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Evidence for a dissipative friction mechanism based on ^{8}Be fragments from the interaction of ^{12}C with ^{59}Co

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Abstract. It is suggested that the spectra of the ^{8}Be ground-state (gs) nuclei produced in the interaction of ^{12}C with ^{59}Co at incident energies varying from 8.3 to 33.3 MeV/amu can be explained by introducing a dissipative friction interaction mechanism preceding projectile break-up.

PACS. 25.70.Gh Compound nucleus – 25.70.Jj Fusion and fusion-fission reactions

Efforts to interpret the continuum spectra of intermediate-mass and heavy fragments produced in the interaction of light-heavy projectiles ($A \leq 20$) with nuclei have been reported since about the late seventies. These studies involved a variety of different projectiles with incident energies of typically a few tens of MeV/amu. One of the most extensively investigated cases was the emission to the continuum of a stable projectile fragment in the transfer of one α particle from the projectile to the target (see for example [1–9]). More recently, the emission to the continuum of the projectile fragments produced in the transfer of a single nucleon from the projectile to the target was thoroughly investigated. A recent work [10] gives extensive reference to these investigations.

In this study we focus on the analysis of the spectra of the fragments produced in the transfer of one α particle from the projectile to the target. Earlier studies [1–6] already suggested that the spectra of these fragments have at least two [1,2,4,6] and maybe even three components [5]. The *first component* is predominant at small emission angles and corresponds to the break-up of the projectile as described by a perturbative Serber approximation [4, 11,12]. This contribution may also be called *far break-up* and shows a maximum at the energy corresponding to the beam velocity, with a width related to the momentum distribution of the observed fragment within the projectile. The *second contribution* peaks at a lower emission energy and has a larger width. According to Udagawa *et al.* [1–3] it may be due to a different mechanism, which these authors assumed to be a *direct transfer* of an α particle from the projectile to the target. In this case the spectrum of the fragment depends on the dynamics of the interaction and not simply on its momentum distribution within the projectile. Hussein *et al.* [5], however, assumed that this contribution originates from a final re-scattering of the observed fragment in the target field, where the fragment is still assumed to be produced in projectile break-up. Martinez and Reif [6] considered also processes in which the heavy projectile fragment is produced in a binary break-up process and subsequently undergoes a dissipative interaction with the target nucleus, while Möhring *et al.* [7,8] considered a friction force acting between the projectile and the target *before* the breaking-up of the former. Finally, Hussein *et al.* [5] suggested a *third contribution* to the observed fragment spectra due to complex multistep processes.

We have decided to investigate this phenomenon further by considering the interaction of ^{12}C with ^{59}Co at incident energies varying from 8.3 to 33.3 MeV/amu, leading to the emission of unbound $^{8}Be_{gs}$ fragments. The observation of $^{8}Be_{gs}$ is of particular interest since it is very unlikely that these ejectiles will survive final state interactions to any significant degree. The $^{8}Be_{gs}$ spectra have been measured at forward angles (between 7° and 20°) with a detector telescope containing a position-sensitive Si strip detector, which allows for coincidence measurements of the correlated break-up α particles from the decay of $^{8}Be_{gs}$. The experiment was made at the National Accelerator Centre, Faure, South Africa and the details of the experimental set-up will be discussed elsewhere [13]. Figure 1 shows the inclusive cross-sections of $^{8}Be_{gs}$ fragments emitted in the interaction of ^{12}C with ^{59}Co at the

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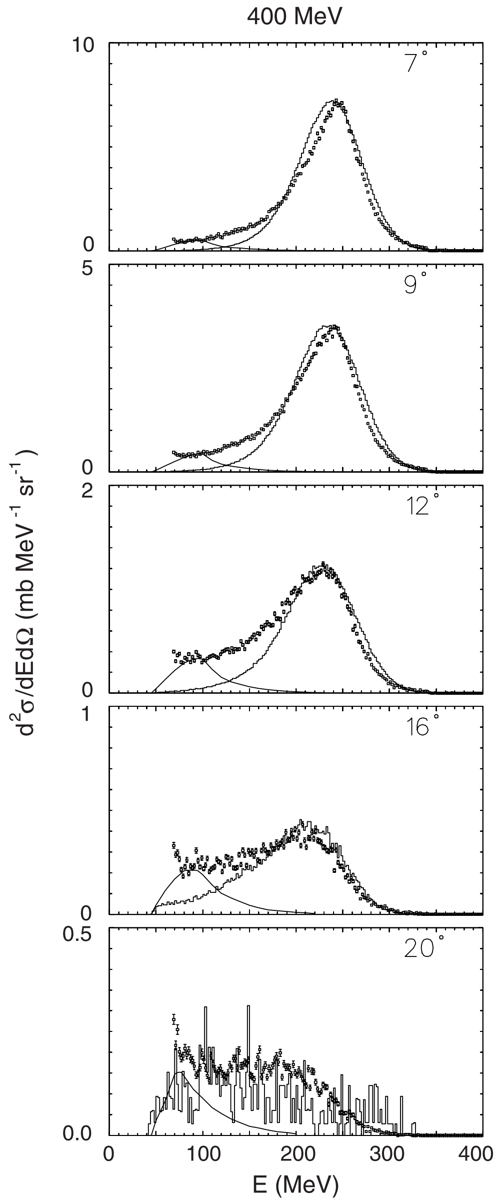

Fig. 1. Double differential cross-sections of the ^{8}Be$_{gs}$ fragments observed at the indicated angles in the interaction of 400 MeV ^{12}C ions with ^{59}Co. The open points are the experimental results, the full-line histograms the predicted spectra which are separately normalized (at each angle) to the measured spectra. The full lines give the contribution predicted by the BME theory.

incident energy of 33.3 MeV/amu. These spectra qualitatively display the same features which also characterize the spectra of stable fragments, *i.e.* a maximum centered at a value corresponding to the beam velocity (at the lower emission angles) and a width considerably larger than that expected on the basis of a perturbative *far breakup* mechanism. With increasing emission angle, the spectrum broadens and at 20° the peak in the spectrum has become almost completely flattened.

If one assumes that it is most unlikely for a ^{8}Be fragment to survive and remain in the ground state after a violent final-state interaction, one can discard those mechanisms describing such processes [5,6]. We may further explore the possibility that the large energy transfer associated with the production of ^{8}Be$_{gs}$ fragments with energies considerably smaller than the value corresponding to the beam velocity may perhaps be due to the fact that *before* breaking up, the ^{12}C suffers a considerable energy loss. Hence, we assume that when moving in the field of the target nucleus, the ^{12}C projectile loses energy in a continuous way (by a type of *nuclear friction* mechanism) thereby exciting the target, with the possibility of breaking up or transferring nucleons to the target nucleus in the course of this interaction. Friction dissipative interactions have been considered in the literature (see for example [6–9,14–18]) and such interactions may lead to a considerable reduction of the kinetic energy of the projectile prior to other interactions in which it does not survive. We further assume that the trajectories of surviving ^{12}C ions are not significantly altered by the slowing-down (friction) process. As a first approximation we adopt a ^{12}C survival probability of $P(E_l) = 1$ for values of the energy loss E_l smaller than a certain limit $E_{l,\min}$. Consequently, in the region $E_l < E_{l,\min}$ the break-up cross-section should be zero.

If one assumes, for simplicity, a constant energy loss per unit length $-\mathrm{d}E_l/\mathrm{d}x = 1/k$ and a constant break-up and mass transfer probability k' per unit length when $E_l > E_{l,\min}$, one immediately obtains for the ^{12}C survival probability $P(E_l)$ after a total energy loss E_l,

$$P(E_l) \propto \exp\big[-kk'(E_l - E_{l,\min})\big]. \qquad (1)$$

We further assume that the multiplicity spectrum $\mathrm{d}^2N^S(E_C, E', \Theta)/(\mathrm{d}E'\mathrm{d}\Omega)$ (normalized to unity when integrated over the energy and the solid angle) of the ^{8}Be$_{gs}$ fragments which are produced when the ^{12}C initial kinetic energy E_o is reduced to $E_C = E_o - E_l$, may still be evaluated in the Serber approximation [11,12]. Ultimately, as the survival probability decreases with increasing energy loss, a point is reached where further ^{12}C survival is unlikely. We then obtain for the break-up spectra of ^{8}Be$_{gs}$,

$$\frac{\mathrm{d}^2N}{\mathrm{d}E'\mathrm{d}\Omega}(E_o, E', \Theta) = \frac{\int_0^{E_o} P(E_l)S(E_C, E', \Theta)\mathrm{d}E_l}{\int_0^{E_o} P(E_l)\mathrm{d}E_l}, \qquad (2)$$

where

$$P(E_l) = 1 \quad \text{for } E_l < E_{l,\min},$$
$$P(E_l) = \exp[-kk'(E_l - E_{l,\min})] \quad \text{for } E_{l,\min} \le E_l \le E_o,$$

and

$$S(E_C, E', \Theta) = 0 \quad \text{for } E_l < E_{l,\min},$$
$$S(E_C, E', \Theta) = \frac{\mathrm{d}^2N^S(E_C, E', \Theta)}{\mathrm{d}E'\mathrm{d}\Omega} \quad \text{for } E_l \ge E_{l,\min}.$$

The sharp limit $E_{l,\min}$ should not be seen as anything more than the consequence of introducing the nuclear friction in a rather simplistic approximation. However, our

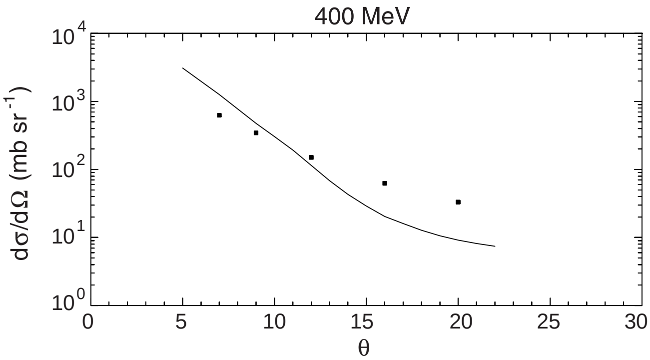

Fig. 2. Comparison of the measured (full points) and calculated (full line) angular distributions of the energy-integrated $^{8}\mathrm{Be}_{\mathrm{gs}}$ cross-sections at an incident ^{12}C energy of 400 MeV.

current approach is to retain this limit until the characteristics of the friction interaction are better understood over the entire energy region of interest.[1] In the present study its value, as well as the value of kk', are obtained from fits to the experimental data. While the part of the spectrum to the right of the maximum of the break-up peak depends sensitively on the values of $E_{l,\min}$ and kk', the spectrum to the left is more determined by the value of kk'. By using values of 53 MeV and 0.03 MeV^{-1} for $E_{l,\min}$ and kk', respectively, spectra of $^{8}\mathrm{Be}_{\mathrm{gs}}$ are calculated, which are shown by the histograms in fig. 1. These show that the shape of especially the higher energy part of the measured spectra is reproduced satisfactorily.

However, in agreement with the suggestions of Hussein *et al.* [5], we also find that a further contribution, which increases with increasing emission angle θ, must be added at the lower emission energies. Intermediate-mass fragments (including ^{8}Be) may be produced by a mechanism which is very different from that considered above. This is the *coalescence* of nucleons during the cascade of nucleon-nucleon interactions which mainly occurs when the projectile fuses with the target. We have evaluated the spectra of the ^{8}Be fragments which are produced in this way with the Boltzmann Master Equation (BME) theory, as suggested in [19]. These contributions to the spectra are calculated using a set of parameters which are consistent with those used in our previous calculations [19,20], and are given by the full lines in fig. 1 without any further normalization.

It is rather encouraging that the broad peak in the spectra, so evident at the smaller angles, almost disappears at 20° both in the measured and in the calculated spectra. It should be noted that at each angle, in fig. 1, the break-up contribution was separately normalized to the data. However, the change in normalization with angle is not dramatic. In fact our calculation allows a reasonable estimate of the absolute cross-sections of the measured spectra. If one multiplies the energy-integrated multiplicity spectra by a cross-section value of $\sigma = 225$ mb (for all angles) and adds the contribution predicted by the BME theory, the angular distribution predicted is given by the full line in fig. 2.

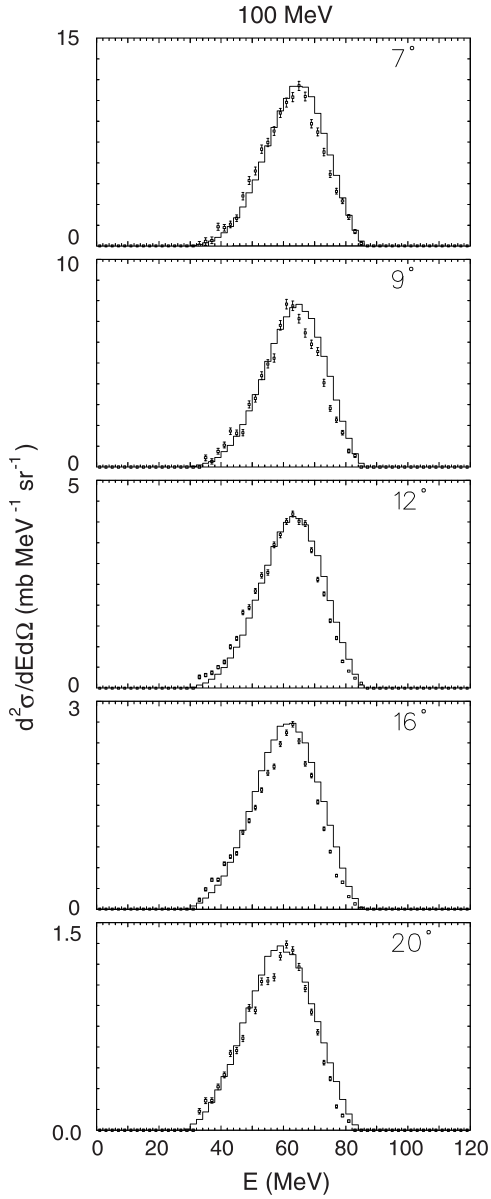

Fig. 3. Double differential cross-sections of the $^{8}\mathrm{Be}_{\mathrm{gs}}$ fragments observed at the indicated angles in the interaction of 100 MeV ^{12}C ions with ^{59}Co. The open points are the experimental results, the full-line histograms the predicted spectra which are separately normalized (at each angle) to the measured spectra.

[1] The assumption of a constant energy loss per unit length along the trajectory of the projectile should not be a bad approximation here since most of the break-up occurs when its velocity (which is the parameter that the energy loss mostly depends on) has not been substantially diminished. According to the calculations the average change in velocity of the projectile associated with its distribution of energy losses is 14% and 21% at incident energies of 400 MeV and 100 MeV, respectively. However, to justify this assumption and to eliminate the need of introducing a sharp cut-off, a more detailed model for the dissipative interaction is required.

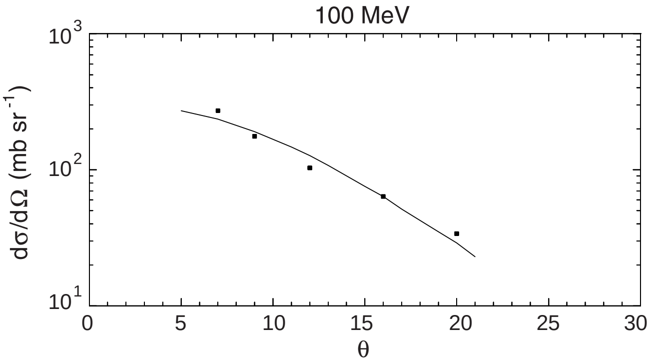

Fig. 4. Comparison of the measured (full points) and calculated (full line) angular distributions of the energy-integrated $^{8}\mathrm{Be}_{\mathrm{gs}}$ spectra at an incident ^{12}C energy of 100 MeV.

At the lowest incident energy employed in this study (8.3 MeV/Amu) one has to expect that a much smaller interval of energy losses should contribute to eq. (2). This is in fact what we observe, as shown in fig. 3, where the theoretical spectra were calculated assuming $E_{l,\min} = 23\,\mathrm{MeV}$ and $kk' = 0.115\,\mathrm{MeV}^{-1}$. At this incident energy the calculations reproduce the observed spectra at all the measured angles without requiring the contribution evaluated with the BME theory, which is indeed predicted to be very small. The trend in angular distribution cross-sections is better reproduced by the theory (see fig. 4). In order to reproduce the observed absolute cross-sections integrated over the energy of the ejectile one must multiply the multiplicity spectra by $\sigma = 50\,\mathrm{mb}$.

To conclude, these calculations reproduce satisfactorily the main features of the measured spectra of the $^{8}\mathrm{Be}_{\mathrm{gs}}$ fragments produced in the interaction of ^{12}C with ^{59}Co at incident energies of 8.3 and 33.3 MeV/amu. It should be noted that, prior to the present experiment in which ^{8}Be fragments are measured explicitly, the available α-particle spectra could be satisfactorily described [12] under the assumption that these unstable fragments are produced only by a far break-up fusion mechanism. However, as may be clearly seen, this mechanism still accounts for the major contribution to the measured inclusive ^{8}Be spectra, and the present results based on additional information are not inconsistent with the earlier conclusions. Clearly this work constitutes an important refinement to the model which we are developing to describe the interaction of ^{12}C with nuclei in a comprehensive way [12].

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