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Emission of Boron Fragments in Reactions Induced by ^{16}O up to 25 MeV/amu

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Abstract.

In this paper we study the emission of B fragments in the interaction of ^{16}O ions with ^{59}Co and ^{93}Nb at incident energies varying from 6 to 25 MeV/amu. As in the case of other intermediate mass fragments (IMF) observed in the same reactions and in reactions induced by other light ions at comparable incident energies, the B spectra are dominated at forward angles by a component originating by break-up of ^{16}O, which at the higher incident energies is found to fragment after a quite sizeable energy loss. Another mechanism, dominating at large emission angles, favours the emission of low energy fragments and is attributed to the coalescence of nucleons during the cascade of N-N interactions by means of which the excited nuclei produced in the primary two-ion interaction thermalize.

1 Introduction

Since its beginning nuclear physics had to deal with nucleon correlations. The emission of α particles by radioactive nuclei was indeed the first truly nuclear phenomenon observed and showed that an unstable nucleus may prefer to emit spontaneously a cluster of particles instead of a single nucleon. Even if the idea, which came from these observations, that nuclei are made of α particles was shown to be incapable of explaining all facets of nuclear structure, many studies have indicated that the concept of α clustering is essential for understanding the structure of light nuclei and is also useful for understanding peculiar features of heavier systems [1].

Nuclear correlations play an ever greater role in nuclear reactions. Emission of clusters, which we call intermediate mass fragments (IMF) if they have $Z \geq 3$, is a quite common feature in heavy ion reactions. Many experimental and theoretical investigations have been made to explain these emissions in the interaction of many different nuclei at relative energies varying from a few up to several hundred MeV/amu (see for instance [2-14] and references therein). The subject is still widely debated and a generally accepted theory which may explain all that is observed is still lacking.

As mentioned above, when an equilibrated excited system decays it is energetically convenient for it to emit clusters of nucleons instead of the single constituents of these clusters. The emission of these clusters, at low excitation energies ($E \leq 100$ MeV) may be statistically and dynamically hindered due to, respectively, the reduction of the available phase space and the high potential barrier which supresses their emission, but with increasing excitation energy to some hundred MeV the emission of even high charge IMF is predicted to become as probable as the emission of low charge ejectiles [2]. On the other hand many dynamical reaction models suggest that it may be difficult to produce highly excited equilibrated nuclear matter and if a large number of IMF emissions is observed these may be due to dynamical effects or to effects related to the internal structure of the interacting ions. The observation, in heavy ion reactions, of a large number of IMF even at rather small incident energies may be an indication of the presence of such effects.

The study of the interaction of light nuclei with more massive partners is presumably a quite simple example of heavy ion interactions and may constitute a bridge between light particle induced reactions of which we have a much deeper understanding [15,16] and the interaction of two massive nuclei. We have undertaken the study of the reactions induced by ^{12}C and ^{16}O ions with energy up to about 50 MeV/amu and in this case too we have found that the emission of IMF is far from being negligible.

This paper is devoted to the study of B fragments produced in the interaction of ^{16}O ions with medium-heavy nuclei such as ^{59}Co and ^{93}Nb at incident energies varying from 6 to 25 MeV/amu.

2 Experimental Results and Qualitative Features of the Observed Spectra

Our data concern the production of B fragments in the interaction of ^{16}O with ^{59}Co and ^{93}Nb at incident energies of 100, 250 and 400 MeV. The spectra of these fragments were measured at the iThemba Laboratory for Accelerator Based Sciences, Somerset West, South Africa (formerly known as the National Accelerator Centre). The experimental details are discussed elsewhere [17].

The identification loci of the IMF which are emitted in the interaction of oxygen with both target nuclei, at all incident energies and both small and large emission angles show that one essentially observes only IMF with charge equal or smaller than the projectile charge. This seems to suggest that these fragments are either produced in the break-up of the projectile or in mass transfer from the projectile to the target or in some more complex process which still mainly involves the projectile's nucleons. Figure 1 shows the spectra of B fragments emitted in the interaction of 400 MeV ^{16}O ions with ^{93}Nb at 8° (black points) and 50°. It is quite clear that these two spectra reflect two different reaction mechanisms. The first has a maximum at an energy exceeding 200 MeV, the second at an energy of about 40 MeV. The intermediate angle spectra, which are shown later, show that there is a gradual transition from one type of energy dependence to the other. The same happens for other IMF produced in light ion interactions at comparable energies [17-19]. At incident energies below about 10 MeV/amu only the highest energy component is observed and its energy dependence does not noticeably change with the emission angle.

It was hypothesized some time ago that the fragments constituting the component of higher energy are produced in the binary fragmentation of the projectile [4,20]. However, a feature was also observed which present experiment confirms, i.e. the average fragment's energy is smaller than that expected for a $pure$ break-up mechanism - that is in the absence of an initial state interaction of

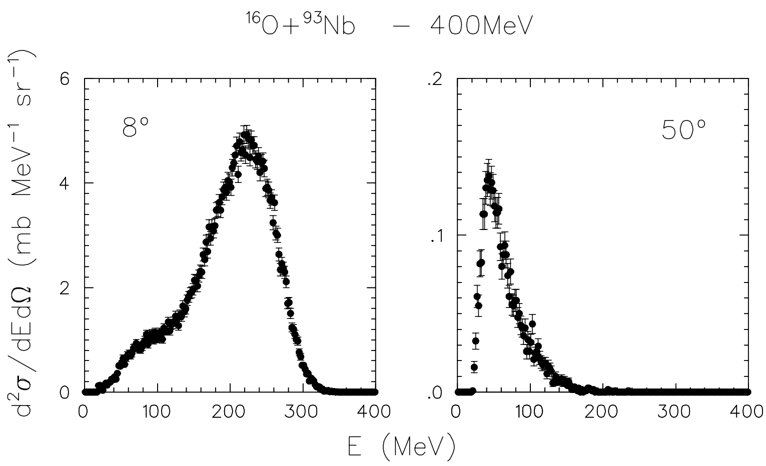

Figure 1. Comparison of the spectra of boron fragments emitted at a small and a large angle.

the projectile before breaking up and/or a final state interaction of the observed fragment. Also, the width of the fragment spectra, which should reflect the fragment's momentum distribution inside the projectile, is considerably larger than expected. In the next section we will try to explain how this may happen.

The component at lower energy in the measured IMF spectra was also observed before [4], however we are not aware of a generally accepted explanation of its presence.

3 Theoretical Analysis

As shown in Figures 2 and 3, at 100 MeV the B spectra have the angular and energy dependence which one expects if they are produced by the projectile's break-up and are quite reasonably reproduced by a *local plane wave approximation* (LPWA) calculation [17,18,20-22]. Things change with increasing energy. The spectra observed at incident energies of 250 and 400 MeV, in Figures 4 to

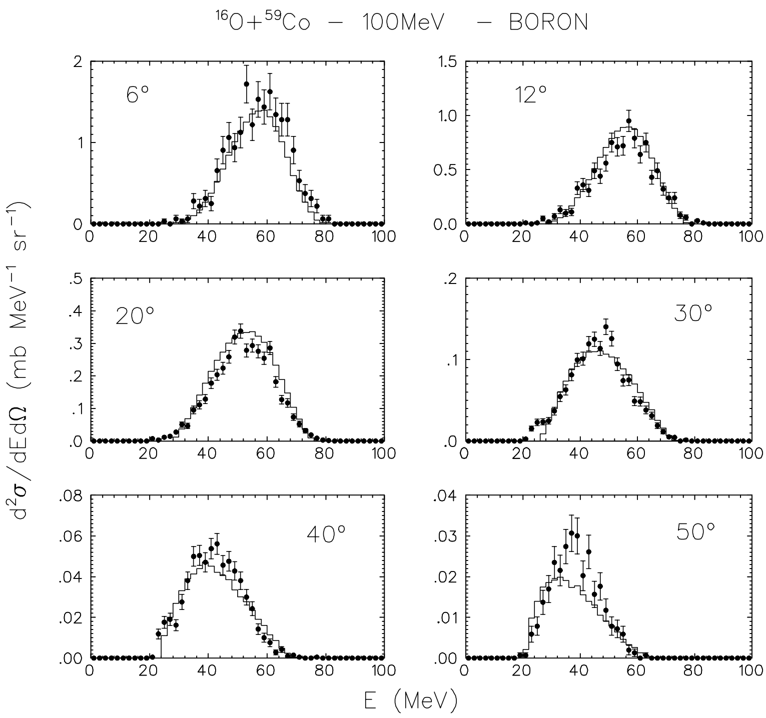

Figure 2. Spectra of boron fragments emitted in the interaction of ^{16}O with ^{59}Co at an incident energy of 100 MeV. The experimental spectra are given by the solid points and the theoretical predictions by the histograms.

7, show two distinct contributions, the one at highest energies dominating at the most forward angles, the other, at the lowest possible energies, dominating at large angles.

The first component, following previous suggestions [4,20], is attributed to the projectile's break-up. However, as mentioned already, it does not completely conform to the expectations because the fragment's average energy is smaller than foreseen and the energy distribution around the mean value too large to be simply due to the fragment's momentum distribution inside the projectile. Later we suggest that this behaviour is due to the energy loss which the projectile may suffer before breaking up.

We suggest that the lowest energy component of the spectra is due to the coalescence of excited nucleons in the course of the equilibration of the intermediate nuclei produced in the two ion partial or complete fusion and will show how well this hypothesis allows one to reproduce the data.

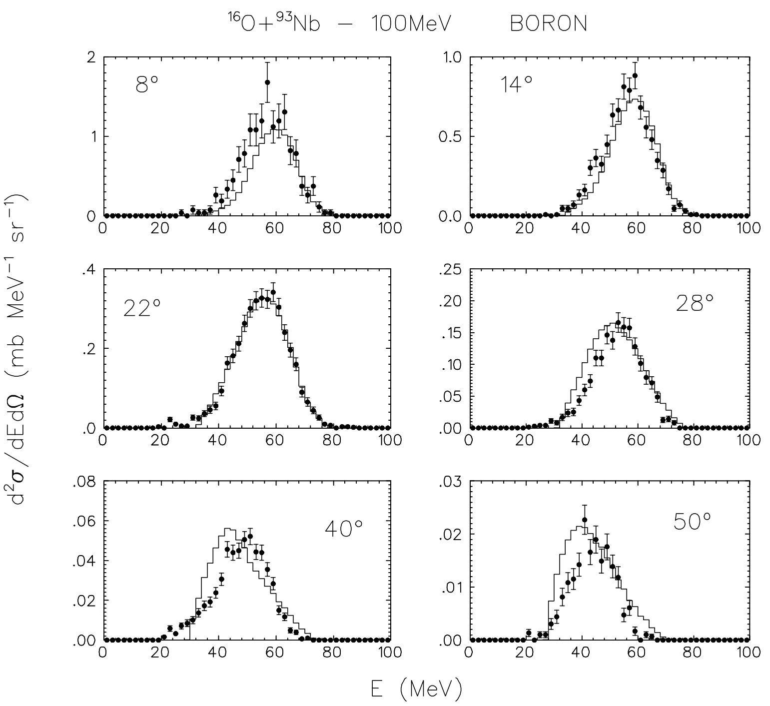

Figure 3. Spectra of boron fragments emitted in the interaction of ^{16}O with ^{93}Nb at an incident energy of 100 MeV. The experimental spectra are given by the solid points and the theoretical predictions by the histograms.

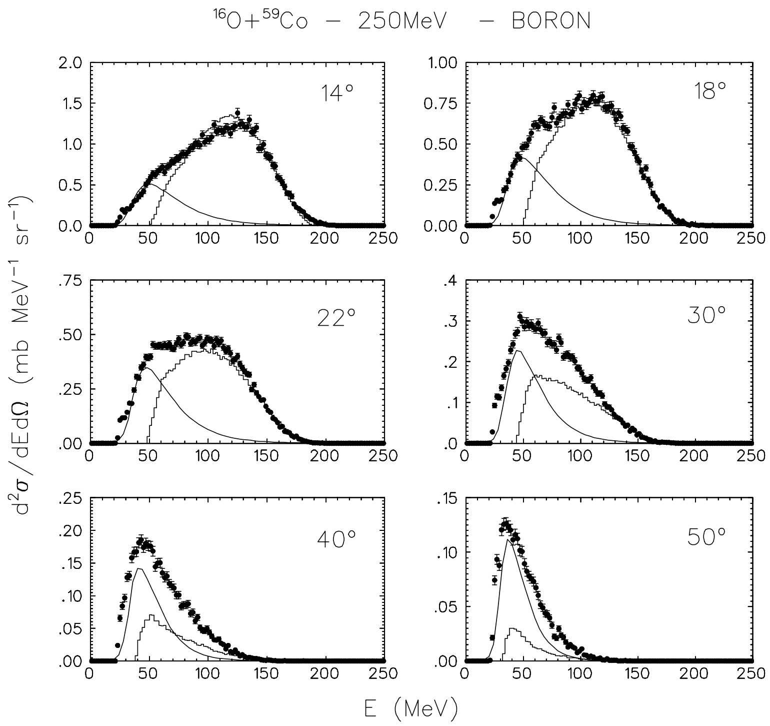

Figure 4. Spectra of boron fragments emitted in the interaction of ^{16}O with ^{59}Co at an incident energy of 250 MeV. The experimental spectra are given by the solid points, the theoretical predictions by the full lines (coalescence) and the histograms (break-up).

3.1 Break-up Fragments

The smaller than expected average energy of the break-up fragments and their wide energy spread around the mean may be explained as due either to an initial state interaction of the projectile and/or to a final state interaction of the observed fragment.

The study of ^{8}Be$_{gs}$ fragments produced in ^{12}C break-up, at energies comparable to the ones we are considering here, suggested the prominence of the initial state interaction [18]. The subsequent analysis of the spectra of C fragments produced in the ^{16}O break-up seems to confirm the validity of this hypothesis [17,19].

One may quite safely assume that projectile break-up, like the projectile inelastic scattering, is a peripheral direct reaction mainly occurring in a window of large angular momenta. It does not seem unrealistic to assume that, in the case of light ions, projectile inelastic scattering and break-up are quite closely linked and

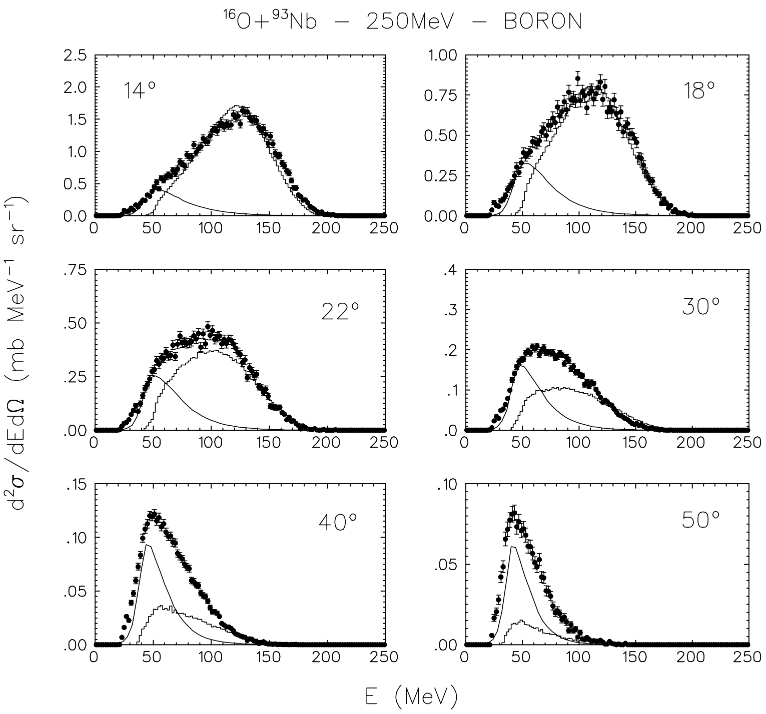

Figure 5. Spectra of boron fragments emitted in the interaction of ^{16}O with ^{93}Nb at an incident energy of 250 MeV. The experimental spectra are given by the solid points, the theoretical predictions by the full lines (coalescence) and the histograms (break-up).

break-up might contribute to the reduction of the flux of the incident ions which are inelastically scattered. We know from experimental observation that inelastically scattered ions may lose a considerable fraction of their energy [23-25] and it does seem quite natural to assume that a considerable energy loss may also occur before the projectile's break-up. We also know that even if collective states of the target nucleus are selectively excited in inelastic scattering, the energy-averaged spectra have a smooth energy dependence and decrease nearly exponentially with increasing ion energy loss. We make the hypothesis that the probability for the incident ions to survive a more disruptive interaction, such as break-up or a mass transfer reaction, has the same energy dependence and consequently we assume that the spectra of fragments produced by projectile's break-up may be evaluated by folding the cross-section evaluated in the LPWA with an exponential survival probability [17,18]. Assuming further that break-up of the incident ion may occur only after a minimal energy loss $E_{l,min}$ we are finally led to the following expression for the double differential cross-section of a fragment emitted at the

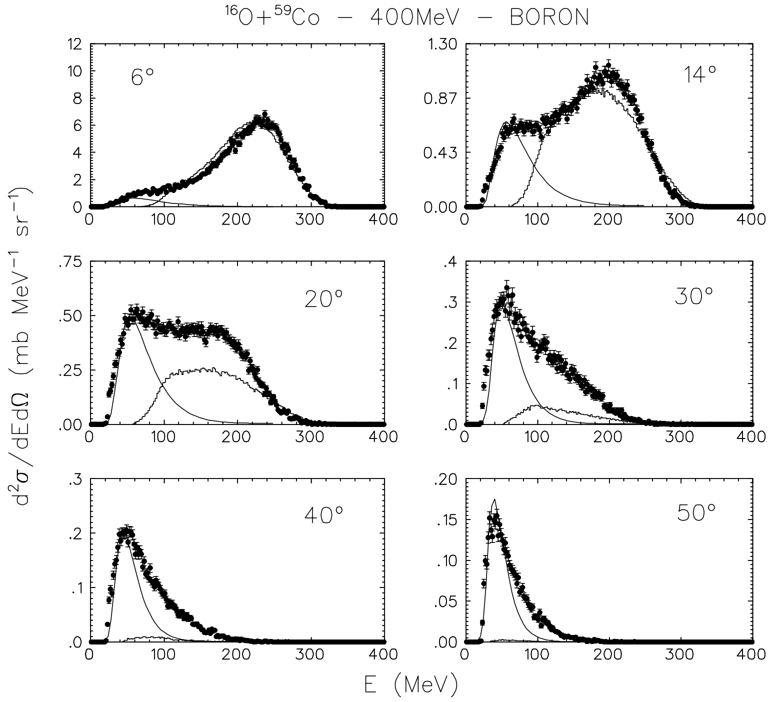

Figure 6. Spectra of boron fragments emitted in the interaction of ^{16}O with ^{59}Co at an incident energy of 400 MeV. The experimental spectra are given by the solid points, the theoretical predictions by the full lines (coalescence) and the histograms (break-up).

angle θ with energy E' in the break-up of a projectile with incident energy E_o :

$$\frac{d^2\sigma}{dE'd\Omega}(E_\circ, E', \theta) = \sigma_{bu} \frac{\int_{E_{l.min}}^{E_\circ} P(E_l)S(E, E', \theta)dE_l}{\int_{E_{l,min}}^{E_\circ} P(E_l)dE_l}, \quad (1)$$

where σ_{bu} is the angle and energy integrated cross section for production of the considered fragments and E_l is the projectile's energy loss. The survival probability $P(E_l)$ is given by:

$$P(E_l) = \exp[-C(E_l - E_{l,min})] \quad (2)$$

and

$$S(E, E', \theta) = d^2\sigma^S(E, E', \theta)/dE'd\Omega \quad (3)$$

where $E = E_o - E_l$ and $d^2\sigma^S(E, E', \theta)/dE'd\Omega$ is the fragment's cross section evaluated in the LPWA. This is given by

$$\frac{d^2\sigma^S(E, E', \theta)}{dE'd\Omega} \propto P' \quad P'' \quad |\psi(\mathbf{p})|^2, \quad (4)$$

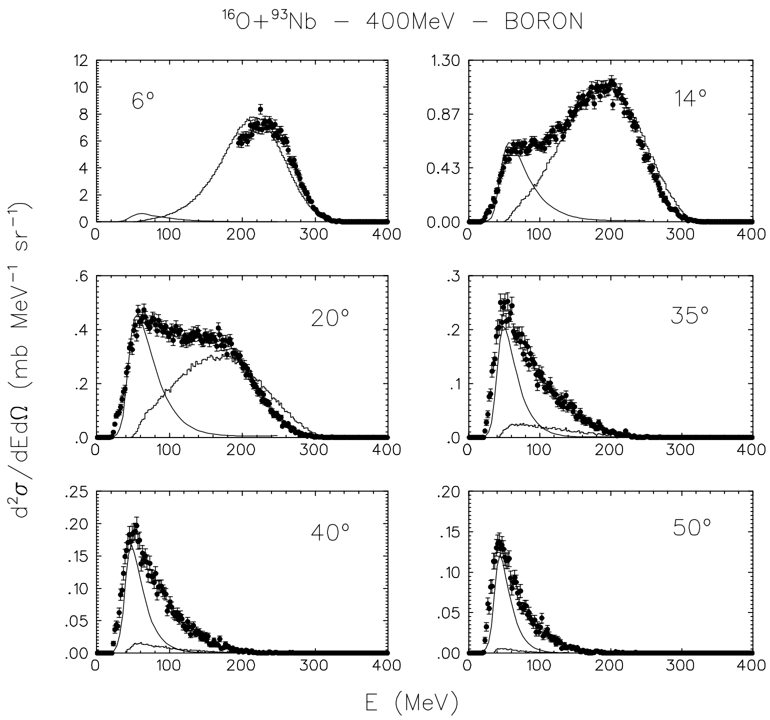

Figure 7. Spectra of boron fragments emitted in the interaction of ^{16}O with ^{93}Nb at an incident energy of 400 MeV. The experimental spectra are given by the solid points, the theoretical predictions by the full lines (coalescence) and the histograms (break-up).

where the function $\psi(\mathbf{p})$ is the Fourier transform of the wavefunction describing the relative motion of the fragment within the projectile :

$$\psi(\mathbf{p}) = \frac{1}{(2\pi\hbar)^{3/2}} \int \psi(r) \exp[-\frac{i}{\hbar}(\mathbf{p}\cdot\mathbf{r})] d\mathbf{r}. \tag{5}$$

The fragment momentum within the projectile is given by :

$$\mathbf{p} = \mathbf{P'} - (m_f/m_P)\mathbf{P}, \tag{6}$$

where **P** is the projectile's momentum when it breaks-up (that is after the energy loss) and $\mathbf{P}'$ is the momentum of the observed fragment just after break-up. This differs from the observed fragment's momentum since after being produced the fragment is boosted by the coulomb repulsion. P'' is the modulus of the momentum of the unobserved fragment and m_P and m_f are, respectively, the masses of the projectile and the observed fragment. The fragment separation energies favour the break-up of ^{16}O into ^{11}B and ^{5}Li. The analysis of the spectra seems indeed to suggest that one observes mainly ^{11}B fragments with only a minor contribution of ^{10}B fragments produced in the break-up of ^{16}O into ^{10}B and ^{6}Li. The spectra of B fragments produced by projectile break-up are given by the histograms in Figures 2 to 7. The values of the parameters C and $E_{l,min}$ for each target nucleus at a given energy are obtained by a best fitting of the experimental spectra. The most interesting quantity is the average kinetic energy loss of the projectile before break-up. At 100 MeV incident energy the kinetic energy loss $\overline{\Delta E}$ is essentially that part of the incident energy which transforms into coulomb potential energy and is in part given back to the spectator fragment when it is boosted by the coulomb repulsion after break-up. At 250 and 400 MeV incident energies the average kinetic energy loss is considerably greater than the coulomb repulsion between the projectile and the target. The values of $\overline{\Delta E}$, which we have found at these incident energies for companion fragments, such as ^{12}C [17] and ^{14}N [26], are given in Table 1. The comparison of these values seems to indicate that $\overline{\Delta E}$ slightly decreases with increasing the mass of the observed fragment. This does not seem unreasonable if the projectile break-up is in most cases accompanied by the fusion of the participant fragment with the target nucleus, since in this case it is reasonable to assume that the angular momentum of the projectile increases with decreasing mass of the participant fragment [27,28] with a corresponding decrease of its energy loss.

Table 1. Values of the average energy losses $\overline{\Delta E}$ of ^{16}O ions interacting with ^{59}Co and ^{93}Nb before breaking-up into the various fragments. E$_{inc}$ is the incident energy and σ_{bu} the angle and energy integrated break-up cross section.

^{59}Co				^{93}Nb			
E_{inc} (MeV)	Frag.	$\overline{\Delta E}$ (MeV)	σ_{bu} (mb)	E_{inc} (MeV)	Frag.	$\overline{\Delta E}$ (MeV)	σ_{bu} (mb)
250	^{10}B	91	3	250	^{10}B	88	29
250	^{11}B	91	63	250	^{11}B	88	45
250	^{12}C	80	181	250	^{12}C	87	150
250	^{14}N	66	88	250	^{14}N	75	50
400	^{10}B	125	23	400	^{10}B	129	20
400	^{11}B	125	85	400	^{11}B	129	100
400	^{12}C	89	288	400	^{12}C	94	339
400	^{14}N	87	108	400	^{14}N	82	75

The agreement between the experimental and calculated spectra is very encouraging considering the simplicity of our approach. Nevertheless one may see that, especially at the higher incident energies, our calculation underestimates the yield of break-up fragments emitted at the larger angles. This is presumably due to the use of a folding function (2) which depends only on energy. It is conceivable that to larger angle emissions may contribute fragments produced in the break-up of incident ions deflected to rather large angles with spectra decreasing more gently with increasing loss of energy. So, both the amplitude of the folding function and the parameter C in (2) should display an angular dependence which in this first approximation approach we have neglected. We expect that inclusion of such dependences, which is actually under study, will increase quite substantially the large angle yield of break-up fragments, improving the agreement of experimental and calculated spectra.

Even if we do not offer a detailed dynamical description of the process by which the projectile loses energy before break-up, it is conceivable that this energy loss occurs while the two ions approach each other and start to come into contact. Break-up follows or accompanies this energy loss. After that, both fragments may fly out or the participant fragment may more or less violently interact or even fuse with the target nucleus. The observation of only the spectator fragments cannot tell us what happens, however on the basis of the comparison of the experimental and calculated cross sections for residue production in the interaction of ^{12}C and ^{16}O with nuclei at incident energies comparable to the ones which we consider in this paper [29,30], and of the measured and calculated recoil properties of these residues (ranges, angular distributions and γ-lines doppler shifts and broadenings) [30,31] we are inclined to think that in a large fraction of the cases the projectile's break-up is followed by the fusion of the participant fragment with the target nucleus.

3.2 Coalescence Fragments

In addition to breaking-up or transferring nucleons to the target, the projectile may fuse with the target nucleus. The fusion of the projectile or part of the projectile with the target nucleus produces an excited intermediate system which is far from statistical equilibrium which is reached by means of a cascade of nucleon-nucleon (N-N) interactions. In the course of this cascade, nucleons or clusters of nucleons may be emitted with higher energies than those with which they would be emitted by an equilibrated system, and, in the case of protons and clusters, a yield much higher than that one would expect from the decay of an equilibrated nucleus.

We describe the cascade of nucleon-nucleon interactions by means of the Boltzmann Master Equation (BME) theory [32,33] which we have developed from the original proposal of Harp, Miller and Berne [34] including in particular the emission of clusters created by nucleon coalescence [35,36]. The BME theory is described in many papers of our group [17,19,32,33,35-37] and does need to be repeated here. However we cannot avoid giving a brief discussion of the main physical assumptions and showing a few formulae even without giving a justification of them.

In this theory the states of the nucleus are described by the nucleon momentum distributions which are given by the occupation probabilities of an ensemble of bins in the nucleus momentum space. We consider bins which, apart from boundary effects, have a constant volume in this space. As long as one evaluates observables such as particle spectra which are averaged over many possible sequences of events one may assume azimuthal symmetry with respect to the beam direction and thus one can characterize the bins by only two independent variables, p^2 and p_z, the square of the nucleon's momentum and the component of the momentum along the beam axis. The bins are thus characterized by constant values of Δp^2 (or $\Delta\epsilon$) and Δp_z. The bin indices i, j, l, m in the following set of BME characterize momentum space intervals with volume $V_p \propto \Delta\epsilon\Delta p_z$ centered around given values of the energy ϵ_i, and $(p_z)_i$. The bin occupation probabilities as a function of time may be indicated either as $n_i(p^2, p_z, t)$ or $n_i(\epsilon, \theta, t)$, where θ is the angle between the nucleon and the projectile direction. The interaction of the two ions (complete or partial fusion) produces a nucleus in a state which is described by the occupation probabilities $n_i(\epsilon, \theta, t = 0)$. The subsequent evolution of this system towards equilibrium is simulated by the set of Boltzmann Master Equations (BME) which is given below, the solution of which gives $n_i(\epsilon, \theta, t)$ [32,33]. Elastic N-N collisions bring the nucleons from the centre of one bin to the centre of another one. With an appropriate ordering of the bins one may label each of them by just one index and, describing the nucleus as a two-fermion gas, one may formally write separately sets of BME for the proton and the neutron gases. For the proton gas we have

$$\begin{aligned}\frac{d(n_i g_i)^\pi}{dt} = &\sum_{jlm}[\omega^{\pi\pi}_{lm\to ij} g^\pi_l n^\pi_l g^\pi_m n^\pi_m (1-n^\pi_i)(1-n^\pi_j) \\ &- \omega^{\pi\pi}_{ij\to lm} g^\pi_i n^\pi_i g^\pi_j n^\pi_j (1-n^\pi_l)(1-n^\pi_m)] \\ &+ \sum_{jlm}[\omega^{\pi\nu}_{lm\to ij} g^\pi_l n^\pi_l g^\nu_m n^\nu_m (1-n^\pi_i)(1-n^\nu_j) \\ &- \omega^{\pi\nu}_{ij\to lm} g^\pi_i n^\pi_i g^\nu_j n^\nu_j (1-n^\pi_l)(1-n^\nu_m)] \\ &- n^\pi_i g^\pi_i \omega^\pi_{i\to i'} g^\pi_{i'} \delta(\epsilon^\pi_i - \epsilon^\pi_F - B^\pi_i - \epsilon^\pi_{i'}) - \frac{dD^\pi_i}{dt},\end{aligned} \tag{9}$$

where π and ν indicate the protons and the neutrons respectively. An analogous set of equations holds for the neutron gas.

The quantities g_i are the total number of states in bin i. The quantities $\omega_{ij\to lm}$, $\omega_{i\to i'}$ and dD_i/dt are, respectively, the internal transition decay rates, the decay rates for emission of single protons of the i^{th} bin into the continuum, and a depletion term which accounts for the emission of protons of the i^{th} bin which are part of a cluster [35,36]. In fact, it is assumed that during the cascade of N-N interactions a cluster may be formed by coalescence of nucleons whose momenta fall into a sphere of radius $p_{c,F}$ in momentum space. The multiplicity spectrum of the clusters emitted with energy $E_c^{'}$ is given by

$$\frac{d^2M_c(E_c', \theta_c)}{dE_c' d\Omega} = \frac{R_c}{2\pi \sin\theta} \int N_c(E_c, \theta_c, t) \frac{\sigma_{inv,c} v_c}{V} \rho_c(E_c', \theta_c) dt, \qquad (10)$$

where $N_c(E, \theta_c, t)$ is the cluster state occupation probability within the excited nucleus at time t and is a function of the state occupation probabilities $n_i(\epsilon, \theta, t)$ of the nucleons constituting the cluster. For a cluster constituted by Z_c protons and N_c neutrons, it is given by :

$$N_c(E, \theta_c, t) = \Pi_i (n_i^{\pi}(\epsilon, \theta, t))^{P_i(E_c, \theta_c) Z_c} \cdot \Pi_i (n_i^{\nu}(\epsilon, \theta, t))^{P_i(E_c, \theta_c) N_c}, \quad (11)$$

where the index i runs over all the bins in which fall the momenta of the protons and the neutrons of the cluster, and $P_i(E_c, \theta_c)$ is the fraction of bin i which falls within the fermi sphere of the cluster c of radius $p_{c,F}$. $\sigma_{inv,c}$ is the inverse process cross section, v_c the relative velocity between the emitted cluster and the residual nucleus, and V the laboratory volume which cancels with an equal term appearing in the expression of $\rho_n(E_c', \theta_c)$, the density of cluster states in the continuum. R_c is a numerical factor (≤ 1) which gives the joint probability that the nucleons constituting the cluster be within the cluster volume in co-ordinate space and that the cluster once formed be emitted before dissolving again into its constituents.

We cannot discuss here the parameters which may influence the calculated multiplicity spectra. A detailed discussion is given in a paper which should appear shortly [17]. We may summarize the main results of that discussion as follows:

(a) Several isotopes (which are not discriminated in the experiment) may contribute to the coalescence spectrum. We have considered the contribution of B isotopes with mass varying from 8 to 14. Their relative yield depends on their mass number A, the mass excess (which influences their emission energy) and their spin. They may be produced with comparable yield both in the complete fusion of oxygen with the target nucleus and in the partial fusion of an oxygen fragment.

(b) One important parameter is the cluster fermi energy $E_{c,F} = p_{c,F}^2/2m$ (where m is the nucleon mass) for which we take the value predicted by the liquid drop model as a function of the cluster charge and mass and the nuclear matter fermi energy E_F [37] for which we take the value of 43.5 MeV. This quite large value may be an effective way of simulating the emission of slightly excited clusters. The corresponding values of the fermi energy of B isotopes vary from 29.3 MeV (^{8}B) to 32.1 MeV (^{14}B)

(c) the nuclei at the moment of cluster emission may be deformed. We assume that they may have the shape of rotational ellipsoids with symmetry axis in the beam direction. The ratio of the minor to the major axis is about 0.6 for nuclei created in the interaction with ^{59}Co and 0.9 for those created in the interaction with ^{93}Nb. This deformation produces an angular dependence of the emitted cluster coulomb barrier which explains the notable energy shift of the maximum of the calculated coalescence spectrum at a forward and a large emission angle which cannot be explained as being simply due to the transformation from the CM to the Lab system.

One must finally remark that even assuming that, once the two ions or part of them overlap, the evolution toward equilibrium is mainly ruled by N-N collisions, mean field effects are far from being negligible. For instance, at 100 MeV, the overlap of the two ions slowed by their coulomb repulsion takes so long that the thermalization occurs while they still form a dinuclear system and a large part of the coulomb potential energy is not yet re-transformed into nucleon kinetic energy [38]. This greatly hinders the emission of fast particles during thermalization and this is the reason why the low energy B fragments produced by nucleon coalescence are not observed at 100 MeV incident energy. At higher incident energy, the two ions overlap much faster and their nucleons may even increase their energy due to the fact that the fermi energy of the composite nucleus is greater than those of both the projectile and the target [37].

In Figures 4 to 7 the calculated coalescence contribution to the spectra is given by the full line. The value of R_c in (10) is found to be about 0.09 with a slight variation around this value according to the mass of the target and the incident energy. This is presumably due to our use of parameters which are fixed *a priori*. A slight variation of these parameters could very easily account for the observed differences. The parameter choice may have also some influence on the absolute value of R_c which altogether is of the order we can expect. The calculation reproduces satisfactorily the angular variation of the yield of the lowest energy fragments and added to the break-up contribution provides a very convincing explanation of the experimental spectra and the variation of their yield and shape with the emission angle. It has to be noted that this calculation allows one to reproduce satisfactorily the spectra of other IMF observed in interaction of ^{16}O with ^{59}Co and ^{93}Nb [17,18].

4 Conclusions

The measured B fragments spectra are very convincingly reproduced by assuming that they are produced by two unrelated processes: projectle break-up before or during the partial overlap of the two ions, and the coalescence of nucleons during the cascade of N-N interactions by means of which the orderly kinetic energy of the overlapping ions transforms into random thermal energy. These two processes occur in a very short time interval. In fact, even the nucleon coalescence, according to our calculations, takes less than about 5×10^{-22} s after the contact time of the two ions.

The alternative explanation that the lowest energy fragments are emitted totally or at least partly in the evaporation of very hot equilibrated nuclei produced in the fusion of the projectile and the target is ruled out in our approach by the fact that the equilibrated nuclei cannot reach the excitation energies necessary to explain the observed IMF yield quantitatively.

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