Eur. Phys. J. A **18**, 639–644 (2003)
DOI 10.1140/epja/i2003-10091-5

THE EUROPEAN PHYSICAL JOURNAL A

Emission of Li, ^{7,9}Be and B fragments in the interaction of ^{12}C with ^{93}Nb between 200 and 400 MeV

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Received: 4 April 2003 / Revised version: 1 July 2003 /
Published online: 18 November 2003 –
Communicated by W. Henning

Abstract. The double differential cross-sections of Li, ^{7,9}Be and B ions emitted in the interaction of ^{12}C with ^{93}Nb at incident energies varying from 200 to 400 MeV show that these intermediate-mass fragments are produced by two different mechanisms: the fragmentation of the projectile and the coalescence of nucleons during the thermalization of the intermediate nuclei produced in the complete and incomplete fusion of carbon and niobium. These results confirm those of previous investigations of our group and are well explained by the theories which we have proposed to describe these two reaction mechanisms.

PACS. 25.70.Gh Compound nucleus – 25.70.Mn Projectile and target fragmentation

In a series of experiments [1–4] we have measured the spectra of intermediate-mass fragments (IMFs) produced when 100 to 400 MeV ^{12}C and ^{16}O ions interact with target nuclei with masses ranging from about 60 to 200. In the case of ^{12}C we have measured the spectra of ^{8}Be [1] and in the case of ^{16}O the spectra of ^{8}Be, B, C and N fragments [2–4]. These studies have shown that in addition to the fragments produced in the binary fragmentation of the projectiles with about the beam velocity, one observes low-energy fragments with an energy and angular distribution which suggest that they are produced by nucleon coalescence during the thermalization of the composite nuclei created in the complete or partial fusion of the interacting ions. The analysis of the spectra of break-up fragments also led to a better understanding of this reaction mechanism, suggesting that before breaking up the projectile may lose quite a substantial amount of its energy. The theoretical assumptions which allow us to satisfactorily explain the measured spectra are discussed in the above-quoted papers.

While the study of IMF emission in the interaction of ^{16}O with nuclei was rather complete, in the case of ^{12}C it was restricted to the spectra of ^{8}Be$_{gs}$ fragments only. In this short communication we show and analyse the spectra of other IMFs produced in ^{12}C interactions, namely Li, ^{7,9}Be and B.

In addition to providing more complete information on the IMF emission in ^{12}C-induced reactions, this study is also considered useful for two other reasons. The first is the possibility of comparing the break-up contribution to the spectra of the three Be isotopes ^{7}Be, ^{8}Be$_{gs}$ and ^{9}Be to study the importance of dissipative interactions before and after break-up. As a matter of fact the spectator's fragments have a lower mean energy and a broader energy distribution around the mean than those expected in absence of any dissipative interaction [5–7]. The study of the spectra of the unstable ^{8}Be$_{gs}$ fragments, produced both in ^{12}C [1] and ^{16}O break-up [4], suggested that in this particular case these features result from an initial-state interaction of the projectile, because it seems very unlikely that, once produced, an unstable ^{8}Be$_{gs}$ might survive a final-state interaction. The spectra of stable B, C and N break-up fragments of ^{16}O could also be explained by assuming only the initial-state interaction [2–4], but it seemed to us that the dominance of the initial-state interaction could be better confirmed or disproved by comparing the spectra of the stable ^{7}Be and ^{9}Be fragments with those of ^{8}Be$_{gs}$. In this particular case one may benefit from the fact that the spectra of the three Be isotopes are free from contamination of other isotopes, a possibility which cannot be excluded for the other fragments which

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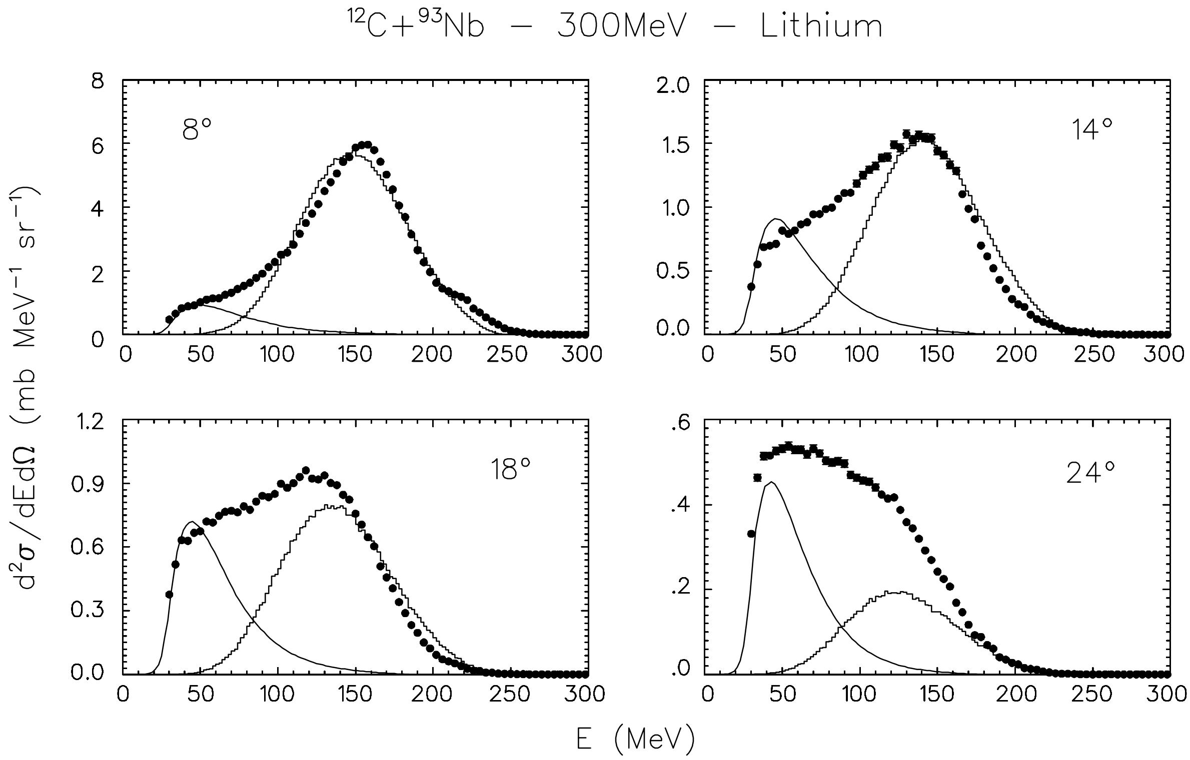

Fig. 1. Spectra of lithium fragments produced in the interaction of ^{12}C with ^{93}Nb at an incident energy of 300 MeV, at the laboratory emission angles as indicated. The experimental cross-sections are given by the solid circles, the theoretical predictions by the full lines (coalescence) and the histograms (break-up).

we have considered. The second reason is to quantitatively determine the break-up of ^{12}C into non-alpha–type fragments, which are often considered to be negligible (see, for instance, [8,9]).

The spectra of Li, $^{7,9}Be$ and B fragments were measured by using two detector telescopes, each consisting of a transmission Si ΔE detector and a NaI(Tl) stopping detector. The Si detectors had thicknesses of nominally 25 and 150 μm, respectively, while 127 mm thick NaI detectors were used on both telescopes. The standard ΔE-E technique was used for particle identification. The energy calibration of the NaI detectors was obtained from the kinematics of elastic scattering of the ^{12}C beam in combination with the relative scintillation responses of the various measured ions according to a formalism by Michaelian [10]. The energy calibration of the Si detectors was based on both the calculated ΔE-E responses of the detector telescopes and collimated α-particles from a ^{228}Th source.

We obtained good Z discrimination of the emitted fragments and in the case of Be, due to the absence in the ΔE-E particle identification spectra of the ^{8}Be locus (because ^{8}Be decays into two correlated α-particles before reaching the detector) we could also separate ^{7}Be and ^{9}Be fragments uniquely above about 50 MeV.

A few representative spectra of Li (300 MeV), ^{7}Be and ^{9}Be (400 MeV) and B (400 MeV) are shown in figs. 1 to 3. In fig. 4 the cumulative spectra of ^{7}Be + ^{9}Be at 400 MeV are presented in order to point out that the coalescence model may reproduce more accurately than in fig. 2 the low-energy part of the beryllium spectra, where the contribution of the two measured isotopes could not be separated.

As suggested in our previous studies [1–4] to which we refer here for a detailed discussion of our theoretical approach, the break-up contribution was evaluated under the hypothesis of a dominance of the initial-state interaction. The fragment's double differential spectra are obtained by folding the spectra predicted by the local plane-wave approximation [6,7] with a function that decreases exponentially with increasing projectile energy loss, which represents the probability that the projectile survives a break-up or a mass transfer reaction. These calculations yield a fair reproduction of all the measured spectra. As mentioned before, especially in the case of ^{7}Be and ^{9}Be, we took into account the possibility that the spectra could be better reproduced by including also a final-state interaction, as suggested for instance by Hussein *et al.* [5]. However, all these attempts deteriorate the agreement between the measured and the calculated spectra, giving further support to the hypothesis of the predominance of the initial-state interaction of the projectile over final-state interactions of the observed fragments.

In the case of Li, the energy needed for splitting ^{12}C into a ^{5}Li and a ^{7}Li fragment (26.588 MeV) does not greatly differ from that needed for its splitting into two ^{6}Li fragments (28.172 MeV). Hence we assumed these two fragmentation modes to be equally probable. The energy

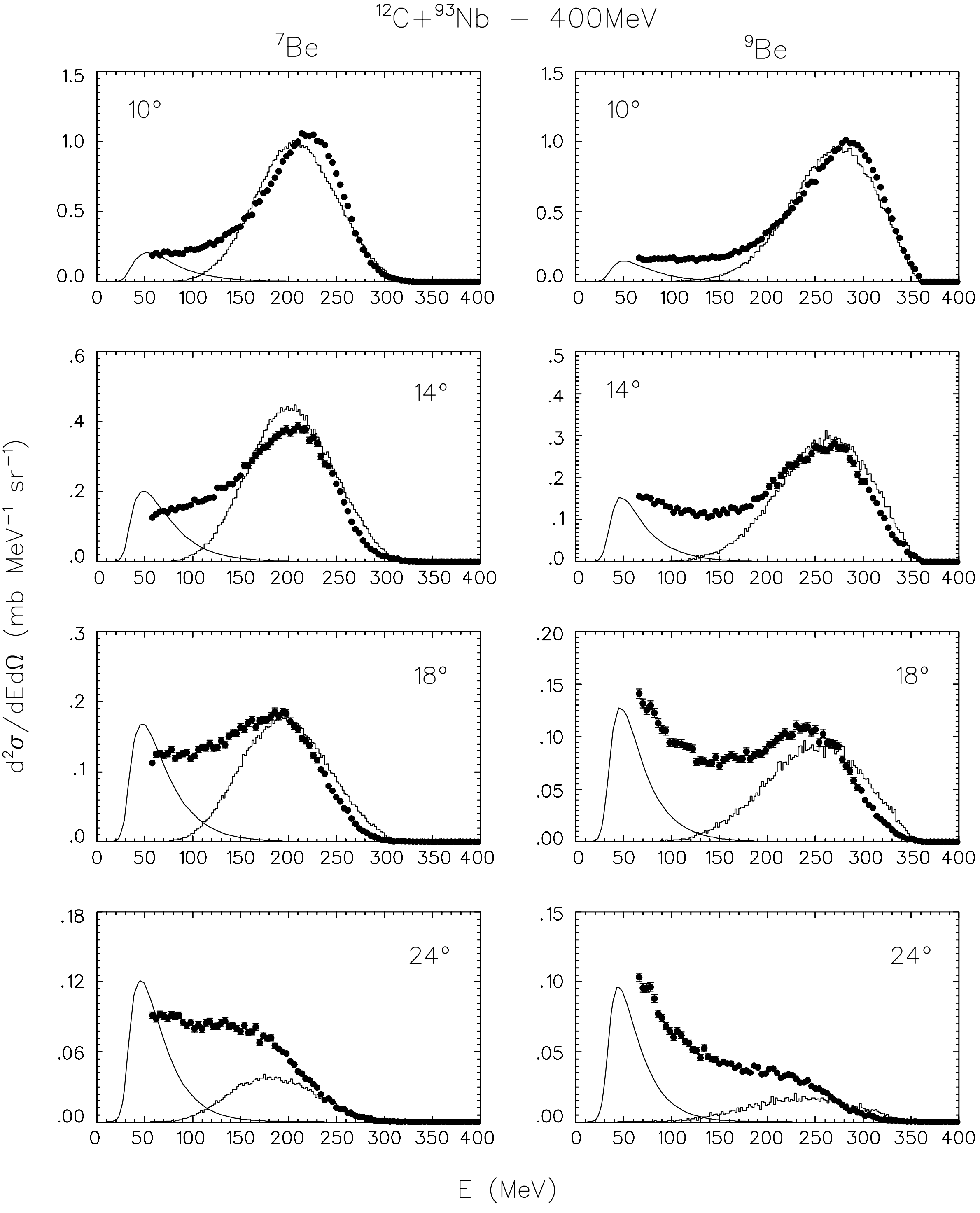

Fig. 2. Spectra of ^{7}Be and ^{9}Be fragments produced in the interaction of ^{12}C with ^{93}Nb at an incident energy of 400 MeV. See also caption to fig. 1 for additional information.

for splitting ^{12}C into a proton and a ^{11}B (15.96 MeV) is considerably smaller than that of fragmentations involving deuterons and tritons and lighter B isotopes. Thus, we assumed a dominant contribution of ^{11}B fragments to the B break-up spectra.

The relative two-fragment angular momentum within ^{12}C is equal to 0 for all the fragment pairs considered except in the case of fragmentation into ^{3}He and ^{9}Be and a proton and ^{11}B where the relative angular momentum is equal to 1. In the first case we used a square-well approximation to evaluate the wave function for the fragment relative motion, which gives an easy-to-handle analytical expression for the Fourier transform necessary to evaluate the fragment spectra [11]. For $L = 1$ we evaluated the

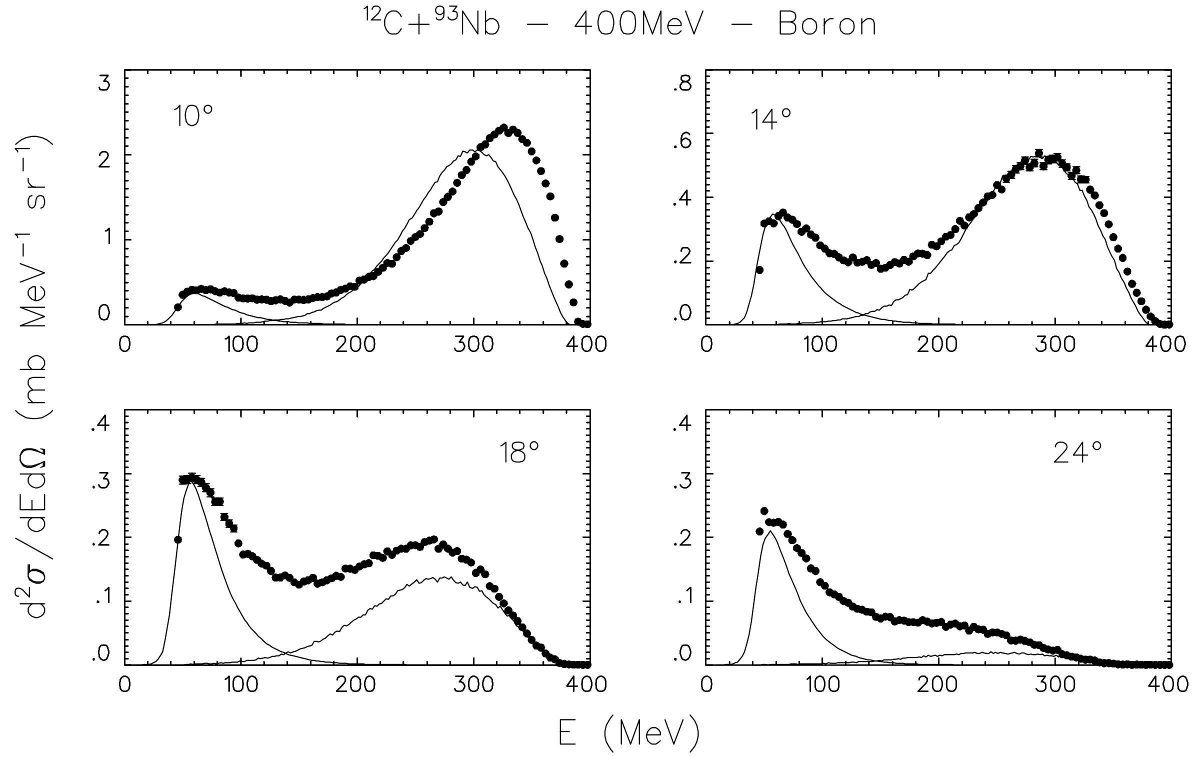

Fig. 3. Spectra of boron fragments produced in the interaction of ^{12}C with ^{93}Nb at an incident energy of 400 MeV. See also caption to fig. 1 for additional information.

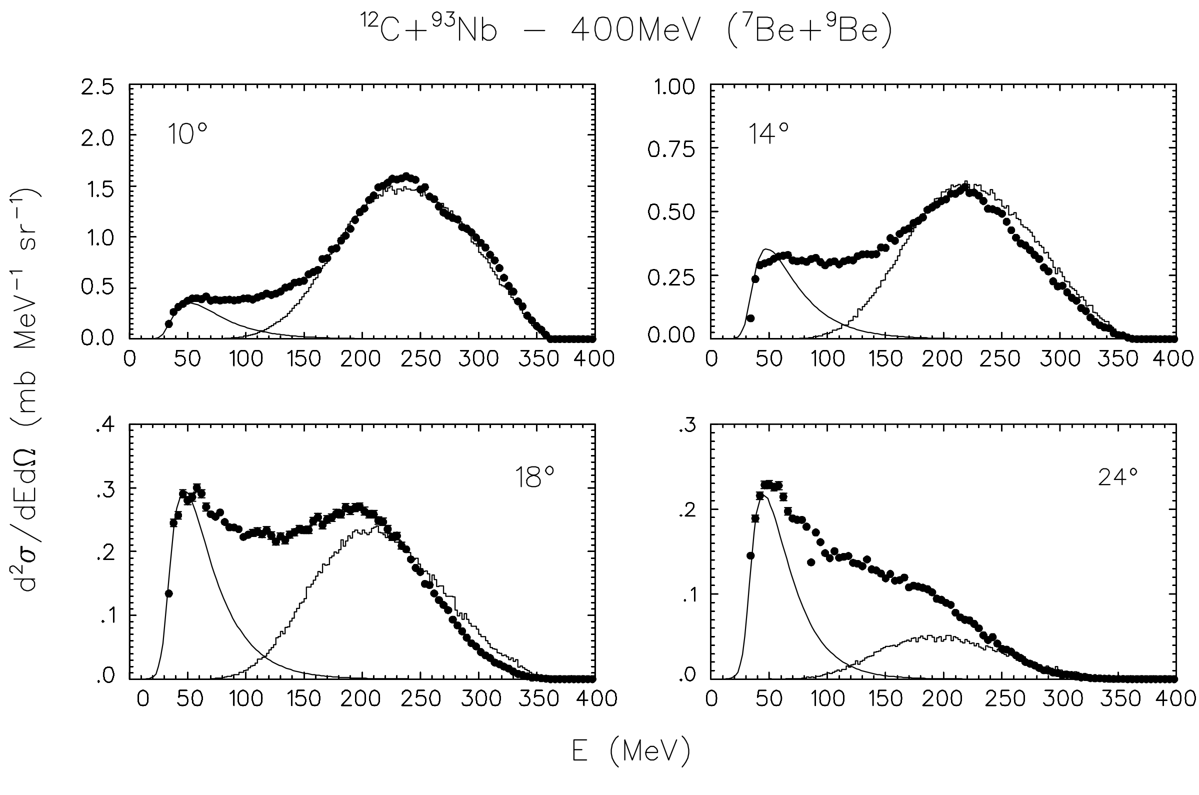

Fig. 4. Spectra of ^{7}Be + ^{9}Be fragments produced in the interaction of ^{12}C with ^{93}Nb at an incident energy of 400 MeV. See also caption to fig. 1 for additional information.

relative-motion wave functions in the cluster approximation using a Saxon-Woods potential. In all cases the depth and the geometrical parameters of the potential well were obtained by a best fit of the measured spectra.

The spectra of all the fragments are reproduced reasonably well at all energies, as shown for a few selected cases in figs. 1 to 3, except at the largest angles where the calculation underestimates quite significantly the observed yields at intermediate emission energies and, in the case of ^{11}B at the most forward angles where the measured spectra seem to be harder than the calculated ones. Unfortunately these shortcomings are to a greater or lesser extent common to all the analyses we have made so far. Considering the results of all these analyses [2–4] we are inclined to attribute the too small predicted large-angle yield to our underestimation of the contribution of close-encounter break-ups of incident ions which have been appreciably deflected from their original direction [4]. The softer calculated spectra at the most forward angles of fragments produced by a nucleon transfer from the projectile to the target are presumably due to our neglecting of transfers of protons to low-energy target states (in addition to the break-up fusion mechanism which we do consider) as suggested by calculations of the spectra of fragments produced in neutron transfer processes [12].

An important piece of information which one extracts from the analysis of these spectra is the mean kinetic-energy loss $\overline{\Delta E}$ of the projectile before breaking up into a specific fragment pair, which is given in table 1 for all the considered fragmentations. This table reports also the values of $\overline{\Delta E}$ and σ, the theoretical angle and energy-integrated cross-section for break-up of ^{12}C into ^{8}Be$_{gs}$ + ^{4}He, studied in our previous work [1]. The values given in table 1 for these quantities differ a little from those given in the above-quoted paper since the ^{8}Be$_{gs}$ spectra have been re-analysed. The newly calculated spectra of ^{8}Be$_{gs}$ do not differ appreciably in shape from those given in [1], but their angular dependence is less forward peaked at incident ^{12}C energies of 300 and 400 MeV. Consequently, they are in much better agreement with the experimental data, which can now be reproduced using a smaller σ than previously indicated. This improvement is due to a different choice of the depth and width of the potential well used for evaluating the fragment relative-motion wave function.

The cross-section values for the production of ^{9}Be given in table 1, at all the energies, are substantially greater than those for the production of ^{7}Be even if, at the 400 MeV incident energy, the spectra of these fragments shown in figs. 1 and 2 seem, in the considered angular interval, to be quite similar in absolute value. This is due to the much higher cross-section predicted for production of ^{9}Be at the most forward angles. The large errors affecting the values of σ in table 1 reflect the uncertainty due to the impossibility of comparing the results of the calculations with any experimental data at very forward angles (because data could not be measured at angles smaller than 8°) where a large fraction of the break-up fragments is confined. Notwithstanding this, the values found for σ suggest that while the cross-sections for fragmentation of ^{12}C into ^{8}Be$_{gs}$ and ^{4}He are definitely greater than those for fragmentation into ^{7}Be and ^{5}He, they are comparable in value to the cross-sections for fragmentation of ^{12}C into ^{9}Be and ^{3}He.

Table 1. ^{12}C + ^{93}Nb. Incident ^{12}C energies, break-up mode, observed fragment, average kinetic-energy loss $\overline{\Delta E}$ of ^{12}C ions before the considered break-up, theoretical angle and energy-integrated production cross-sections (σ).

E_{inc} (MeV)	Break-up	Fragment	$\overline{\Delta E}$ (MeV)	σ (mb)
200	^{6}Li + ^{6}Li	^{6}Li	40	30 ± 10
200	^{5}Li + ^{7}Li	^{7}Li	40	30 ± 10
200	^{7}Be + ^{5}He	^{7}Be	37	20 ± 10
200	^{8}Be$_{gs}$ + ^{4}He	^{8}Be	55	80 ± 15
200	^{9}Be + ^{3}He	^{9}Be	24	55 ± 25
300	^{6}Li + ^{6}Li	^{6}Li	60	35 ± 5
300	^{5}Li + ^{7}Li	^{7}Li	60	35 ± 5
300	^{7}Be + ^{5}He	^{7}Be	74	30 ± 10
300	^{8}Be$_{gs}$ + ^{4}He	^{8}Be	72	105 ± 15
300	^{9}Be + ^{3}He	^{9}Be	45	50 ± 15
300	^{11}B + p	^{11}B	$\leq$40	300 ± 100
400	^{6}Li + ^{6}Li	^{6}Li	63	40 ± 5
400	^{5}Li + ^{7}Li	^{7}Li	63	40 ± 5
400	^{7}Be + ^{5}He	^{7}Be	92	35 ± 5
400	^{8}Be$_{gs}$ + ^{4}He	^{8}Be	95	110 ± 15
400	^{9}Be + ^{3}He	^{9}Be	49	90 ± 10
400	^{11}B + p	^{11}B	$\leq$53	400 ± 100

At 200 MeV, for all the break-up modes, $\overline{\Delta E}$ is not substantially larger than the Coulomb repulsion of the projectile and the target at the moment of break-up. Its small value for the break-up mode forming ^{9}Be suggests that, at this energy, this fragment is produced in a more peripheral interaction. With increasing projectile energy $\overline{\Delta E}$ becomes larger than the Coulomb repulsion, as was also found in our previous experiments, except for the heaviest observed fragments (^{9}Be and ^{11}B) where it is about equal to the Coulomb repulsion.

As was also found in our previous measurements of IMF spectra, especially at the largest emission angles, the break-up mechanism cannot explain the yield of low-energy IMFs. This low-energy yield, the importance of which increases with increasing emission angle, can be satisfactorily explained by assuming it to be due to the coalescence of nucleons during the thermalization of the composite nuclei produced in the complete or incomplete fusion of the two interacting ions. Since we do not resolve the different isotopes in the case of Li and B, several of them may contribute to the coalescence part of the spectra. We consider lithium fragments with mass from 6 to 9 and boron fragments with mass 8 to 14 (except for ^{9}B which fragments into a proton and two alpha-particles before reaching the detector). Figures 1, 3 and 4 show that the calculated coalescence spectra reproduce the lowest-energy part of the measured spectra quite accurately. In evaluating this contribution we used the theory and the

Table 2. Cross-sections for the complete fusion ($\sigma_{\rm cf}$) of ^{12}C and the incomplete fusion ($\sigma_{\rm Be}$) of Be fragments with ^{93}Nb which were used for evaluating the coalescence spectra.

$E_{\rm inc}$ (MeV)	$\sigma_{\rm cf}$ (mb)	$\sigma_{\rm Be}$ (mb)
200	840	774
300	564	459
400	430	344

parameters given in our previous papers [2–4], except for the values of

a) the cross-sections for the complete fusion of ^{12}C and ^{93}Nb for which we used the values predicted by [13] and the values of the cross-sections for the incomplete fusion of Be fragments (the incomplete-fusion reaction which we expect to provide the most important contribution to the coalescence spectra) which are given in table 2. In our opinion, the data which allow one to estimate with less uncertainty the values of these cross-sections are the excitation functions for the formation of the residues which are predominantly produced by this incomplete-fusion process. This is the case of the In, Cd and Ag isotopes produced in the interaction of ^{12}C with ^{103}Rh [9,14,15]. The most recent analysis of these excitation functions [15] suggests that the cross-section for incomplete fusion of Be fragments reaches, in this case, a maximum at an incident energy of about 160 MeV and thereafter decreases approximately as the inverse of the projectile's energy, as predicted by the critical-distance model [8]. In order to evaluate its values for the interaction of ^{12}C with ^{93}Nb, the values found for the interaction of ^{12}C and ^{103}Rh have been scaled assuming an $\left(A_p^{1/3}+A_T^{1/3}\right)^2$-dependence, and are given in table 2;

b) R, the factor appearing in the expression of the IMF spectrum which gives the probability that the IMF, once produced, be emitted before dissolving into its constituents [2–4]. As in previous cases, R is obtained from the comparison of the experimental and theoretical spectra. For the three IMFs the survival factors are found to be equal to 0.33 ± 0.08 for Li, 0.1 ± 0.025 for ^{7}Be and ^{9}Be and 0.12 ± 0.03 for boron. These values might depend on our choice of the IMF Fermi energies for which we used the expression given in our previous papers [2–4], which cannot be assumed to be accurate for the lighter nuclei. Nevertheless, the values found for R in this analysis agree quite well with those found in our previous works. For instance, in the case of a boron IMF, the value of R is equal, within the respective uncertainties, to that found in the interaction of ^{16}O with ^{59}Co and ^{93}Nb (0.09 ± 0.03) [4].

To conclude, the analysis of the spectra of Li, ^{7}Be, ^{9}Be and B fragments produced in the interaction of ^{12}C with ^{93}Nb at incident energies up to 400 MeV confirms the presence of two contributions, one due to the binary fragmentation of ^{12}C, and the other due to nucleon coalescence during the thermalization of the composite nuclei created in the complete and incomplete fusion of the two ions. The theories proposed in our previous papers [1–4] reproduce reasonably also these data and this seems to confirm their approximate validity. However, especially the calculation of the break-up contribution should be greatly improved and the hypothesis of the dominance of the initial-state interaction should be justified by a more microscopical dynamical theory of the break-up process by assessing the relevance of processes such as, for instance, in the case of ^{8}Be$_{\rm gs}$, the final-state interaction of two alpha-particles which may have been scattered in and out of its resonant state by their interactions with the remainder of the target.

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