Can breakup reactions be used to probe high-lying inelastic channels in $^{12}C + ^{12}C$ scattering?

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Abstract. The $^{12}C(^{24}Mg,^{12}C\ ^{12}C^{*})^{12}C$ reaction has been studied to investigate a possible overlap with the $^{12}C{-}^{12}C$ scattering resonances observed in the gs $-\ 0_2^+$ and gs $-\ 3^-$ channels. Evidence for the breakup of ^{24}Mg was observed, but the yield was too low to be able to associate it with specific resonances.

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1. Introduction

In recent years a number of studies have been reported on the breakup of ^{24}Mg to ^{12}C+^{12}C [1, 2, 3, 4]. The breakup is observed to occur from a sequence of states in the region E_x = 21–30MeV [5] and the spin systematics of the states are consistent with a highly deformed rotational structure [6]. In a high resolution breakup measurement [7], evidence was reported which suggests that the states seen in the breakup measurements are the same as the resonances observed in ^{12}C+^{12}C scattering at energies around the Coulomb barrier, the so called *barrier resonances* or *molecular resonances*. The observation of the same states in the breakup measurements is important in that it confirms that the states are linked to the ^{24}Mg nucleus (rather than being a feature of the ion - ion scattering potential produced in the scattering process) and also enables new information on the structure of the states to be determined. For example, the observation that the breakup states are strongly excited when an alpha pickup reaction is used to excite the ^{24}Mg nucleus, suggests that they have a 4p-4h configuration [8]. This has led to the suggestion that the states are based on a hyperdeformed (3:1 axis ratio) minimum which appears in the ^{24}Mg potential energy surface in Nilsson-Strutinsky (NS) calculations [9]. The same structure is also observed in Hartree-Fock (HF) calculations [10] and in Bloch-Brink Alpha Cluster Model (ACM) calculations [11].

Recently there has been a renewal of interest in the excitation of higher lying states in ^{12}C+^{12}C scattering. This has arisen from the observation by Wuosmaa *et al* [12] of a striking resonance in the ^{12}C(^{12}C,^{12}C$^*{}_{7.6}$)^{12}C$^*_{7.6}$ reaction. Since the 7.65 MeV 0_2^+ state has been suggested to have an elongated structure, close to a linear chain of 3 alpha particles [13], there has been considerable discussion as to whether this resonance is evidence for the existence of a 6-α chain state in ^{24}Mg. As part of these investigations, studies have been made of the other channels involving excitation of the 7.65 MeV 0_2^+ state and other nearby alpha unbound states such as the 3_1^- (9.64 MeV), the 0_3^+ (10.3 MeV) and the 1^- (10.84 MeV) [14, 15]. Hirabayashi *et al* [16] have recently reported comprehensive coupled channels calculations for the ^{12}C+^{12}C scattering system which include the gs -gs, gs-2_1^+, gs-3_1^-, gs- 0_2^+, gs-2_2^+, and 0_2^+-0_2^+ channels. This calculation predicts a structure at E_{cm}=32.5 MeV in the $0_2^+-0_2^+$ channel, raising the possibility that this is not related to an intrinsic state in ^{24}Mg.

In their paper Hirabayashi *et al* comment that their calculations also predict structure in the gs-0_2^+ channel at E_{cm}=29 MeV. In fact structured yield was first observed in this channel some years ago in the measurements of Fulton *et al* [17] and later by Pate *et al* [18]. Fulton *et al.* also report structure in the gs $-$ 3^- channel. In view of the success of associating the states observed in the breakup of ^{24}Mg with the barrier resonances observed in ^{12}C+^{12}C scattering [7], it is of interest to see if breakup to these higher lying, and structurally more exotic channels can be observed also. If this can be achieved, then the breakup technique may provide additional structural information about the states which can give further insights into the nature of the scattering resonances. In particular, the breakup measurements do not suffer from the background contributions from other reaction processes which can make it difficult to extract resonance spins and widths from the scattering measurements.

The yeild observed in a breakup experiment will depend on the cross section for exciting the cluster state, the decay width (assumed large) and the detection efficiency. The recent advent of large area strip detectors means that high detection efficiencies can be achieved, even for channels involving multiple alpha particles. However, since the reaction mechanism for exciting the breakup state is not known, it is not possible to extimate the production rate by a model calculation. Hence an experimental measurement is required to assess whether the technique is feasible. We have analysed existing data from a measurement performed several years ago at the Daresbury Laboratory to search for the breakup of ^{24}Mg to the ^{12}C+^{12}C(0_2^+) channel following scattering from a ^{12}C target. The experimental setup used in that measurement covers the excitation region where the scattering resonances are observed in the 7.65 MeV channel (around 50 MeV).

2. Experimental detail

A 170 MeV beam of ^{24}Mg from the Daresbury tandem Van de Graaff accelerator was used to bombard a 450 μgcm^{-2} natural carbon foil. The ^{12}C breakup fragment was recorded in a telescope comprising a gas ionisation chamber and a position-sensitive silicon stopping detector [20]. This was placed 240 mm from the target at an angle of 14.6° and subtending 43 msr. The three alpha particles from the breakup of the ^{12}C(0_2^+) fragment were detected in a silicon strip detector placed 120 mm from the target at an angle of $-19.7°$ and subtending a geometric solid angle of 174 msr. The strip detector comprised 16 independent, horizontal, position-sensitive strips, each 3 mm high and 50 mm long. A 125 μm thick mylar sheet was placed in front of the strip detector to remove the high flux of heavy ions. During the analysis, ^{12}C ions were identified from their energy loss signal in the gas ionisation detector. Triple alpha hits in the strip detector were kinematically reconstructed to identify those which corresponded to the 7.65 MeV state in ^{12}C, decaying sequentially through the ^{8}Be ground state. From the measured momentum of the two breakup fragments, the missing momentum of the recoil nucleus could be determined, allowing a full determination of the reaction kinematics. A full account of the detector setup and analysis techniques has been given by Curtis *et al* [20].

3. Results

Figure 1(a) shows the Q-value spectrum for the ^{12}C+^{12}C(0_2^+) coincidence events. This is derived from the summed energy of the two observed fragments, plus the energy of the unobserved recoil particle, determined from conservation of momentum, and so represents the total energy release in the reaction. A small peak is observed in this spectrum at an energy which corresponds to the beam energy minus the breakup Q-value for the reaction, but this is very weak. Figure 1(b) shows the Q-value spectrum for ^{16}O+^{8}Be coincidence events, with clear evidence for the Q_{ggg} peak (all particles emerging in their ground state) at the correct energy, and peaks at lower energies corresponding to the ^{12}C and ^{16}O nuclei emerging in their first excited states. The fact that this spectrum shows these peaks clearly confirms that the peak in the ^{12}C+^{12}C(0_2^+) channel is genuinely weak and not the result of poor resolution in the measurement. The cross sections calculated for the ^{12}C + ^{12}C(0_2^+) and ^{16}O + ^{8}Be channels are 0.33 ± 0.12 μb sr^{-2} and 18 ± 4 μb sr^{-2} respectively.

The curves on Figure 2 show the predicted detection efficiency for the two channels recorded in the present measurement as determined from a Monte Carlo simulation of the scattering and detection process. In this simulation an exponential distribution was assumed for the initial scattering process and an isotropic distribution for the subsequent breakup stage. The emerging particles were then tracked to see if they hit the detectors, taking into account energy thresholds and, in the case of the multiple alpha detection, the inability to record events where more than one of the alpha particles enters the same strip. The simulation shows the region of excitation energy over which breakup could be measured. For comparison, Figure 2(c) indicates the energy of the breakup states observed in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction [5] and the scattering resonances observed in ^{12}C(^{12}C,^{12}C)^{12}C(0_2^+)[17, 18, 19] and ^{12}C(^{12}C,^{12}C)^{12}C(3^-) [17].

4. Discussion

The Q$_{gg}$ peak could in principle contain a contribution from an alternative breakup mode in which the target nucleus is excited to the 7.65 MeV state in the collision and the ^{24}Mg nucleus subsequently breaks up into two ground state ^{12}C nuclei. Such events would be indistinguishable from the reaction of interest on the basis of Q-value measurements alone. However, any such yield would be expected to be negligible compared to the primary reaction for two reasons. Firstly, no previously published spectra for the ^{12}C(^{24}Mg,^{12}C ^{12}C)^{12}C reaction have shown any indication for a peak in the Q-value spectrum which would indicate inelastic excitation for the recoiling ^{12}C nucleus. Secondly, because of the detection geometry, any such yield in the present measurement would correspond to the ^{24}Mg nucleus scattering to very large angles ($\theta_{c.m.}$

$\approx 115° - 155°$) where any yield would be expected to be greatly reduced compared to the forward angle coverage ($\theta_{c.m.} \sim 0° - \sim 20°$) for the ^{12}C + ^{12}C(0_2^+) breakup channel (see, for example, the rapid fall-off of the angular distributions in Reference [23]).

While the clear peak in the Q-value spectrum provides intriguing evidence for ^{12}C + ^{12}C(0_2^+) breakup, the low yield precludes any further analysis to look for an association with the scattering resonances observed in the ^{12}C(^{12}C,^{12}C)^{12}C(0_2^+) inelastic channel (corresponding to excitation energies from 41 − 50 MeV). Of course it is possible that the breakup yield is too low simply because the reaction mechanism in the ^{12}C+^{24}Mg collision does not excite the ^{24}Mg nucleus at high excitation energy with sufficient cross section. On the other hand, the lack of any yield in the breakup would be consistent with the model of Hirabayashi *et al.* in which the structures in the scattering yield arise as a result of the energy dependent coupling between the inelastic channels excited in the scattering. In this description there is no need to invoke a particular structure in the ^{24}Mg nucleus, and hence no expectation that there should be states observed in the breakup process.

As the Monte Carlo efficiency calculations show, the experiment also covered the lower excitation range above 27 MeV where breakup to the ^{12}C+^{12}C channel has been observed [5]. If the present understanding of the structure of the ^{24}Mg states observed in the ^{12}C+^{12}C is correct, then there is no structural reason why they should not be observed in the ^{12}C+^{12}C(0_2^+) channel. Previous measurements have shown the breakup yield in the ^{12}C + ^{12}C channel to be in the order of 20 μb sr^{-2} MeV^{-1} over the ^{24}Mg excitation energy range from 21–29 MeV [5] to be contrasted to the 0.3 μb sr^{-2} observed in this measurement of the ^{12}C + ^{12}C(0_2^+) channel (this includes a factor of two between the efficiency for detecting ^{12}C + ^{12}C, as compared to ^{12}C + 3α, determined from the Monte Carlo simulations). However the ^{12}C + ^{12}C(0_2^+) channel decay is greatly inhibited by a decreased decay energy relative to the Coulomb barrier. The spin of the states observed in the ^{12}C + ^{12}C breakup channel are of the order of J = 12 at this excitation energy, giving a predicted decay ratio around 4000:1 on penetrability grounds for the ^{12}C + ^{12}C to ^{12}C + ^{12}C(0_2^+) channels (for an assumed radius of $r_o = 1.4(A^{\frac{1}{3}} + A^{\frac{1}{3}})$ fm). The observed inhibition factor of > 100 is consistent with the suppression of the 7.65 MeV channel simply by penetrability effects, and it is not possible to draw conclusions on structural effects.

In summary, a measurement of the breakup of ^{24}Mg to ^{12}C+^{12}C(0_2^+) in the ^{12}C(^{24}Mg,^{12}C^{12}C(0_2^+))^{12}C reaction has revealed evidence for the breakup, but at too low a yield to look for an association with the resonances observed at higher energies in the scattering of ^{12}C+^{12}C to the 0_2^+ state. However, given that breakup yield is observed, it would be of considerable interest to repeat the present measurement with a more efficient detection system. An increase of at least an order of magnitude would be required, but it is possible that the continuing development of arrays of strip detectors will make such a measurement feasible. Until an alternative mechanism for probing these structures can be found, scattering studies will remain the only way to probe these puzzling structures.

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Figure captions

Figure 1. Q-value spectra for (a) ^{12}C(^{24}Mg,^{12}C ^{12}C(0_2^+))^{12}C and (b)^{12}C(^{24}Mg,^{16}O ^{8}Be))^{12}C .

Figure 2. a) Calculated Monte Carlo efficiency for ^{24}Mg breakup to ^{12}C + ^{12}C(0_2^+). b) Calculated Monte Carlo efficiency for ^{24}Mg breakup to ^{16}O + ^{8}Be. c) Diagram to show where states have already been observed showing the overlap with the present measurement. [5], [17-19]