclotron. The produced nuclei were subsequently extracted with the IGISOL method [10], accelerated to 40 keV, mass separated, and finally transferred to the detection system where they were stopped in a 50 $\mu$g/cm$^2$ carbon collection foil. In this approach, the $^{12}$N beam is implanted at a well-defined depth in the collection foil and the breakup $\alpha$ particles following the $\beta$ decay suffer reduced energy loss compared to the reaction approach of [6].

The detection system consisted of two double sided Si strip detectors (DSSSDs) placed on either side of the

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which subsequently breaks up: $^{12}\text{C} \to \alpha_1 + \alpha_2 + \alpha_3$ with no influence of the $\alpha-\alpha$ interaction. This is shown with the dot-dashed (blue) curve in Fig. 1 as obtained from Eq. (18) of [5]. In this model, the decay amplitude is calculated as the lowest order term in an expansion in hyperspherical harmonics functions [5], which is symmetrized due to the presence of identical bosons in the final state. Note that absence of interactions does not infer a phase-space distribution of the events as the conservation of angular momentum induces correlations among the fragments. Also, quantum correlations from the effects of the symmetrization are present. This model qualitatively describes the presence of three peaks in the $\alpha$-particle spectrum, but it clearly fails to reproduce the position of these peaks. Hence, the $\alpha-\alpha$ interaction does play a role in this breakup. The only existing three-body model [7] taking this interaction into account could not reproduce the previous data [6]. We therefore turn to sequential models.

In the sequential model, one $\alpha$ particle is emitted leaving the two remaining particles in a resonant state of $^8\text{Be}$, which subsequently breaks up: $^{12}\text{C} \to \alpha_1 + ^8\text{Be} \to \alpha_1 + \alpha_2 + \alpha_3$. The amplitude is fully determined by specifying the relative energy of the two secondary $\alpha$ particles, $E_{23}$, and the angle between the directions of the primary and secondary $\alpha$-particle emissions, $\Theta$. Neglecting Bose symmetry, the $E_{23}$ dependence of the decay amplitude is in the $R$-matrix formalism [3] given by

$$|f|^2 \propto \frac{\Gamma_1 \Gamma_2}{(E_{23} - E_0 - \gamma_2^2(S_f(E_{23}) - S_f(E_0))^2 + \Gamma_2^2/4},$$

where $\Gamma = 2P_1(E)\gamma^2$ with $P_1(E)$ the penetrability for either the $\alpha-^8\text{Be}$ ($\Gamma_1$) or $\alpha-\alpha$ ($\Gamma_2$) breakup, $\gamma^2$ is the reduced width, $S_f$ is the shift function, and $E_0$ is the formal energy of the $^8\text{Be}$ resonance. The angular distribution can
be calculated from Ref. [14] to be $W(\Theta) = \sin^2(2\Theta)$. For
the breakup of a $1^+ \rightarrow 0^+$ state via $^8$Be$(2^+)$, the first $\alpha$ particle
is emitted with angular momentum $l = 2$, while for the
secondary emission $l' = 2$. The dotted (green) curve in
Fig. 1 is obtained from Monte Carlo simulations based on
Eq. (1). We use the recent parameters from Ref. [15] for
the description of the $^8$Be$(2^+)$ resonance. In this model,
the central peak is dominated by the first emitted $\alpha$ particle
while the other two peaks originate from the
secondary emitted $\alpha$ particles. The angular correlation
$W(\Theta)$ determines the shape of these peaks. Although the
position of the peaks agrees with data, this model fails to
reproduce the depths of the minima. Note that all previous
analyses of the $\alpha$ decay of the 12.71 MeV state fed in the
$\beta$ decay of $^{12}$N [16] are based on Eq. (1).

The importance of Bose symmetry interference effects
in the decay spectrum of the 12.71 MeV state was already
discussed in [6] where a modified $R$-matrix expression
was also given [Eq. (3) of [6]].

Dalitz plot in these coordinates effects of Bose symmetry
and interactions can be separated to a large extent.

We now turn to a discussion of the deviations between
the data and the sequential model. The difference between
the data and Eq. (2) is mainly at the low energy and high
energy sides of the $\alpha$ spectrum and is kinematically
equivalent with there being too few events in the data
with a small opening angle between pairs of $\alpha$ particles.
This is the expected signature for Coulomb repulsion in
the final state. In the parametrization of Eq. (2), the
interaction between the first emitted particle and the
two particles formed after the breakup of the $^8$Be
intermediate state is ignored. This interaction is expected to be
small when the first emitted particle travels a long
distance during the lifetime of the intermediate state. In a
first estimate, based on a kinetic energy of the order of
1 MeV, the typical distance traveled by the first emitted
particle is only $\sim5$ fm. At that distance, the electrostatic
energy between the first and second emitted $\alpha$ particles is
$\sim1$ MeV, and therefore the relevant Coulomb barrier for
the secondary breakup ought to be significantly modified
from that assumed in the $R$-matrix formalism. Alternatively,
in the tunneling picture of the first emission process, the $\alpha$
particle emerges outside the Coulomb barrier of the
$\alpha$-$^8$Be system at a distance closer to $\sim10$ fm with a corresponding reduction of the
electrostatic energy. By simply introducing extra barrier
penetrabilities in the numerator of Eq. (2) for each of the two
secondary $\alpha$ particles in the final state, and adjusting the
radius used in the calculation of the penetrability to
$\sim10$ fm between the $\alpha$ particles, near perfect agreement
can be achieved. These estimates are rather crude, but
serve to underline that dynamic correlations are present,
and that the Coulomb repulsion of the $\alpha$ particles
is important.

Related final state Coulomb effects have previously
been identified for the $3\alpha$ system [17,18] where the energy
shifts were calculated by solving the classical Hamilton
equations for the three particles in the final state.
Interestingly, these calculations could only reproduce
the data with a seemingly unphysically large distance traveled by the first emitted particle.

In conclusion, we have measured the \( \frac{3}{\alpha} \) breakup of the 12.71 MeV state in \(^{12}\text{C}\) in complete kinematics with unprecedented precision. The sequential model Eq. (2) can describe the data rather well when correlations due to conservation laws and Bose symmetry are included. The remaining deviations indicate that dynamic correlations beyond the sequential model are important for this breakup. To get a complete description of the data, quantum mechanical three-body models will be needed.

Although it might seem surprising that the sequential model fits the data relatively well, we note that many other nuclear breakup processes can be described in a similar way [19–22]. It will be interesting to see if in the future ground state two-proton radioactivity [23,24] can also be described in a sequential model.

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