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SOURCE CHARACTERISTICS OF EVAPORATION RESIDUES AND INTERMEDIATE MASS
FRAGMENTS IN Kr INDUCED REACTIONS AT 26.4 AND 34.4 MeV/NUCLEON*

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* Experiment performed at GANIL

Keywords : Nuclear reactions C, Al, ^{nat}Ti(Kr,X), E = 26.4,
34.4 MeV/nucleon ; measured σ (mass, charge, velocity, θ). Statistical
model calculations.

Abstract : Fragments from Z = 3 up to Z = 37 , produced in the Kr + C,
Al, ^{nat}Ti reactions at 26.4 and 34.4 MeV/nucleon were detected. Velocity,
energy, mass and atomic number of fragments were measured. Analysis of the
velocity spectra and angular distributions of the intermediate-mass fra-
gments shows the presence of an isotropic component with the characteris-
tics of an asymmetric binary splitting of a hot nucleus. A comparison of
the source characteristics associated to these fragments and to evaporation
residues indicates that the measurement of intermediate-mass fragments al-
lows to select the most dissipative collisions. The results are discussed
in the framework of the statistical decay model following complete and in-
complete fusion.

1. Introduction

Experimental studies on heavy-ion induced reactions in the energy domain of several tens of MeV/nucleon have shown a rich variety of dissipative phenomena, such as complete and incomplete fusion and deep-inelastic scattering [1,2]. These fusion-like reactions lead to nuclei with high excitation energies and angular momenta. It was seen [3-5] that such nuclei emit Intermediate-Mass Fragments (IMF) in competition with light particles. The studies have shown that statistical model calculations including all the binary splittings of the compound nucleus can account for the IMF production. Consequently, a typical distribution of the decay products of a nucleus covers the range from lithium (the lightest IMF) to the heaviest evaporation residue, in contrast with the low energy regime where only the residue peak and, in some cases, the symmetric fission are populated. Furthermore the shape of the distribution and the IMF yields depend strongly on the spin and excitation energy stored in the emitter. For example, it was observed that IMF come from the most dissipative collisions [5,6]. Thus, systematic studies of this exit channel could be a good probe of the characteristics and stability limit of the hottest nuclei formed in fusion-like reactions. In the present work, we present a detailed analysis of inclusive data on IMF and heavy residues observed in reverse kinematics reactions $^{84}\text{Kr} + ^{12}\text{C}$, ^{27}Al , ^{nat}Ti at 26.4 and 34.4 MeV/nucleon.

This choice has been made to study entrance channel effects on incomplete fusion process. From the available center of mass energies and grazing angular momenta, composite nuclei with similar masses but very different excitation energies and angular momenta are likely to be formed with the investigated systems.

This paper is organized as follows. The experimental set-up and global results are presented in section 2. Properties of IMF and heavy residues are presented in section 3 together with the excitation energies of the hot emitters. The comparison of the experimental mass-distributions to the predictions of a statistical model is presented in section 4. Conclusions are drawn in section 5.

2. Experimental set-up and results

The experiment was performed using the 26.4 and 34.4 MeV/nucleon ^{84}Kr beams delivered by the GANIL facility. Beam intensities were about 10^{10} particles per second and the C, Al, ^{nat}Ti targets were respectively 350, 960 and 850 $\mu\text{g}/\text{cm}^2$ thick.

Velocity, energy, atomic number Z and mass M of the fragments with $M > 10$ were measured in the angular range from 2° to 16° by means of a time of flight counter telescope consisting of three silicon detectors (50, 100, 5000 μm). Stop and start detectors were located respectively at .94 and 3.05 m from the target. Time and energy signals were calibrated by means of a pulse generator and elastically scattered projectiles on a gold target. A time resolution of 150 ps (FWHM) allowed to resolve the masses of the fragments up to $M \sim 70$. Fig. 1 shows a typical mass spectrum obtained for the

reaction $\text{Kr} + \text{Al}$ at 26.4 MeV/nucleon.

Two other silicon counter telescopes were installed in the reaction chamber to extend the angular range covered by the time of flight telescope. The first one (100, 2000 μm) was mainly dedicated to the atomic number Z and to energy E measurement of the heaviest fragments on the angular range from $.75^\circ$ to 4° . The second one (100, 2000, 6000 μm) provided Z and E for $Z \geq 3$ fragments collected at laboratory angles between 15.5° and 50° .

Inclusive events from the three telescopes were recorded and analysed off-line. An absolute normalization, with an overall uncertainty of 15%, was obtained from known target thicknesses, solid angles (respectively 0.027, 0.015 and 0.28 msr) and integrated beam currents.

Some results obtained with the time of flight telescope are reported on figs. 2-4. Typical scatter-plots of velocity versus the atomic number measured at 4° for the three systems at 34.4 MeV/nucleon are shown on fig. 2. In these plots, the velocity of the fragments with $Z \leq 20$ ($M \leq 40$) is distributed on two branches, well separated in the reaction induced on the C target, broader, but still distinct, when bombarding Al or Ti targets. These two branches merge together as the atomic number of the detected fragment increases. The products with $Z \geq 25$ have their velocity ranging from the projectile one (V_p) down to roughly $.75 V_p$. A better insight on the production mechanism is provided by the velocity spectra reported for the six reactions in fig. 3 for the mass bin 21-25 and in fig. 4 for the mass bins 61-65 and 76-80.

As shown in figs. 2 and 3 the lightest detected fragments ($M \leq 40$) present two velocity branches which overlap gradually as the detection angle increases. This behaviour together with the Z -dependence we already pointed out are the well-known fingerprints of a binary decay process from a hot fast moving nucleus as it is the case in reverse kinematic reactions [5,7,8]. The analysis of these light products ($M \leq 40$) is developed in section 3.1.

Velocity spectra of the heaviest products ($M \geq 50$) show two components (fig. 4). One populates the domain around the beam velocity with a yield dropping very fast either as the detection angle increases or as the detected fragment is lighter than the projectile. This class of events can be attributed to peripheral reactions. The second component is located at a lower velocity than the projectile one, suggesting a more dissipative process. Fragments with such velocities are the evaporation residues resulting from the decay of hot nuclei. Further information on these products will be given in section 3.2.

Combining the data collected with the three telescopes, we were able to integrate the angular distributions for fragments with $Z \geq 3$. Such distributions are shown on fig. 5 for Li and B isotopes produced at 26.4 MeV/nucleon with C and Ti targets. In both reactions the maxima of the angular distributions are reached and the data can be easily extrapolated to 0° .

For the fragments with Z up to 30-32, the $d\sigma/d\theta$ distributions present a maximum and their total cross-section can be extracted. In addition for

fragments with $Z > 30$, the $d\sigma/d\Omega$ data follow a Gaussian distribution. Assuming such a Gaussian shape for the $Z = 30-32$, we found an agreement within 20% with respect to the direct integration procedure. Thus, we used a Gaussian extrapolation for estimating the cross sections for $Z \geq 33$ fragments.

The total cross-sections for fragments with $Z \geq 3$ are reported in fig. 6 for the six reactions studied in this work. Pronounced U-shape yields are observed with minima located around $Z = 15$. For a given target, we found a slight dependence with the incident energy. On the contrary, the yields around the minima increase strongly as the mass of the target increases: by a factor 10 from $\text{Kr} + \text{C}$ to $\text{Kr} + \text{Al}$ and by around a factor 30 from $\text{Kr} + \text{C}$ to $\text{Kr} + {}^{238}\text{Ti}$ reactions. Finally, the integrated yields from the minima up to the heaviest fragment exhaust about 50 to 70% of the total reaction cross-section taken from ref. [9].

3. Analysis of data

3.1 $M \lesssim 40$ products

As already mentioned, the shape of the velocity spectra shown in figs. 2 and 3 suggests that IMF originate from a binary disintegration of a composite system. In such a scenario, due to the reverse kinematics and to the incomplete transfer of the linear momentum, the velocity of the source (V_s) is located between the velocity of the center of mass (V_{cn}) and the projectile one (V_p). The mean emission velocity V_e associated to a given splitting of the hot emitter can be approximated assuming a Coulomb repulsion energy [5, 7, 8]. Such a process can explain the main features of the experimental results. Indeed, the centroids of the two branches in the velocity spectra have been reported in fig. 7 in a $V_{\parallel}$ - $V_{\perp}$ plot. The centroids sit well on circles for the different mass bins, indicating that the splitting mechanism releases the same kinetic energy regardless the emission angle, in agreement with the previous scenario. Nevertheless, the presence of target-like products can be inferred from the low velocity component of the lightest fragments emitted at 34.4 MeV/nucleon with C and Al targets (see also fig. 2).

From the data presented in fig. 7, one can extract the velocity of the source V_s and the emission velocity V_e . For a given reaction, the circles are centered at the same value on the $V_{\parallel}$ axis, indicating a well defined velocity source within the experimental errors. The results are reported in table 1 as well as the mass M_s and the excitation energy per nucleon of the source ϵ^* , both deduced from massive transfer hypothesis. For each reaction induced on C target, V_s coincides with the center of mass velocity V_{cn} , which means a complete fusion process. In the other cases, the source velocities are greater than V_{cn} indicating an incomplete fusion mechanism.

The emission velocities V_e are reported in fig. 8 as a function of the mass of the fragment. One observes a linear decrease of the emission velocity when the fragment mass increases. For a given target, the velocity of

a detected fragment decreases slightly as the bombarding energy goes from 26.4 to 34.4 MeV/nucleon. In fact, the observed fragments are the final products of a de-excitation process where the splitting can either be preceded or followed by a light-particle evaporation. On the basis of phase space constraints, the fragment emission occurs presumably at the first step of the whole process, even though such an hypothesis has not been experimentally demonstrated. Thus, from energy and momentum conservation and assuming that light particle evaporation does not change the average emission velocity, one can deduce the linear dependence reported in fig. 8. M_1 and M_2 are the masses of the primary fragments, with $M_1 + M_2 = M_s$ having the kinetic energy E_1 and E_2 related to the symmetric fragmentation energy E_{sym} via the relationship [5] :

$$E_{12} = E_1 + E_2 = 4E_{sym} M_1 M_2 / M_s^2 \quad (1)$$

The velocity V_1 of the primary fragment is given by :

$$V_1 = \sqrt{\frac{8E_{sym}}{M_s} \frac{M_s - M_1}{M_s}}$$

The full line in fig. 8 represents the results of a calculation with E_{sym} taken from the Viola systematics [10] and with M_s taken from table 1. The observed shift with respect to the experimental data is due to the light-particle evaporation. For the reaction induced on C and Al targets, the shift increases with the mass of the IMF. This trend supports a sharing of the remaining excitation energy $E_s^* - E_{12}$ according to the mass ratio of the two partners as it is when thermal equilibrium between them is achieved (E_s^* is the excitation energy of the source). Indeed, the dashed line of fig. 8 corresponds to final products assuming a thermal equilibrium ; the mass loss is estimated by taking a mean energy of 13 MeV for each emitted particle. As one can see, this schematization of the decay process explains reasonably well the data on C and Al targets.

The comparison becomes not so satisfactory when the reactions on the Ti target are considered. The data seem shifted with the same amount of mass loss regardless the mass of the primary fragments, which means roughly the same amount of excitation energy in both partners. However, the characteristics of the emitters produced in Kr + Al and Kr + Ti are very similar (see table 1), and it is doubtful to invoke a rapid change in the sharing of the excitation energy, as long as the same scenario for the disintegration is kept. A plausible and conservative explanation for the disagreement is that in the Kr + Ti reaction, the whole de-excitation process can no longer be described by a simple binary splitting scenario. As indicated in table 1, the excitation energy in the emitter could be high enough to allow more than one splitting in the chain which evidently complicates the simple previous schematization. One might note that the peculiar shape of the velocity spectra of the IMF measured at forward angles, with no well pro-

nounced minima between the two components, could support multiple splitting of the emitter formed in the Kr + Ti reactions.

The experimental angular distributions were obtained in the source frame using the values V_s and V_e from the $V_{\parallel}$ - $V_{\perp}$ plot analysis. Fig. 9 shows some examples of experimental distributions ; the $1/\sin\theta$ behaviour is also drawn for comparison. Even though some forward-backward asymmetry can be seen, the data are compatible with the assumption of an emission process from an equilibrated source. The asymmetry could be produced by the remnants of target-like fragments coming from peripheral collisions which populate the backward hemisphere when the reverse kinematics is used.

Thus from the kinematical analysis of the fragments having $M \leq 40$, one can conclude that all experimental features indicate the formation of a hot compound nucleus which decays through an asymmetric fission. In order to extract the part of the cross section associated to the emission from this equilibrated nucleus, we performed a simulation of the decay process, including the previous features.

The calculations were done assuming that the initial nucleus, characterized by its mass M_s , its charge Z_s and its excitation energy E_s^* , undergoes an asymmetric fission at the first step and then the two resulting fragments evaporate particles down to a complete cooling. M_s and E_s^* were deduced from kinematics as described previously. Z_s was estimated assuming that the absorbed part of the projectile has the N/Z ratio of the projectile.

The total kinetic energy of both fragments was sampled randomly out of a Gaussian distribution whose mean value is given by eq. (1). The width of this Gaussian distribution was fixed by fitting the experimental spectra measured in the reaction $^3\text{He} + \text{Ag}$ at 200 MeV (ref.[11], where the broadening due to the evaporation should be very small. We assumed a $\sqrt{T}$ dependence of this width where $T = \sqrt{8E_s^*/M_s}$ is the temperature of the fissioning nucleus. The angular distribution in the emitter frame was taken as $1/\sin\theta$ and the excitation energies of both fragments were estimated assuming a thermal equilibrium : $T_{1,2} = \sqrt{8E_{1,2}^*/M_{1,2}}$ are the temperatures of the primary fragments with $E_{1,2}^* = \frac{M_{1,2}}{M_s} (E_s^* - E_{12})$

The evaporation of nucleons was treated in average over the decay chain : the recoil nucleus of mass number $M_{r,1}$ has a Gaussian velocity spectrum centered at zero and with a width given by $\sigma_{\text{eva},1}^2 = n_{\text{eva},1} T_1 / M_{r,1}^2$, where n_{eva} is the number of evaporated nucleons and T_1 is the temperature of the initial nucleus [12]. The energy taken away by each evaporated particle $\bar{\epsilon} \sim 13$ MeV was estimated with an evaporation code [13]. Some calculations are compared to experimental spectra in fig. 3 (solid lines). Note that an unique normalization factor is used for each reaction. Also shown are the results of a calculation done by assuming that the hot emitter evaporates nucleons before undergoing an asymmetric fission (dashed lines). As can be seen in the figure, the predictions of the simulation for the two extreme hypotheses, where fission occurs before or after light-particle evaporation, are nearly identical. Thus, in the following, we assume that

particles are evaporated after fission. The general agreement is very satisfactory. The deviations observed for the low velocity component and related to the forward-backward asymmetry already discussed (fig. 9), is probably due to a deep inelastic-like component [12].

In summary, the simulation of the velocity spectra confirms that an important part of the IMF production can be attributed to the asymmetric fission of a nucleus formed in a complete or an incomplete fusion process. The mass and the excitation energy of this nucleus are compatible with the values obtained from the massive transfer hypothesis.

To extract the incomplete fusion contribution of these IMF, we normalized the calculated spectra to the experimental ones, as shown in fig. 3. The spectra are well reproduced by the simulation, even at large angles. The integrated cross-section extracted in this way (squares in fig. 12) does not depend strongly on the ingredients of the calculation. We will call it, in the following, the "maximum transfer cross-section".

3.2. $M \gtrsim 50$ products

Typical velocity spectra of heavy fragments have been presented in fig. 4. As already discussed, the spectra are Gaussian-like at large angles with an additional forward-peaked high velocity component. The fragments corresponding to the forward-peaked component have the characteristics of the projectile-like fragments associated to peripheral collisions. Regardless the origin of such products, we assumed for them a Gaussian velocity distribution. The lower velocity component is associated to the evaporation residues, its velocity distribution at a detection angle θ is a Gaussian centered at $V_g \times \cos\theta$, where V_g is the velocity of the incomplete fusion nucleus. Therefore, a two Gaussian fitting procedure was used down to the first mass bin where the two velocity branches begin to appear and thus the incomplete fusion component can no longer be approximated by a Gaussian. This happens between $M = 60$ and $M = 50$, depending on the system. One example of such an analysis is shown in fig. 10. The data are well fitted by a single value of the parameter V_g for all mass bins in a given reaction, suggesting that these heavy products are the evaporation residues of the same incomplete fusion nucleus. The V_g values are reported in table 1, together with the masses and the excitation energies of the sources calculated with the massive transfer hypothesis.

Angular distributions $d\sigma/d\Omega$ of the two components are shown in fig. 11. The integrated cross-sections have been extracted for each mass bin by assuming Gaussian shapes (solid lines). Evaporation-residue cross-sections are shown as triangles in fig. 12, together with the total production cross-section obtained using the combined information of the three telescopes (stars). The incomplete fusion component exhausts a decreasing part of the total cross-section as the mass of the target increases. The evaporation-residue mass-distribution progressively flattens and moves towards lighter masses from Kr + C at 26.4 MeV/nucleon up to Kr + Ti at 34.4 MeV/nucleon.

3.3. Comparison of the results

For the IMF and the evaporation residues, we calculated the ratio R_1 of the source velocity normalized to the center of mass velocity. It is more convenient to express this ratio as it would be in direct kinematics. Such a conversion is given by $R = 1 + \frac{A_p}{A_t}(1 - R_1)$, where A_p , A_t are the masses of the projectile and the target and R_1 is the value of the ratio we measured.

The values we obtained are shown in fig. 13 as a function of the relative velocity V_{rel} calculated at the Coulomb barrier.

Both ratios decrease as the velocity of the target increases. The decrease of the linear momentum transfer as the bombarding energy increases characterizes the fusion-like reactions in the intermediate energy domain and illustrates the growing failure in forming a compound nucleus with fusion of the entire projectile and target. This feature has been well documented [14,15] from numerous experimental studies based on angular correlation between fission products and evaporation residue velocity spectra. The momentum transfer deduced from our evaporation residue data agrees with the trend of the systematics, with a transfer somewhat lower than expected in the reaction induced on the Ti target.

The second striking feature seen in fig. 13 is the difference between the values deduced from the analysis of the two classes of final products (IMF and residues). Whatever the couple of reactants and energy chosen, the value extracted from the IMF channel is always higher. This result indicates that this exit channel is associated to the highest momentum transfers in the reaction. We also observe that the gap between the two ratios becomes smaller as one goes from the C to Ti target, suggesting weaker selectivity for the heaviest targets.

These features reflect the interplay between the distribution of the various compound nuclei formed in the incomplete fusion process and the properties of the IMF emission. The IMF yields strongly increase with angular momentum and excitation energy. So it is conceivable that the IMF emission comes from the high angular momentum and excitation energy part of the initial distribution of the formed nuclei. On the contrary, the evaporation residues reflect the whole initial distribution. The selectivity of IMF emission is very strong for an asymmetric entrance channel as $Kr + C$ because the excitation energy and the angular momentum of the emitter drop rapidly as the fusion process becomes more incomplete. The fact that the angular momentum and the excitation energies are expected to be larger in the reaction on Al and Ti could explain the weaker selectivity observed in these systems.

Coincidence measurements are needed to isolate among the heavy residues, the products which end up a de-excitation chain where a IMF emission has occurred. As such a technique was not used in our work, we estimated the

cross-section of heavy residues which have the same velocity source as the IMF one (table 1). For that, we applied the same procedure as the one used for simulating the velocity spectra of the IMF and we assumed that this component exhausts the lower velocity tail of the experimental spectra. In this way, we got an upper limit of the cross section of the heavy products having the same emitters as IMF. The results are reported in fig. 12 (squares). These data together with the direct measurement of the IMF contribution give nearly the whole mass distribution of final products associated to the highest momentum transfer in the collision.

As can be seen in fig. 12, the mass yields for the Kr + C reaction is U-shaped with an evaporation residue bump. Such characteristics are still present in the Kr + Al reaction at 26.4 MeV/nucleon with an amplifying factor of 10 in the cross sections with respect to the reaction on C. The distribution flattens for Kr + Al at 34.4 MeV/nucleon and Kr + Ti at 26.4 MeV/nucleon. A regular decrease of the distribution is observed for Kr + Ti at 34.4 MeV/nucleon. This evolution can reasonably be associated to a shift of the angular momentum and excitation energy distributions of the emitters towards higher values as one goes from Kr + C at 26.4 MeV/nucleon to Kr + Ti at 34.4 MeV/nucleon. This will be confirmed within the framework of a statistical model.

At a given bombarding energy, the maximum transfer cross-section for $A > 50$ exhausts an increasing part of the total incomplete fusion cross section from C to ^{nat}Ti . For a given target, this contribution becomes smaller as the incident energy increases. In the case of carbon, the maximum transfer cross-section reaches only 8% and 4% at 26.4 and 34.4 MeV/nucleon respectively of the total incomplete fusion cross-section, in good agreement with the systematics [16] for complete fusion. These results show that in the Kr + C collisions, only a few events corresponding to the largest momentum transfers of the whole distribution can lead to an IMF emission, whereas in the case of Kr + Al and Kr + Ti, this decay mode is much less selective.

Excitation energies per nucleon of the sources ϵ^* extracted assuming a massive transfer (see table 1) are shown in fig. 14 as a function of the center of mass energy per nucleon ϵ_{cm} . The values deduced from IMF are always higher than the evaporation residue ones. In all cases, a regular increase of the excitation energy is observed. For the system Kr + Ti at 34.4 MeV/nucleon, an excitation energy of 5.8 MeV/nucleon is reached; this value is close to the theoretical stability limit [17] which, for a mass 100 nucleus, is about 5.6 MeV/nucleon.

4. Statistical model calculations

The previous analysis shows that a sizeable part of the IMF production has the characteristics of an emission from an equilibrated hot nucleus. The statistical model provides a framework for the calculation of the cross sections of the final products. For nuclei with an excitation energy less than 100 MeV, the decay by light-particle emission or by fission have been

successfully treated within two different formalisms [18,19]. At higher energies, the emission of IMF becomes a significant decay mode. A generalization of the fission formalism has been proposed by Moretto [20] and Swiatecki [21] to treat the asymmetric fission.

In these formulations, the transition probability for IMF production is proportional to the level density at the saddle point :

$$\Gamma = \frac{1}{2\pi} T \left(\frac{E^*}{E^* - B} \right)^2 \exp(2 \sqrt{a(E^* - B)} - 2\sqrt{aE^*})$$

where E^* is the excitation energy of the nucleus, T its temperature, B the barrier at the saddle point and a the level density parameter.

We developed a Monte-Carlo version of our EDCATH code [4,5] where the previous formula has been used. In this new version, the barrier at the saddle point is taken from the rotating finite range model calculation of Sierk [22]. Last, the evaporation of light particles with $Z \leq 2$ is calculated with the Hauser-Feshbach formalism [18].

In the following, we present the analysis of the "maximum transfer cross section" which is associated to the de-excitation products of the hottest source. The statistical model calculations were performed assuming masses and excitation energies of the emitters given in table 1. As the angular momentum transfer during an incomplete fusion reaction is not known experimentally, the spin $J_{\text{transf.}}$ of the decaying nucleus was deduced through the relation $J_{\text{transf.}} = \frac{\Delta M}{M_T} l_{\text{inc.}}$ where M_T is the target mass, ΔM the transferred mass and $l_{\text{inc.}}$ the angular momentum in the entrance channel. The distribution of the spin $J_{\text{transf.}}$ was taken with the sharp cut-off approximation in the range $[0, J_{\text{transf.}}^{\text{max}}]$ corresponding to the entrance channel range $[0, l_{\text{inc.}}^{\text{max}}]$ with a cross section given by $\sigma = \frac{\pi}{k^2} (l_{\text{inc.}}^{\text{max}})^2$ where $\hbar k$ is the momentum in the center of mass. The results of the calculations are compared in fig. 15 to the experimental mass distributions.

Among the three systems studied, the reaction on ^{12}C are very constraining, as a complete fusion is observed. This means that the mass, charge, and excitation energy of the emitter are supposed to be known without approximations. The maximum transfer cross-sections correspond to $J_{\text{transf.}}^{\text{max}} = 22 \hbar$ at 26.4 MeV/nucleon and 19 $\hbar$ at 34.4 MeV/nucleon. Calculations assuming complete fusion and this maximum angular momentum are drawn as full lines in fig. 15. They reproduce reasonably well the cross-sections of the evaporation residues but strongly underestimate the yields of the IMF. Increasing the maximum angular momentum up to 53 $\hbar$ at 26.4 MeV/nucleon and 52 $\hbar$ at 34.4 MeV/nucleon (dashed lines), one observes a good agreement for the IMF cross-sections, showing that these exit channels are mainly associated to nuclei formed with high spins. Such high values agree with the critical angular momenta for fusion [9]. However, the evaporation residue yields clearly exceed the experimental data. Indeed, the calculations exhaust almost the whole cross-sections of the evaporation residue indicated

with triangle symbols in fig. 15. This would imply that the mean value of the velocity spectra of the evaporation residue would correspond to a full transfer which would contradict the experimental findings. These calculations suggest that there is co-existence of complete and incomplete fusion mechanisms in the range $[0, \approx 50\hbar]$. A complete fusion mechanism localized in a high- l window is the simplest way to simulate such a mixing. Indeed a better agreement with the whole mass distribution is obtained assuming that the complete fusion nuclei have angular momenta $J_{\text{transf.}}$ in the range $48 - 53 \hbar$ at 26.4 MeV/nucleon and $47 - 52 \hbar$ at 34.4 MeV/nucleon (dotted lines). These analyses show that the description of the fusion mechanism in the intermediate energy domain needs a reaction model able to predict the probability of the different fusion-like channels, at each impact parameter.

For the reactions induced on Al and Ti targets, the maximum angular momentum was kept free. The calculations reported with full lines in fig. 15 were obtained with $J_{\text{transf.}}^{\text{max}} = 70\hbar$ for Kr + Al and $J_{\text{transf.}}^{\text{max}} = 80\hbar$ for Kr + Ti. The corresponding maximum entrance channel angular momenta are reported in table 2. The $J_{\text{transf.}}^{\text{max}}$ values are compatible with the maximum angular momentum that a nucleus with $M \sim 100$ can sustain according to the rotating liquid drop model. The overall agreement with the data is good. Nevertheless, one might note a systematic overestimation of the evaporation residue cross-section. As in the Kr + C reactions, one improves the agreement with the evaporation residue yields by keeping the previous $J_{\text{transf.}}^{\text{max}}$ value and by reducing the width of the l -window. This suggests that in the case of Kr + Al and Ti reactions the highest momentum transfers could correspond to a high l -window. It is however difficult, with the present data, to be more quantitative.

5. Conclusions

Fragments with $Z \geq 3$ produced in the Kr + C, Al, ^{nat}Ti reactions at 26.4 and 34.4 MeV/nucleon were detected. Velocity spectra and angular distributions of all the fragments contain a component corresponding to fusion-like reactions. Analysis of this component shows that the IMF ($M \leq 40$) are associated to the most dissipative collisions while heavy residues are produced in a wider range of impact parameter.

Very large momentum transfers are observed which correspond, in a massive transfer picture, to nuclei having an excitation energy up to 5.8 MeV/nucleon. This value is close to the theoretical stability limit in this mass range.

Statistical model calculations reproduce the experimental mass distributions providing that some assumptions on the spin distribution of the emitters are done. Reliable entrance channel model and more exclusive data are needed to conclude whether some discrepancies are due to entrance channel effects or to a new disintegration mechanism.

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Table captions

Table 1 Experimental values of velocities, masses and excitation energies per nucleon of the evaporation residue and IMF sources deduced with the massive transfer hypothesis.

Table 2 Excitation energies per nucleon, maximum angular momentum of the IMF source and corresponding entrance channel angular momentum used in the statistical model analysis.

Figure captions

- 1 : Mass spectrum measured using the time of flight telescope for angular settings from 4° to 10°
- 2 : Identification versus velocity matrices obtained with the time of flight telescope located at 4° for the systems $\text{Kr} + {}^{12}\text{C}$, $\text{Kr} + {}^{27}\text{Al}$, $\text{Kr} + {}^{\text{nat}}\text{Ti}$, at 34.4 MeV/nucleon
- 3 : Velocity spectra for the mass-bin $M = 21 - 25$. Solid and dashed lines are the results of a simulation developed in section 3.1
- 4 : Velocity spectra for the mass-bins $M = 61 - 65$ and $M = 76 - 80$ of the three systems at 26.4 and 34.4 MeV/nucleon
- 5 : Angular distributions of Li and B produced in $\text{Kr} + {}^{12}\text{C}$ and $\text{Kr} + {}^{\text{nat}}\text{Ti}$ reactions at 26.4 MeV/nucleon. Curves are just to guide the eyes.
- 6 : Charge distributions for $\text{Kr} + {}^{12}\text{C}$, ${}^{27}\text{Al}$, ${}^{\text{nat}}\text{Ti}$ reactions at 26.4 and 34.4 MeV/nucleon
- 7 : Centroids of low and high velocity branches in the $(V_{\parallel}, V_{\perp})$ plane. V_{CN} , V_{S} and V_{P} are respectively the compound nucleus, source and projectile velocities
- 8 : Emission velocities of the IMF. Solid and dashed lines are explained in section 3.1. ϵ^* is the excitation energy per nucleon of the source of the IMF
- 9 : Angular distributions $d\sigma/d\Omega$ of the IMF in the frame of the source compared to a $1/\sin\theta$ trend (solid line)
- 10 : Velocity spectra of the mass-bin $M = 66 - 70$ for the $\text{Kr} + {}^{\text{nat}}\text{Ti}$ reaction at 26.4 MeV/nucleon. The curves correspond to incomplete fusion and peripheral-like reactions components as explained in section 3.2
- 11 : Angular distributions of the total cross section (full circles), the incomplete fusion (triangles) and the peripheral mechanisms (squares) for the mass-bin $M = 61 - 65$ of $\text{Kr} + {}^{\text{nat}}\text{Ti}$ system at 34.4 MeV/nucleon
- 12 : Total (stars), incomplete fusion (triangles) and maximum transfer cross-sections (squares) as a function of the mass of the detected fragments
- 13 : Ratio of the velocity of the source to the compound nucleus velocity as a function of the relative velocity at the barrier ; full (open) symbols are related to the evaporation residues (IMF) data
- 14 : Evolution with the center of mass energy per nucleon of the excitation energies per nucleon ϵ^* of the sources for the evaporation residues (full symbols) and for the IMF (open symbols)
- 15 : Maximum-transfer mass-distributions (squares) compared with statistical model calculations using parameters from table 2 (solid line). For $\text{Kr} + \text{C}$ reactions, the triangle symbols represent the total evaporation residue cross-section. The dashed lines correspond to calculations in which $J_{\text{transf.}}^{\text{max}} = 53 \hbar$ (26.4 MeV/nucleon) and $52 \hbar$ (34.4 MeV/nucleon). In the calculations represented by a dotted line $J_{\text{transf.}}$ was restricted to the range 48 - 53 $\hbar$ at 26.4 MeV/nucleon and 47 - 52 $\hbar$ at 34.4 MeV/nucleon

TABLE 1

	IMF			EVAPORATION RESIDUES		
E_{beam} MeV/nucl.	V_s cm/ns	M_s	ϵ^* MeV/nucl.	V_s MeV/nucl.	M_s	ϵ^* MeV/nucl
26.4	6.14 ± 0.06	96	2.8	6.41 ± 0.04	92	2.1
34.4	6.98 ± 0.07	96	3.8	7.37 ± 0.05	91	2.4
26.4	5.73 ± 0.06	103	4.0	5.98 ± 0.04	99	3.4
34.4	6.64 ± 0.07	101	4.8	6.96 ± 0.05	96	3.9
26.4	5.38 ± 0.05	110	4.8	5.65 ± 0.04	105	4.2
34.4	6.28 ± 0.06	107	5.8	6.61 ± 0.04	102	5.0

TABLE 2

		E_{beam} MeV/nuc1.	ϵ^* MeV/nuc1.	$J_{\text{transf}}^{\text{max}} (\hbar)$	$l_{\text{inc}}^{\text{max}} (\hbar)$
$^{84}\text{Kr} + ^{12}\text{C}$	{	26.4	2.8	22	22
		34.4	3.8	19	19
$^{84}\text{Kr} + ^{27}\text{Al}$	{	26.4	4.0	70	99
		34.4	4.8	70	111
$^{84}\text{Kr} + \text{natTi}$	{	26.4	4.8	80	148
		34.4	5.8	80	167

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

26.4 MeV/nucleon

34.4 MeV/nucleon

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15