Breakup studies with ^{23}Na

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The breakup of ^{23}Na nuclei into ^{11}B$+^{12}$C and of ^{24}Mg nuclei into ^{12}C$+^{12}$C has been studied using the reactions ^{12}C(^{23}Na,^{11}B ^{12}C)^{12}C and ^{12}C(^{23}Na,^{12}C ^{12}C)^{11}B. Clear evidence was found for the breakup of the ^{23}Na and ^{24}Mg nuclei into the ground states of both fragments. The yield from the ^{12}C(^{23}Na,^{11}B$_{\rm g.s.}$ ^{12}C$_{\rm g.s.}$)^{12}C$_{\rm g.s.}$ reaction was concentrated in the region of excitation energy in ^{23}Na between 24 and 28 MeV and fragmented among a number of states. The ^{12}C(^{23}Na,^{12}C$_{\rm g.s.}$ ^{12}C$_{\rm g.s.}$)^{11}B$_{\rm g.s.}$ reaction was found to proceed chiefly via broad states at 22.1 and 23.9 MeV in ^{24}Mg.

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I. INTRODUCTION

In recent years a number of studies of the symmetric and near-symmetric breakup of *sd*-shell nuclei have been carried out in order to search for evidence of large-scale clustering [1–4]. Some of this work and associated measurements have been reviewed by Fulton and Rae [5]. The earliest studies included measurements of the symmetric breakup of ^{24}Mg following its scattering from ^{12}C at 180 MeV by Fulton *et al.* [1], and at 357 MeV by Wilczynski *et al.* [6]. In both experiments the two ^{12}C fragments were detected in coincidence using silicon detector telescopes on either side of the beam axis. Both studies identified breakup from distinct states in ^{24}Mg between 21 and 25 MeV. Wilcynski *et al.* [6] reported broad states at 21.9, 23.6, and 24.8 MeV, consistent with radiative capture measurements [7–9]. However, a recent study of the spins and parities, J^π, of the ^{24}Mg breakup states, using a 170 MeV ^{24}Mg beam [4], found distinct narrow states in this energy region with J^π values of 4^+, 6^+, and 8^+.

The earlier measurements on ^{24}Mg by Fulton *et al.* [1] also gave evidence of breakup to the ^{16}O$+^{8}$Be channel and to the ^{12}C$+^{16}$O channel, following an α transfer from the target. The ^{16}O$+^{8}$Be channel was later studied in detail [3] and found to be populated with greater strength than the ^{12}C$+^{12}$C channel. Despite the difficulties in performing a direct comparison of the excitation spectra from the two experiments, it could be seen that the breakup was occurring from states in a similar region of excitation energy in both instances. However, little correlation could be found with the states observed by Sandorfi *et al.* [10,11] in the electrofission of ^{24}Mg to ^{16}O$+^{8}$Be.

The success of the early ^{24}Mg breakup studies prompted the search for similar phenomena in neighboring nuclei. The breakup of ^{28}Si to ^{12}C$+^{16}$O using a ^{28}Si beam and C target was found to proceed only very weakly [5,12], with a much smaller yield than that from the α transfer reaction ^{12}C(^{24}Mg,^{16}O ^{12}C)^{8}Be. The yield of the ^{12}C(^{32}S,^{16}O ^{16}O)^{12}C reaction was too small [5,12] for the breakup events to be unambiguously identified.

The nuclei discussed above are all α-conjugate nuclei. In order to obtain further information on the breakup process, measurements on non-α-conjugate nuclei are required. The breakup of ^{25}Mg has been studied by Gyapong *et al.* [13]. No evidence of the breakup of ^{25}Mg to ^{12}C$+^{13}$C was observed, the yield being at least two orders of magnitude below that observed for ^{24}Mg breakup [4]. In this paper we report an investigation of breakup processes in ^{23}Na, another non-α-conjugate nucleus adjacent to ^{24}Mg.

Studies of heavy ion resonances in the ^{23}Na compound system have been reported by several authors [14–18] Frawley *et al.* [15,16] studied the excitation functions for the elastic, inelastic, ^{8}Be, and α-particle exit channels of the ^{11}B$+^{12}$C system over the range $E_{\rm c.m.} = 9.81$ to 17.79 MeV. They identified nine narrow ($\sim$ 300 keV wide) resonances in ^{23}Na at excitation energies between 28.3 and 34.2 MeV.

Feldman and Heikkinen [14] report measurements of the high energy γ radiation produced by the

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$^{11}B(^{12}C,\gamma)^{23}Na$ radiative capture reaction. They observed a prominent resonance at 24.5 MeV from the reaction and a less striking structure at 25.9 MeV.

Mateja *et al.* [17] investigated the elastic scattering of $^{7}Li+^{16}O$ and $^{10}B+^{13}C$, but found no strongly correlated structures, and concluded that the two reactions were dominated by statistical processes. However, their measurements of the elastic scattering of $^{11}B+^{12}C$ show resonances at 10.95 and 16.0 MeV, corresponding to excitation energies of 29.15 and 34.2 MeV, indicating that the resonances excited are entrance-channel dependent.

The observation of $^{11}B+^{12}C$ scattering resonances and structure in the $^{11}B+^{12}C$ radiative capture suggests that the ^{23}Na system at high excitation might breakup into the $^{11}B+^{12}C$ channel. A study of the breakup of ^{23}Na also allows the simultaneous investigation of the symmetric breakup of ^{24}Mg produced by the one proton transfer reaction $^{12}C(^{23}Na,^{24}Mg)^{11}B$, thus allowing a comparison of the states populated via this transfer reaction with those observed in the breakup experiments using a ^{24}Mg beam [1,4]. This paper presents measurements of the breakup states in ^{23}Na and ^{24}Mg excited using the reactions $^{12}C(^{23}Na,^{11}B\,^{12}C)^{12}C$ and $^{12}C(^{23}Na,^{12}C\,^{12}C)^{11}B$.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A beam of ^{23}Na ions from the tandem accelerator at the SERC Daresbury Laboratory, was used to bombard a target of natural carbon, with an areal density 400 $\mu g\,cm^{-2}$. The breakup fragments from the excited nuclei were detected in coincidence using the CHARISSA array and data acquisition system [19]. The array consisted of six telescopes of position-sensitive silicon detectors mounted upon two movable arms located in the forward hemisphere. The three telescopes on each arm were mounted in the same vertical plane. Each of the pair of telescopes in the horizontal scattering plane contained a 30 μm ΔE and a 600 μm E detector; the other four telescopes, which were situated two above and two below the horizontal scattering plane, also included a 2000 μm detector to veto events where the detected particle had passed through the ΔE and E detectors. The ΔE and E detectors were oriented so that their position-sensitive axes were orthogonal; the active areas were defined by 9 mm square collimators placed 110 mm from the target, giving each telescope a solid angle of 6.7 msr.

Data were recorded for coincidences in the "in-plane" pair of telescopes, located in the horizontal scattering plane, and in the two pairs of diagonally opposite "out-of-plane" telescopes. Each of the "out-of-plane" pairs included one telescope above and one below the horizontal scattering plane, on opposite sides of the beam axis. The angular settings used and other experimental parameters are summarized in Table I.

Using this experimental arrangement, the charge, energy, and angle of emission of each breakup fragment could be established. From these data a total energy (E_{tot}) spectrum was constructed by summing the energy of the breakup fragments together with the calculated energy of the recoiling targetlike nucleus.

TABLE I. Telescope angles and effective integrated charge. θ_R and θ_L give the scattering angle to the center of the relevant detector; ϕ indicates whether the detector was above the horizontal scattering plane (+), in the plane (0), or below this plane (-).

Telescope angles				Integrated charge
θ_R	ϕ	θ_L	ϕ	
13.63°	+	-14.50°	-	
9.70°	0	-10.50°	0	5.26 mC
13.74°	-	-14.53°	+	
13.99°	+	-14.50°	-	
10.20°	0	-10.50°	0	1.99 mC
14.09°	-	-14.53°	+	

In these experiments we detect either an ^{11}B and a ^{12}C or two ^{12}C nuclei. We differentiate between the $^{11}B+^{12}C$ and $^{12}C+^{12}C$ breakup channels by studying the E_{rel} spectra for different detector pairs using a technique developed by Rae *et al.* [20].

In addition our experimental technique is designed to favor reactions with the dominant final state interaction being between the two detected fragments. For both the breakup of the ^{23}Na beam and ^{24}Mg formed by single proton pickup the two breakup fragments are strongly forward focused by the kinematics and thus the efficiency for detection is high. For reactions which involve a final-state interaction between one detected fragment and the recoil nucleus there is no kinematic focusing and our detection efficiency is very much smaller.

A. The $^{12}C(^{23}Na,^{11}B\,^{12}C)^{12}C$ data

Figure 1 shows an E_{tot} spectrum for the $^{12}C(^{23}Na,^{11}B\,^{12}C)^{12}C$ reaction at 176 MeV.

Several distinct peaks can be observed in this spectrum, each corresponding to different excitations of the breakup and recoil particles. The peak at E_{tot} = 156 MeV corresponds to all three of the final-state nuclei

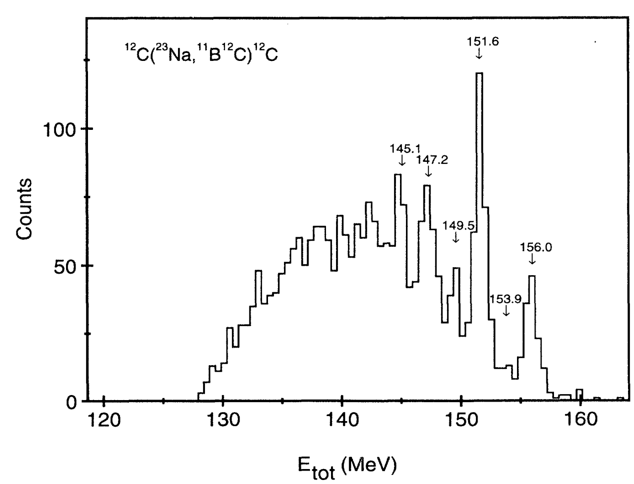

FIG. 1. E_{tot} spectrum for the $^{12}C(^{23}Na,^{11}B\,^{12}C)^{12}C$ reaction.

being in their ground states (Q_{ggg}). This energy corresponds to the incident beam energy minus the breakup Q value (18.2 MeV) and allowing for a loss of 1.8 MeV in the target. Peaks due to the fragments being in excited states are visible at lower values of $E_{\rm tot}$. At low values of $E_{\rm tot}$ the spectrum shows a continuum of overlapping higher excited states in the residual nuclei and the effects of four-body (or many-body) breakup events. The low energy cutoff in the $E_{\rm tot}$ spectrum is a consequence of the energy threshold for detecting ^{12}C or ^{11}B ions.

Using only the events that contributed to the Q_{ggg} peak, excitation spectra of the decaying nuclei can be constructed. The excitation spectrum for the ^{12}C (^{23}Na,^{11}B$_{\rm g.s.}$ ^{12}C$_{\rm g.s.}$)^{12}C$_{\rm g.s.}$ reaction is shown in Fig. 2 assuming an ^{11}B+^{12}C final-state interaction. This spectrum has not been corrected for detection efficiency or Coulomb barrier effects. The dashed line in the figure shows the variation of the detection efficiency with energy. This indicates that the excitation energy region observed is mainly determined by the detection efficiency. The energy resolution is estimated to be 100 keV, and the energy calibration has uncertainties of $\pm$50 keV. The figure shows evidence for some sharp states which are correlated in the data for all pairs of detectors. We, therefore, conclude that there is a dominant ^{11}B+^{12}C final-state interaction and that these data indicate the sequential breakup of the ^{23}Na nucleus. The energies of some of the peaks observed are shown in the figure.

B. The ^{12}C(^{23}Na,^{12}C ^{12}C)^{11}B data

The $E_{\rm tot}$ spectrum for the ^{12}C(^{23}Na,^{12}C ^{12}C)^{11}B channel is shown in Fig. 3. The Q_{ggg} peak appears at 156.0 MeV. The peaks at lower values of $E_{\rm tot}$ correspond to combinations of excited states in the residual nuclei. As for the ^{12}C (^{23}Na,^{11}B ^{12}C)^{12}C reaction, the channels involving the first excited state of ^{11}B at 2.1 MeV are less well populated than the other channels.

The ^{24}Mg excitation spectrum for this reaction is shown in Fig. 4, assuming a ^{12}C+^{12}C final-state interaction. The variation of detection efficiency is again shown as a dashed line. This spectrum is derived

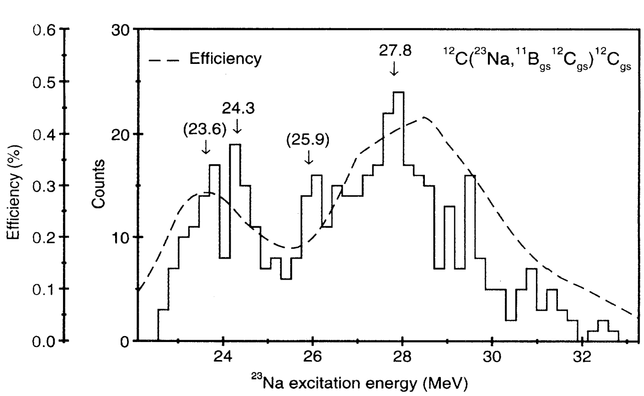

FIG. 2. ^{23}Na excitation spectrum from the ^{12}C (^{23}Na,^{12}C$_{\rm g.s.}$ ^{11}B$_{\rm g.s.}$)^{12}C$_{\rm g.s.}$ reaction.

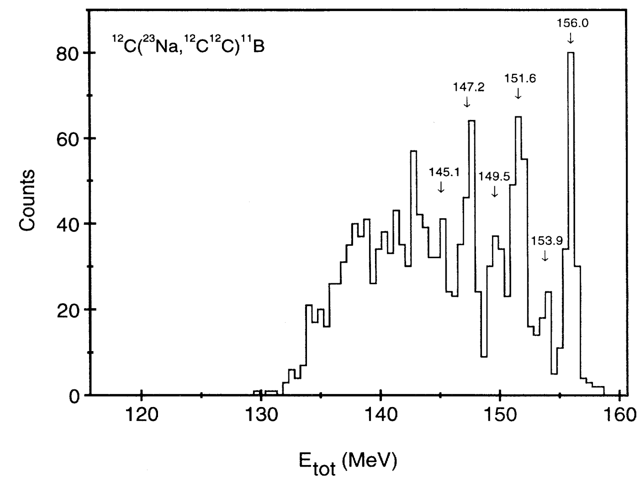

FIG. 3. $E_{\rm tot}$ spectrum for the ^{12}C (^{23}Na,^{12}C ^{12}C)^{11}B reaction.

only from the Q_{ggg} events and, similar to that in Fig. 2, has not been corrected for detection efficiency or Coulomb barrier effects. The resolution and energy calibration are approximately the same as for the ^{12}C (^{23}Na,^{11}B$_{\rm g.s.}$ ^{12}C$_{\rm g.s.}$)^{12}C$_{\rm g.s.}$ data. There are two prominent features in this spectrum at energies of 22.1 and 23.9 MeV and two less prominent features at 20.5 and 24.8 MeV. Again, these structures correlate with the data from all the pairs of detectors so we are confident of the final-state interaction.

III. DISCUSSION

A. The breakup of ^{23}Na

Figure 2 shows the excitation spectrum observed from the breakup of ^{23}Na into ^{11}B and ^{12}C fragments. The spectrum shows an indication of a number of states with energies between 23.6 and 27.8 MeV. Table II gives the energies of these states along with an upper estimate of their width. Using those events in the Q_{ggg} peak of the $E_{\rm tot}$ spectrum an estimate of the breakup cross section can be obtained. For the present measurements a value of 0.078 $\pm$ 0.005 mb sr^{-2} has been obtained. This is an order of magnitude smaller than the value of 0.79 $\pm$ 0.09 mb sr^{-2}, obtained by Fulton *et al.* [4] for the breakup

TABLE II. Energies and widths of the peaks in the ^{23}Na excitation spectrum from the present work compared to energies obtain in previous work.

Present work		Previous work
Energy (MeV)	Upper limit of width (keV)	Energy (MeV)[a]
(23.6)	630	
24.3	680	24.5
(25.9)	570	(25.9)
27.8	570	

[a]Taken from Ref. [15].

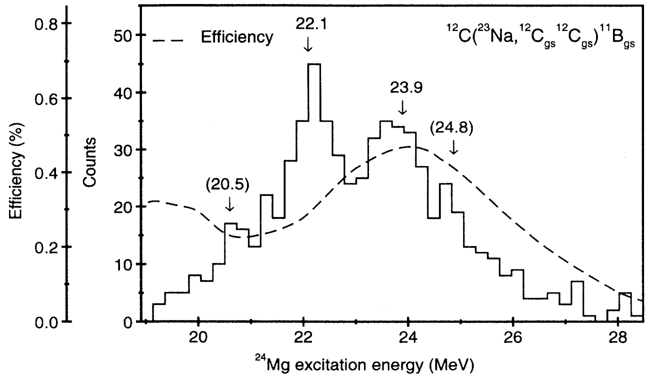

FIG. 4. ^{24}Mg excitation spectrum from the ^{12}C (^{23}Na,^{12}C$_{g.s.}$^{12}C$_{g.s.}$)^{11}B$_{g.s.}$ reaction.

of ^{24}Mg measured under almost identical experimental conditions.

Due to the low yield in the present data it has not been possible to determine the J^{π} of any of these states from an analysis of the angular correlation of the fragments. The low yield also makes a comparison of the present data with those of Frawley *et al.* [15,16] and Feldman and Heikkinen [14] difficult and it is not possible to make unambiguous correspondence between the states seen in the three sets of measurements. However, based on the energies of the states it is possible to make some tentative links. These are shown in column three of Table II; they suggest that in the present experiment we are exciting the same states as seen in the scattering resonance and radiative capture experiments

B. The breakup of ^{24}Mg

The excitation spectrum observed for the symmetric breakup of ^{24}Mg formed by proton transfer to ^{23}Na is shown in Fig. 4. This shows four possible breakup states with energies between 20 and 25 MeV, the energies and corresponding upper limit for the widths of the peaks observed in the spectrum are given in Table III. If the present data are compared with those of Fulton *et al.* [4] measured using a ^{24}Mg beam then two major differences are obvious. First, there is little correspondence between the states excited in the two measurements. Fulton *et al.* observe seven narrow states in the excitation energy region 20 to 25 MeV whereas in the present measurements only four relatively broad states are observed. There is

TABLE III. Energies and widths of the peaks in the ^{24}Mg excitation spectrum for the present work.

Present work	
Energy (MeV)	Upper limit of width (keV)
(20.5)	1250
22.1	1360
23.9	800
(24.8)	(460)

also no correspondence in the energies of the states seen in the two measurements. The second major difference between the two measurements is the yield of the reaction. For the present data the yield is measured to be 0.069 ± 0.005 mb sr^{-2} and this compares with 0.79 ± 0.09 mb sr^{-2} measured by Fulton *et al.* As the experimental conditions under which the two measurements were made were very similar the difference in the cross section must be due to the different mechanisms which populate the breakup states. The differences in the spectra observed in the two measurements give a strong indication that the two excitation mechanisms do not populate the same structures.

Another measurement of the ^{12}C (^{24}Mg,^{12}C ^{12}C)^{12}C reaction was made by Wilczynski *et al.* [6], using a much higher beam energy of 357 MeV. This produced an excitation spectrum which is very similar to that obtained in this work. The states reported in Ref. [6] were located at excitation energies of 21.9, 23.6, and 24.8 MeV, in good agreement with three of the states observed in the present work. A state at 22.1 MeV is also reported in the 2^+ strength of the electrofission measurements of Sandorfi *et al.* [10,11] and one at 23.9 MeV in the radiative capture measurements [8–10]. The observation [8] of high energy photons from each of these states to the ground state of ^{24}Mg identifies them as having spins of 2^+. This is consistent with the electrofission work, which reported a 2^+ angular distribution for the state at 22.0 MeV, and also with the alpha-induced fission work [21], which found a 2^+ total angular distribution for the region 23–29 MeV. It has been suggested [5,6,8,21] that the 2^+ states seen in this energy region in ^{24}Mg could originate from the high energy tail of the $E2$ giant quadrupole resonance (GQR). This interpretation would be consistent with the observation of the same states in the ^{12}C (^{23}Na,^{12}C ^{12}C)^{11}B reaction, as the GQR is an excitation of a particle-hole nature, and one would also expect proton transfer to populate $1p1h$ states. In contrast, the states reported by Fulton *et al.* with J^{π} values of 4^+ to 8^+ cannot originate from the GQR and hence must be of a different origin.

IV. SUMMARY AND CONCLUSIONS

In the present work the breakup of ^{23}Na into ^{11}B + ^{12}C fragments has been observed, following the interaction of a 176 MeV ^{23}Na beam with a carbon target. The reaction yield is approximately one order of magnitude smaller than that for the breakup of ^{24}Mg into ^{12}C + ^{12}C measured, by Fulton *et al.* [4], using a 170 MeV ^{24}Mg beam interacting with a carbon target. The breakup states observed in the present work have energies similar to those observed in ^{11}B + ^{12}C resonance studies [15,16] and the ^{11}B + ^{12}C radiative capture measurements [14].

The symmetric breakup of ^{24}Mg produced by one proton transfer to the ^{23}Na projectile was also observed. In this case also the yield was approximately one order of magnitude smaller than when the ^{24}Mg was used as the projectile [4]. Additionally, the spectrum of states observed in the present work was different from that observed by Fulton *et al.* [4] but is similar to that observed by Wilczynski *et al.* [6] at 375 MeV.

At this point it should also be noted that in the study of ^{25}Mg breakup following its interaction with a carbon target, Gyapong *et al.* [13] found no evidence for the breakup of ^{25}Mg but they did observe the symmetric breakup of ^{24}Mg formed by a one neutron transfer from the target. The yield for this reaction was approximately two orders of magnitude smaller than that observed when the ^{24}Mg was used as the projectile.

The evidence of the present work and associated studies [14–16] strongly suggests that a different reaction mechanism is responsible for the population of the breakup states observed by Fulton *et al.* and those reported in this paper and associated measurements [13].

Recent calculations by Rae and Merchant [22] suggest that a major component in the breakup of ^{24}Mg observed by Fulton *et al.* may result from the reaction proceeding via a highly deformed band in the ^{36}Ar compound nucleus. The state formed in ^{36}Ar decays via the ^{12}C + ^{24}Mg channel leaving the ^{24}Mg in states that breakup to ^{12}C + ^{12}C. Among the other reaction mechanisms that could contribute to the yield would be inelastic excitation of the ^{24}Mg prior to breakup or massive (^{12}C) transfer. The compound nucleus mechanism could explain the J^π values of 4^+, 6^+, and 8^+ reported in Ref. [4] and the fact that they do not observe any states with $J^\pi=2^+$ would indicate that the yields from other mechanisms such as inelastic excitation were much smaller than that for the compound nucleus mechanism.

The difference in the yield for the breakup of ^{23}Na reported in this paper and that for the breakup of ^{24}Mg reported by Fulton *et al.* can also be explained on the assumption that two or more mechanisms contribute to the ^{24}Mg yield but only the noncompound mechanisms contribute to the ^{23}Na breakup, as there is no suitable band in the appropriate compound nucleus, ^{35}S. Similarly, the breakup of ^{24}Mg produced by proton transfer could also not proceed via the compound nucleus reaction.

The similarity between the ^{23}Na breakup states and those observed in electrofission and in the ^{11}B and ^{12}C resonance studies indicates that the reaction mechanism responsible for their excitation could well be inelastic excitation.

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