6α particle emission in the reaction $^{13}N+^{11}B$

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The six-α decay of ^{24}Mg has been studied via the reaction ^{13}N+^{11}B at two beam energies, 29.5 MeV and 45 MeV. Large detector arrays allowed this reaction to be studied with low intensity radioactive ^{13}N beam. The excitation energy in the ^{24}Mg* was in the region of the 46 MeV resonance in ^{12}C+^{12}C scattering. From the six-α particles, events of interest were selected by associating two of the α particle pairs as the decay products of ^{8}Be. The c.m. energy spectra for two ^{8}Be+two α events have been extracted. The analysis revealed that most of these events originate from $^{12}C_{3_1^-}+{}^{12}C_{3_1^-}$. The total cross section for these six-α events has been extracted at the two beam energies. [S0556-2813(99)06902-2]

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It is known that ^{12}C+^{12}C scattering shows a large number of prominent resonances even at high excitation energy [1]. In the recent years, considerable interest has been focused on an unusual resonant behavior occurring in a number of exit channels at excitation energies around 46 MeV. A broad resonance was originally discovered in the $^{12}C_{0_2^+}+{}^{12}C_{0_2^+}$ exit channel at $E_{c.m.}=32.5$ MeV [2], and was postulated to be associated with a six-α linear chain in ^{24}Mg [3] based on the ^{12}C three-α linear configuration of the (0_2^+) state.

In addition cross section structures have been observed for the same colliding nuclei and same excitation energy region but for different exit channels. In particular much narrower resonances have been found at around the same excitation energy for the $^{16}O_{g.s.}+{}^{8}Be_{g.s.}$ [4] and $^{12}C_{3_1^-}+{}^{12}C_{3_1^-}$ exit channels [5].

In this paper we report on the six-α channel resulting from the reaction ^{13}N+^{11}B which populates the compound nucleus (CN) ^{24}Mg at two different beam energies $E_{lab}=45$ MeV and $E_{lab}=29.5$ MeV. The reaction using the radioactive beam ^{13}N on ^{11}B target was initially motivated with other aims, namely: to study the structure of ^{13}N nucleus especially the loosely bound proton [6], and to study the effect of isospin purity/mixing on the giant dipole resonance (GDR) γ decay [7,8]. However, since the excitation energy of our CN system was around the 46.4 MeV resonance we looked with interest for evidence of six-α particle decay coming from ^{12}C+^{12}C intermediate state. The interest of such an analysis came from the fact that in this experiment the entrance channel has a single-particle structure rather than an α cluster structure used in previous studies. The results of this analysis are reported here.

Previous studies of non-α-particle exit channels include Cormier *et al.* [9,10] who studied the contribution of the nucleon rearrangement collision ^{12}C(^{12}C,^{11}B) and ^{12}C(^{12}C,^{10}B) to the ^{12}C+^{12}C resonances in an excitation energy region for ^{24}Mg ranging from 36 to 48 MeV. They found a strong structure in the excitation function for the ^{12}C(^{12}C,^{10}B) at $E_x\sim31$ MeV correlated with the inelastic channel $^{12}C_{2^+}+{}^{12}C_{2^+}$. In their data no strong structures were found in the channel ^{12}C(^{12}C,^{11}B) at least in the very limited angular range explored for this channel. Excitation energy for the one and two nucleon transfer was also measured by Szilner *et al.* [11], however their experimental method did not enable them to disentangle between the two transfer channels ^{12}C(^{12}C,^{11}C) and ^{12}C(^{12}C,^{11}B). Moreover, the two nucleon transfer in the angular range covered does not show up the strong structure found by Cormier *et al.*

The experiment was performed at the radioactive beam facility in Louvain la Neuve. It was undertaken at ^{13}N laboratory energies of $E_{lab}=45$ MeV and $E_{lab}=29.5$ MeV. The radioactive ^{13}N beam had an intensity of $\sim10^8$ pps. Self-supporting ^{11}B targets having thicknesses 1300 and 800 μg/cm^2 were used for the 45 MeV and the 29 MeV runs, respectively. The beam energy loss in the total target thickness was ~4.6 MeV and ~3.7 MeV, respectively. At these two beam energies, taking into account the energy loss in the target, the corresponding minimum excitation energies for the compound nucleus ^{24}Mg is $E_x=46.5$ MeV and $E_x=39.8$ MeV, respectively. Therefore the higher bombarding energy used in this experiment is around the maximum for the previously reported broad state at 46.4 MeV [2].

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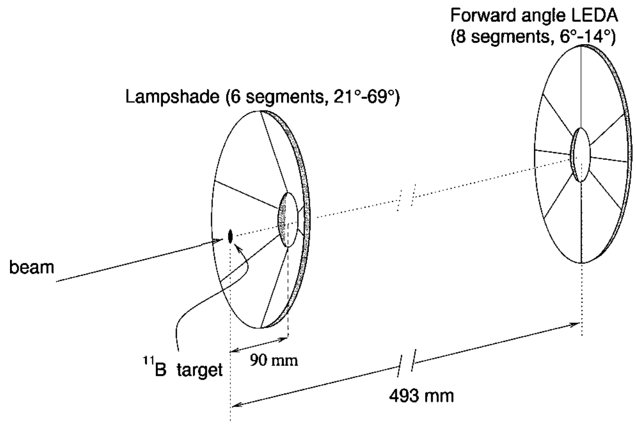

FIG. 1. Experimental setup.

The experimental setup (Fig. 1) consisted of two large area annular silicon strip detectors 300 μm thick. The forward detector array (LEDA Louvain-Edinburgh-Detector-Array) consisted of 8 sector detectors each containing sixteen strips and covering the angular range $6° \leqslant \theta \leqslant 14°$ and an azimuthal angular range $0° \leqslant \phi \leqslant 360°$. The detector array placed at larger angles (LAMP Lampshade) consisted of six sectors angled forward at 45°, to give larger solid angle acceptance. In this case the angular range covered was $21° \leqslant \theta \leqslant 69°$ and $0° \leqslant \phi \leqslant 360°$. The angular resolution with the geometry configuration used in these experiments was $\Delta\phi = \pm 22.5°$ and $\Delta\theta = \pm 0.75°$ for LEDA and $\Delta\phi = \pm 30°$ and $\Delta\theta = \pm 1.5°$ for LAMP. The total solid angle (LEDA +LAMP) in the laboratory system was $\Omega \sim 3.6$ sr. Each detector strip was separately instrumented allowing charged-particle coincidence events with different multiplicities to be recorded.

Particle identification was performed using the time of flight (TOF) vs energy technique. The resulting mass resolution in LEDA detector was enough to disentangle alphas from protons and heavy ions (HI). In the LAMP detector the close distance to the target resulted in a poor separation between p, α, and HI mass peaks.

The data analysis has been performed for both bombarding energies by selecting events with six charged particles in the final channel. From this data subset α particles were selected by putting software gates in the TOF-Energy 2D spectra. In Fig. 2 the Q-value spectra for such events at $E_{\rm lab} = 45$ MeV is shown. The Q-value spectra at the two beam energies were constructed according to the relationship:

$$Q_{\rm val} = \sum_{i=1,6} E_i - E_{\rm inc}, \qquad (1)$$

where the beam energy, $E_{\rm inc}$, and the particle energy, $E_{\rm i}$, have been corrected for energy loss in traversing half the target. The variation of target thickness with the angle of the emitted particles has been taken into account.

These Q value spectra show peaks at around -500 keV which correspond to the Q value for the reaction ^{13}N$+^{11}$B $\rightarrow 6\alpha$. For further analysis a gate was imposed around the Q value peak, as shown in Fig. 2.

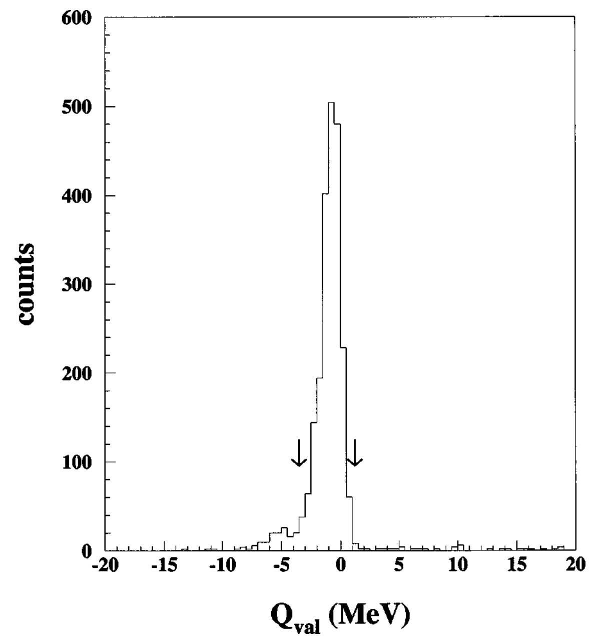

FIG. 2. Q-value spectrum for six-α events at $E_{\rm lab} = 45$ MeV. The two arrows indicate the events selected in the analysis.

Six α particle events could come from sequential evaporation of α particles from the compound nucleus. Therefore, to select α particles coming from the breakup of ^{24}Mg into two ^{12}C* nuclei, a further selection has been performed. From the knowledge that the breakup of the 0_2^+ and 3_1^- states in ^{12}C proceeds largely via ^{8}Be$_{\rm g.s} + \alpha$ channels [12], two ^{8}Be$_{\rm g.s}$+two α events were selected from the 6 α data set. The two ^{8}Be were selected by looking for alpha particles detected in adjacent strips. The relative energy of such α particles pairs has been extracted and is shown in Fig. 3. The peak at $E_{\rm rel} \sim 90$ keV was used to select ^{8}Be$_{\rm g.s.}$ events. By measuring energies and angles of these ^{8}Be and α-particles the intermediate states leading to the six α decay of ^{24}Mg were reconstructed.

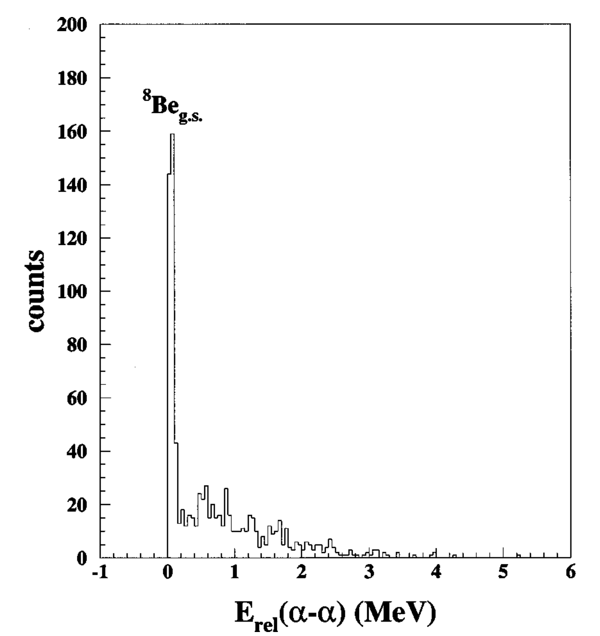

FIG. 3. Alpha-alpha relative energy spectrum. The peak at ~ 90 keV corresponds to ^{8}Be$_{\rm g.s.}$ events.

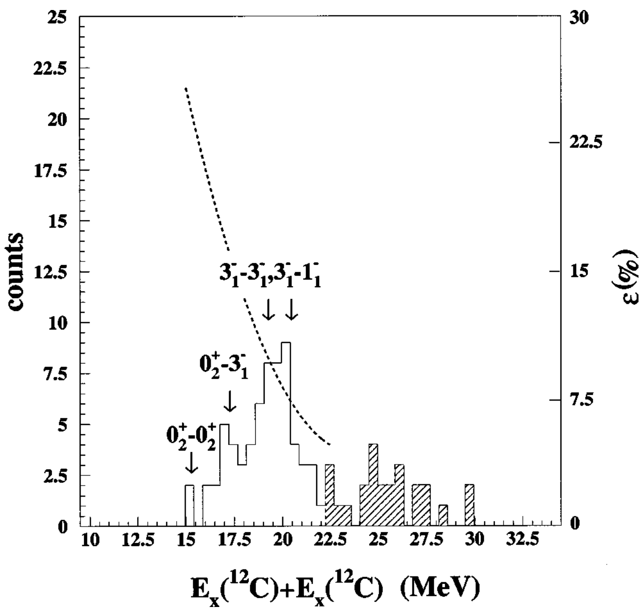

FIG. 4. Total excitation energy spectrum for six-α coincidence data for $E_{lab}=45$ MeV uncorrected for the efficiency of the detector. The dashed curve indicates the efficiency (ε) of the apparatus for each combination of excited states. The hatched region shows where miscorrelated events contribute to the spectrum. The arrows mark the position of different possible combinations of ^{12}C states.

Assuming the two ^8Be nuclei originated from two $^{12}C^*$, the excitation energy of $^{12}C^*$ nuclei is calculated from the α particles according to

$$E_x=\sum_{i=1,3} E_{\alpha i}-\frac{P^2}{2M}+Q, \qquad (2)$$

where P is the momentum of ^{12}C determined by the momenta of the three α particles, and Q is the threshold Q value for the breakup of ^{12}C into three α particles (7.27 MeV).

Having identified the two $^{12}C^*$ events it is possible to deduce their total combined excitation energy before the dissociation. Figure 4 shows this double excitation energy spectrum for the two ^{12}C for the 45 MeV run. The arrows mark different possible combinations of ^{12}C excited states from the $^{12}C^*$-$^{12}C^*$ pair. There are too few statistics to obtain a significative double excitation energy spectrum for the 29.5 MeV run. The energy resolution of this spectrum is dominated by the angular resolution and by the binning chosen because of the low statistics. There is an ambiguity in the analysis due to the wrong association between the two ^8Be and the two alphas. This ambiguity leads to an incorrect ^{12}C excitation assignment for some of the events. This problem is more severe for the lower energy run where the smaller c.m. velocity induces a wider kinematical spread in the breakup fragments. A way to reduce this background is to look for ^8Be-α particle events in the same or in adjacent sectors but due to the poor ϕ resolution of our detection system it is impossible to eliminate the background completely.

Monte Carlo simulations have been performed to understand the contribution of miscorrelated events on the double excitation energy spectrum (i.e., associated the wrong α particle with a ^8Be). These simulations show that miscorrelated events contribute only to the high excitation energies of Fig. 4 (hatched region).

In Fig. 4 one can observe that experimental yield seems to correlate with states in ^{12}C which contribute to the breakup into three α particles. They are mainly the double excitation of the 3_1^- at 9.64 MeV with a contribution of the 3_1^--1_1^- and 0_2^+-3_1^-.

The Monte Carlo program UNIMONTE was also used to deduce the efficiency of our setup. This efficiency depends upon the states which are excited, therefore simulations have been performed for each combination of listed final states and is shown as a dashed curve in Fig. 4. In the absence of detailed knowledge of the reaction mechanism, it was assumed for the simulations an isotropic center of mass angular distribution for the primary scattering as well as for the subsequent decays. Energy threshold and multiple hits in a single strip have also been included to extract the efficiency.

The ratio between the states contributing to this spectrum have been used to perform a weighted average of the total efficiency. As mentioned above, due to the low statistics it was not sensible to reconstruct the multiple excitation energy spectrum for the lower energy run. Therefore to extract the total yield at the low energy we assumed the same ratio between the states as in the higher energy run. However the estimated difference in efficiency between doing a weighted average or considering that only the 3_1^- contributes to the spectrum is less than 2% well within the systematic error. In this way a relative normalization of the data at the two different beam energies is possible and the total cross section for the selected six-α events has been extracted for the two beam energies. We obtained $\sigma=28.3\pm7.1$ μb for $E_{lab}=45$ MeV and $\sigma=6.6\pm1.6$ μb for $E_{lab}=29.5$ MeV.

Six alpha particle final states have been analyzed for the reaction $^{13}N+^{11}B$ at two beam energies. A detection system having a very large solid angle coverage and with high segmentation was used. Such a detector system allowed us to reconstruct the very complicated kinematics of six α particle events in the experimentally challenging environment of a radioactive beam with its associated low beam intensity and high background radiation.

Experimentally this is an important development because it demonstrates that complicated reaction scenarios can be measured with low intensity RNB provided highly efficient and segmented detector arrays are used.

The breakup into a six α particle channel at an excitation energy corresponding to the compound nucleus at around the 46 MeV resonance found in $^{12}C+^{12}C$ scattering has been studied. The analysis showed that many of the six-α events originate from the breakup of two ^{12}C excited in the 9.64 MeV 3_1^- state, but also decays from the 0_2^+-3_1^- are observed. Within the limited statistics there is not strong evidence for the 0_2^+-0_2^+ decay taking place. The total cross section for these events at the two beam energies has been extracted. Although our data set is much smaller, there is reasonable consistency between the present $^{13}N+^{11}B$ results and the $^{12}C+^{12}C$ inelastic scattering [5], where feeding from the 3_1^--3_1^- and 0_2^+-3_1^- states of ^{12}C to the six-α breakup is observed together with a reduced feeding from the 0_2^+-0_2^+.

Bearing in mind the single particle nature of the $^{13}N+^{11}B$ channel compared to the α cluster nature of $^{12}C+^{12}C$ this finding is surprising. However, before inferring any structure to the CN ^{24}Mg intermediate system from observation, a more detailed experiment should be undertaken where excitation functions for various combinations of excited states in ^{12}C are measured; also, for any model of the structure, calculations where structures feed various exit states should be performed. We hope that the next generation of RNB facilities will allow such a study.

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