Decay of excited ^{116}Ba* formed in the ^{58}Ni+^{58}Ni reaction via the emission of intermediate mass fragments

Raj K. Gupta and M. Balasubramaniam
Physics Department, Panjab University, Chandigarh-160014, India

Chiara Mazzocchi* and M. La Commara†
Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

Werner Scheid
Institut für Theoretische Physik, J.-L.-Universität, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

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A new cluster decay process is proposed for the intermediate mass fragments (IMFs) observed in the low energy ^{58}Ni+^{58}Ni→^{116}Ba* reaction. The IMFs arise as multiple "clusters" of masses less than ∼20, having their origin in macroscopic liquid drop energy. The α nuclei, in particular ^{12}C (or the complementary ^{104}Sn), are predicted to be the most probable decays for this reaction. The multiple light particle ($Z\leqslant 2$) emission, other than via the statistical evaporation process (not considered here), is also shown possible, but at higher energies. The calculations are shown to fit the available data on fragment production cross sections, with the total kinetic energy (TKE) of fragments taken as the parameter. The TKE is a measurable quantity, but at present no data on TKE exist for this reaction.

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I. INTRODUCTION

Intermediate mass fragments ($Z\geqslant 3$), also referred to as clusters or complex fragments, emitted from excited compound systems have been of much interest recently [1–4]. Studies are made at low, intermediate, and high energies. Here, we are concerned only with low energies (<15 MeV/nucleon), where, e.g., for the decay of excited ^{116}Ba* formed in 375 MeV ^{58}Ni+^{58}Ni reaction, a strong selectivity of intermediate mass fragments (IMFs) is indicated over the multiple light particle ($Z\leqslant 2$) production [2]. For a negligible fission component, the multiple light particles constitute the evaporation residue [5], best treated in the statistical Hauser-Feshbach analysis (the equilibrated compound nucleus emission) [3,6]. Heavy cluster emissions (up to $Z=20$), the IMFs, are also included [3] in the Hauser-Feshbach analysis (BUSCO code) but without much success for this reaction [1]. Alternatively, the binary decays, considered responsible for complex fragments, are treated in a statistical fission model [7], the GEMINI code [6], which has not yet been used for this reaction. It would certainly be worthwhile to use GEMINI also for this reaction and see the differences with respect to BUSCO, the pure Hauser-Feshbach code. The evaporation of light fragments ($Z\leqslant 2$) in GEMINI is also calculated within Hauser-Feshbach formalism. For the higher energy limit of the low energy range, where incomplete fusion occurs, the statistical multifragmentation models [8–11] have also been used, which are perhaps more suited for the intermediate (>35 MeV/nucleon) and high energy (>5 GeV/nucleon) heavy-ion reaction studies. These models use the participant-spectator picture and their main aim is to calculate the relative phase space for a given partition of primary fragments, using [9,11] or not using [8,10] the principle of minimal information or maximum entropy. These models are thus better designed to calculate the IMF multiplicity that gives the possible signatures of multifragmentation (not heavy but several, more than two, light fragments), though mass and charge distribution yields have also been calculated [12]. The essential point to note here is that these models, as well as the ones using thermodynamical equilibrium [13–15], are nondynamical models and are better suited to intermediate and high energy data.

In this paper, we propose a new reaction mechanism for the production of IMFs, which stems from the experimental signatures for temperatures of the emitter of the complex fragments having, e.g., in a 630 MeV ^{58}Ni+^{58}Ni reaction [3], a value of about a factor of 2 smaller than the expected value of the compound nucleus temperature, strongly dependent on the mass and charge of the emitted fragments. A similar result was obtained in an earlier experiment [16] and is again observed in the very recent experiment [1] where the total excitation energy (TXE) in the exit channel is observed to be too small (∼50 MeV) compared to the available compound nucleus excitation energy ($E^*_{\rm CN}$) of 96.4–130.9 MeV for the ^{58}Ni+^{58}Ni reaction. Apparently, the remaining available energy is taken away by the emitted fragments as the Q value ($Q_{\rm out}$) and their total kinetic energy (TKE), while penetrating the barrier. This follows from the fact that in the entrance and exit channels, neglecting the deformation effects of the fragments,

$$E^*_{\rm CN}=E_{\rm c.m.}+Q_{\rm in} \quad \text{(entrance channel)} \tag{1}$$

$$=Q_{\rm out}+{\rm TKE}+{\rm TXE} \quad \text{(exit channels)}, \tag{2}$$

*Permanent address: Universita' degli Studi di Milano, I-20133 Milano, Italy.

†Present address: Dipartimento di Scienze Fisiche, Universita' "Federico II," Napoli, Italy.

where $E_{\mathrm{c.m.}}$ is the entrance-channel center-of-mass energy and Q_{in} $(=-66.12$ MeV for $^{58}\mathrm{Ni}+^{58}\mathrm{Ni}\rightarrow^{116}\mathrm{Ba})$ and Q_{out} (positive and different for different exit channels) are the Q values. Such a situation is best represented by a fission or a cluster decay model, applied so far to compound systems with $A\sim 70$ [17]. Therefore, we present here a cluster decay calculation based on the preformed cluster model (PCM) of one of us and collaborators [18,19], also used earlier for the ground-state decay of Ba nuclei [20] (see also Ref. [21] for the ground-state decay of Ba nuclei). In other words, we treat the IMFs as a cluster decay process, which in the PCM of Gupta and co-worker [18] is a dynamical collective mass motion of preformed fragments through the barrier. We do not include here the (statistical) evaporation of light particles that occur before the begining of the binary decay process of cluster emission studied here in this paper. Hence, any discussion of multiple light particles in this paper relates to those expected at higher energies only, and these are in addition to those emitted promptly.

The model is described briefly in Sec. II and the calculations of its application to excited $^{116}\mathrm{Ba}^*$ nucleus are presented in Sec. III. A summary of our results is given in Sec. IV.

II. THE PREFORMED CLUSTER MODEL (PCM)

The PCM of Gupta and co-worker is based on the well known quantum mechanical fragmentation theory [22–25] where, in addition to the usual relative separation R and deformation β_i $(i=1,2)$ coordinates, we have two other dynamical collective coordinates of mass and charge asymmetries $\eta=(A_1-A_2)/(A_1+A_2)$ and $\eta_Z=(Z_1-Z_2)/(Z_1+Z_2)$. Then, the decay half-life $T_{1/2}$ and the decay constant λ, in decoupled R and η motions [18,19,34], is

$$\lambda=\frac{\ln 2}{T_{1/2}}=P_0\nu_0 P, \tag{3}$$

where the preformation probability P_0 refers to motion in η and the penetrability P to R motion. The ν_0 is the assault frequency. The $P_0=\sqrt{B_{\eta\eta}}|\psi(\eta(A_i))|^2(2/A)$ $(i=1$ or $2)$, with $\psi^{\nu}(\eta)$, $\nu=0,1,2,3,\ldots$, as the solutions of stationary Schrödinger equation in η, at fixed R,

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V_R(\eta)\right\}\psi^{\nu}(\eta)=E^{\nu}\psi^{\nu}(\eta), \tag{4}$$

solved at $R=R_a=C_t$ $(=C_1+C_2)$, fixed empirically for the ground-state decay, since this value of R (instead of $R=R_0$, the compound nucleus radius) assimilates to a good extent the effects of both the deformations of two fragments and neck formation between them [26]. The C_i are Süssmann central radii $C_i=R_i-(1/R_i)$, with the radii $R_i=1.28A_i^{1/3}-0.76+0.8A_i^{-1/3}$ fm. For the decay of an excited compound nucleus, we take $R=R_a+\Delta R$, depending on TKE or Q_{eff} defined in Eq. (8) and Fig. 1. The temperature effects are also included here in this model through a Boltzmann-like function $|\psi|^2=\sum_{\nu=0}^{\infty}|\psi^{\nu}|^2\exp(-E^{\nu}/T)$, where the temperature T (in MeV) is related as $E^*_{\mathrm{CN}}=(A/9)T^2-T$.

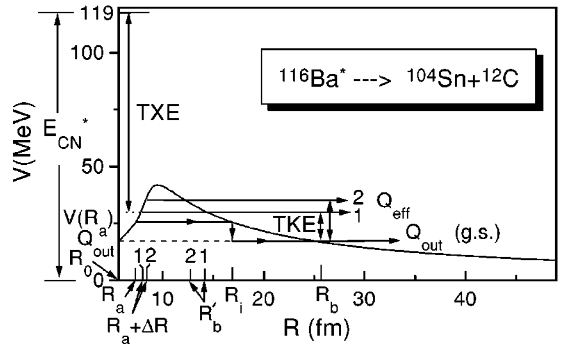

FIG. 1. The scattering potential for $^{116}\mathrm{Ba}^*\rightarrow^{104}\mathrm{Sn}+^{12}\mathrm{C}$, giving the paths for both the ground- and excited-state decays.

The fragmentation potential $V_R(\eta)$ in Eq. (4) is calculated within the Strutinsky renormalization procedure, as

$$V_R(\eta)=\sum_{i=1}^{2}[V_{\mathrm{LDM}}(A_i,Z_i)]+\sum_{i=1}^{2}[\delta U_i]\exp\left(-\frac{T^2}{T_0^2}\right)+(Z_1Z_2e^2/R)+V_P, \tag{5}$$

where the liquid drop energy $V_{\mathrm{LDM}}=B-\delta U$, with B as the experimental binding energy [27] and shell correction δU calculated in the ''empirical method'' of Myers and Swiatecki [28], with its constants readjusted [29] to fit the calculated binding energies of Möller *et al.* [30] for $8\leqslant Z\leqslant 29$ and extrapolated to $Z<8$. V_P is the additional attraction due to the nuclear proximity potential [31]. The charges Z_i in (5) are fixed by minimizing it in η_Z. The shell corrections δU are considered to vanish exponentially, with $T_0=1.5$ MeV. The mass parameters $B_{\eta\eta}(\eta)$, representing the kinetic energy part in Eq. (4), are the smooth classical hydrodynamical masses [32], since we are dealing here with a situation where the shell effects are almost completely washed out (see below).

The WKB tunneling probability $P=P_iP_b$, calculated for the tunneling path shown in Fig. 1, with

$$P_i=\exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_i}\{2\mu[V(R)-V(R_i)]\}^{1/2}dR\right], \tag{6}$$

$$P_b=\exp\left[-\frac{2}{\hbar}\int_{R_i}^{R_b}\{2\mu[V(R)-Q_{out}]\}^{1/2}dR\right], \tag{7}$$

was solved analytically [18]. R_a $(=C_t=C_1+C_2)$ and R_b are, respectively, the first and second turning points, with $V(R_b)=Q_{out}$ for ground-state decay. For the decay from an excited state of the compound nucleus with total excitation energy TXE of decay fragments, we assume

$$V(R_a+\Delta R)=V(R'_b)=Q_{\mathrm{eff}}=\mathrm{TKE}+Q_{\mathrm{out}}, \tag{8}$$

with $P=P_b$ given by Eq. (7), where Q_{out} is replaced by Q_{eff} and the limits of integration are from $R_a+\Delta R$ to R'_b.

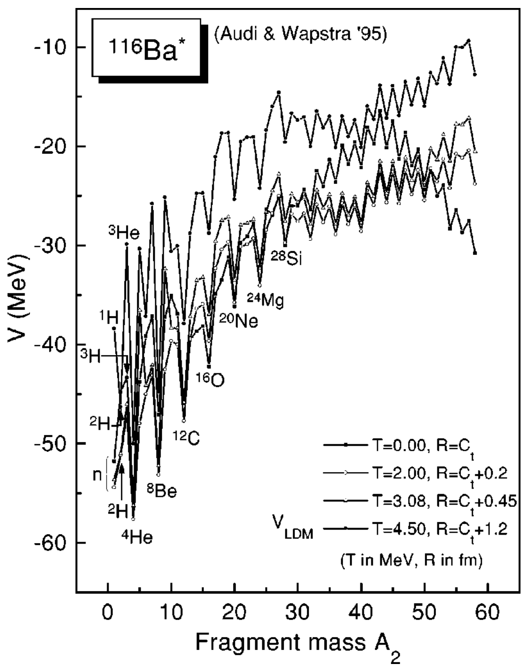

FIG. 2. The fragmentation potential $V(A_2)$ for a ^{116}Ba* nucleus, calculated at the ground state ($T=0$, $R_a=C_t$) and at various temperatures including the one at $E_{\mathrm{c.m.}}=185.5$ MeV ($T=3.08$ MeV) [1], with R_a values as shown. A_2 is the mass of light fragment.

The assault frequency ν_0 in Eq. (3) is given simply as $\nu_0=(2E_2/\mu)^{1/2}/R_0$, with $E_2=(A_1/A)Q_{\mathrm{out}}$ [or $=(A_1/A)Q_{\mathrm{eff}}$ for the case of decay from an excited state] as the kinetic energy of the lighter fragment, for Q_{out} (or Q_{eff}) shared between the two fragments.

III. CALCULATIONS

We have first calculated the fragmentation potentials $V(A_2)$ for ^{116}Ba* (Fig. 2) at various T (or E^*_{CN}) values, including the ones corresponding to experiments of Ref. [1], with $R=R_a+\Delta R$ chosen as described below. At $T=0$, $R=R_a=C_t$, and at $T=4.5$ MeV, $R=C_t+1.2$, where δU reduce almost to zero and one is left with only the liquid drop part of potential V_{LDM}. The calculated liquid drop surface is smooth for the heavier fragments, as expected, but for the lighter $N=Z$, $A\leqslant 28$ fragments, the α-nucleus structure, seen at $T=0$, persisted at all temperatures, including for the extreme case of V_{LDM}. Thus the α-nucleus structure has its origin in the macroscopic liquid drop energy, as was shown earlier in Ref. [17], and is due to the "Wigner term" in the binding energies of Ref. [30], used here (see also Ref. [28] and references therein for the role of Wigner term in the liquid drop energy). In other words, with increased T only the shell structure effects go to zero and *not* the α-nucleus structure. Note that the V_{LDM} used here is not dependent on T, and the use of a T dependence in V_{LDM} [11,33] could also be important. In any case, there is no α-nucleus structure in the Strutinsky shell corrections of Ref. [30], as is also explicitly shown in Ref. [34]. Also, V_P does not contain any α-nucleus structure [35]. Hence, within the context of temperature independent V_{LDM}, the $N=Z$ α-nuclei IMFs should be produced preferentially at all temperatures, though the light-particle ($A\leqslant 3$) structure is still found to change with T.

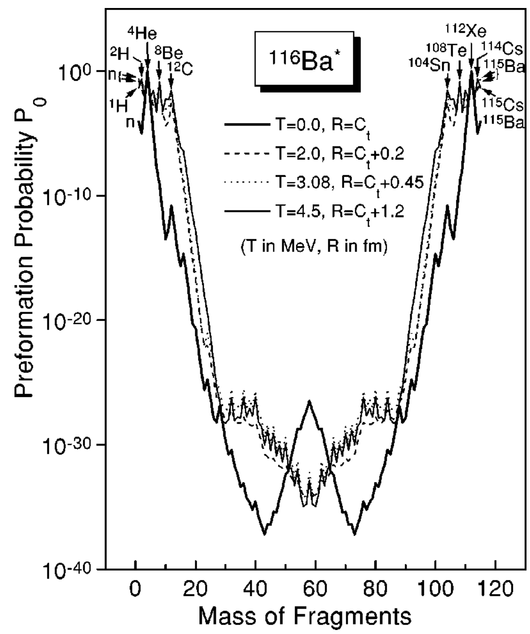

FIG. 3. The fragment preformation probability P_0 for the decay of ^{116}Ba* nucleus, calculated for the potentials in Fig. 2.

Figure 3 gives the preformation probability P_0 of the fragments, calculated for the potentials presented in Fig. 2. First of all we notice that at $T=0$ (the ground-state decay), the α-nucleus structure is obtained but only ^{4}He (and the complementary heavy fragment ^{112}Xe) is strongly preformed. The yields for all other fragments are very small. Second, as temperatures are added, the yields for *all* fragments with mass up to $\sim$16, including the light particles with $A\leqslant 3$, increase tremendously. The light-particle preformation depends strongly on the temperature [e.g., exactly as in $V(A_2)$, a neutron and ^{3}H at $T=0$, 2.0, and 3.08 MeV change, respectively, to a proton (^{1}H) and ^{3}He, with the minimum becoming a maximum at ^{2}H, for $T=4.5$ MeV] as well as on the choice of first turning point $R_a+\Delta R$ or the TKE (see Fig. 5, inset). The preformation yields are largest for $T=4.5$ MeV (the V_{LDM} potential) and for deutrons (^{2}H) and the α fragments ^{4}He, ^{8}Be, and ^{12}C. This means that P_0 for the IMFs with masses less than $\sim$16 are largest for the extreme case of the V_{LDM} potential, and the particle production (other than the evaporation residues, not included here) also becomes equally probable. In other words, compared to the total mass spectrum observed for the lighter heavy-ion collisions [17,36], here we see only a small window for the formation of light particles and IMFs, and their complementary fragments, as is explicitly shown in Fig. 4.

Figure 5 shows our results for the decay constant λ. The n and ^{3}H emissions are not shown here because Q_{eff} values are negative for all the T and R_a values considered here. For other light particles, Q_{eff} are positive only for the cases shown, i.e., for ^{1}H and ^{2}H at $T=3.23$ and 4.5 MeV, and only ^{3}He at $T=4.5$ MeV, which further depend on the ΔR value (see inset).

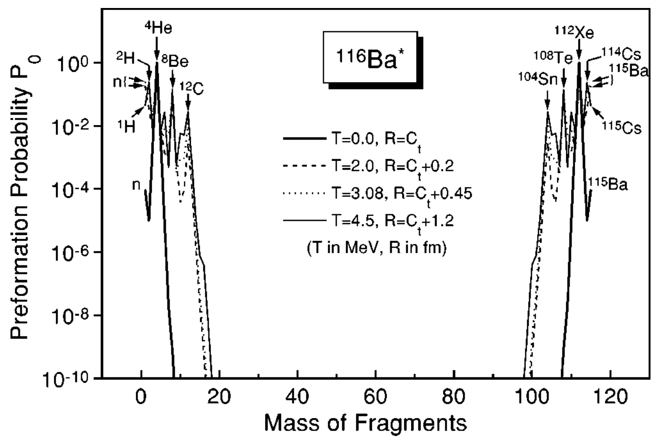

FIG. 4. Same as for Fig. 3, but only for the light particles and IMFs.

In Fig. 5, the large (negative) orders of λ values suggest that, except for the ^{4}He cluster, the other results are of interest only for $T \geqslant 2$ MeV, where $\lambda \sim 10^{-3}$ to 10^{10}. In other words, no IMFs are predicted for $T < 2$ MeV, or equivalently $E_{\mathrm{c.m.}} < 115$ MeV (this number can be calculated precisely if more points between $T=1$ and 2 MeV are calculated in Fig. 5), a result in general agreement with that of Beckerman *et al.* [5] for fusion of ^{58}Ni+^{58}Ni below $E_{\mathrm{lab}} = 220$ MeV. ^{4}He has the largest decay constant for the $T = 0$ case, but at higher T values it lies lower than the other two equally probable α-nuclei (^{8}Be and ^{12}C) decays. Also, the light-particle ($A \leqslant 3$) production (in addition to the evaporation residues) becomes probable only for $T \geqslant 3.23$ MeV, the largest experimental energy of Ref. [1]. At higher T, or larger ΔR, the proton (^{1}H) emission becomes more probable than the deuteron (^{2}H), and the non-α-like decays, including ^{17}O with very low P_0, are equally predominant (due to the penetrability factor P). Interestingly, at the extreme case of $T = 4.5$ MeV, the decay rates for all the α-nucleus IMFs are not only higher but also identical with the light-particle production rates, thereby stressing the importance of the macroscopic liquid drop effect in these reactions.

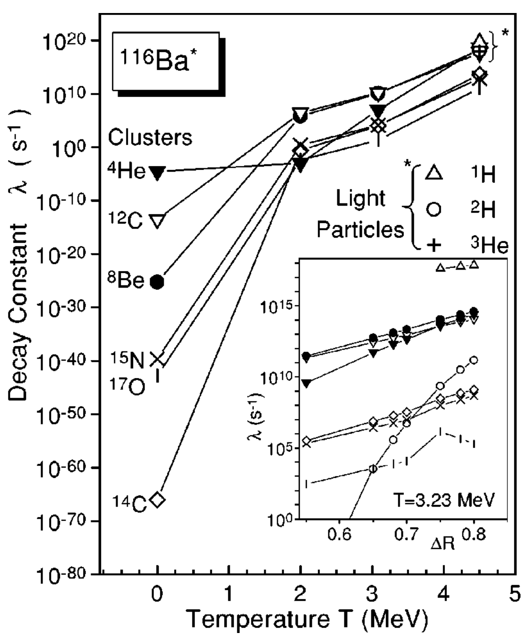

FIG. 5. The cluster decay constant λ as a function of the temperature T for emissions of light particles, α, and some non-α-like clusters from ^{116}Ba*, calculated at the same four T and R_a values as in Fig. 2. The inset shows the variation of λ with ΔR for one fixed T value.

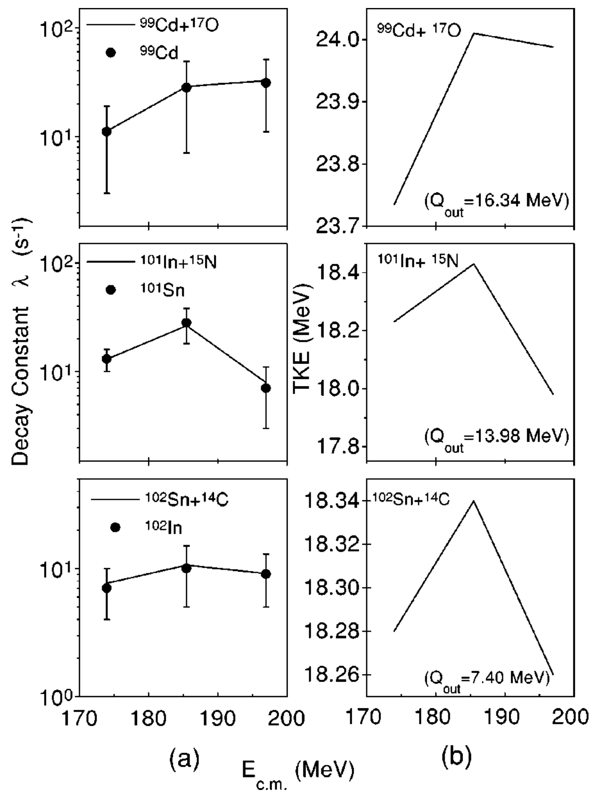

FIG. 6. (a) The decay constant λ as a function of the center-of-mass energy $E_{\mathrm{c.m.}}$ for various decays of ^{116}Ba*. The experimental data are from Ref. [1] and, in each case, are normalized to the calculations by a constant factor. (b) The TKE vs $E_{\mathrm{c.m.}}$, with the corresponding R_a values given in text.

Finally, Fig. 6(a) shows our calculated λ versus $E_{\mathrm{c.m.}}$ for the best choice of the TKE $[=V(R_a+\Delta R)-Q_{\mathrm{out}}]$ values, given in Fig. 6(b). The calculations are made for the three experimentally measured decays of Ref. [1], and in each case for the three experimental $E_{\mathrm{c.m.}}$ (corresponding to $T=2.93$, 3.08, and 3.23 MeV) of Ref. [1]. The TKE values in Fig. 6(b) are chosen as the potentials $V(R_a+\Delta R)$ with $R_a = C_t$ and $\Delta R = 0.438$, 0.463, and 0.461 for ^{99}Cd+^{17}O, $\Delta R = 0.22$, 0.24, and 0.195 for ^{101}In+^{15}N, and $\Delta R = 0.26$, 0.265, and 0.258 for ^{102}Sn+^{14}C decays. The data of Ref. [1] are then *normalized* to the calculated λ values since, theoretically, the two quantities (the measured fragment production cross sections and the calculated fragment decay constants) refer to the fragment probability $|\psi(\eta)|^2$ and hence are the same, except for a simple normalization constant to be multiplied throughout.

We notice in Fig. 6(b) that the variation of TKE (and hence of $R_a+\Delta R$) with $E_{\mathrm{c.m.}}$ depends very much on the decay, a result that needs experimental verification. Notice that the last two calculated decays are for ^{101}In and ^{102}Sn fragments, since these are the most probable fragments in our calculations for 101 and 102 masses, whereas the experimental data available for comparisons are for ^{101}Sn and ^{102}In, respectively. For this reason, our fitted TKE values for these two decays may be considered only as suggestive. Also, the TKE values are measurable quantities. Such measurements are already available for lighter heavy-ion collisions [37], and we would like to stress that the same for the reaction ^{58}Ni+^{58}Ni would put the model calculations presented here to a stringent test. The TKE is the only parameter of this model.

IV. SUMMARY

Summarizing, the new cluster decay process studied for the first time for IMFs shows that only the IMFs with $Z \geqslant 2$, $A<20$, and not the complete mass spectrum, are emitted from an excited compound nucleus like ^{116}Ba* and that these IMFs, produced only at $E_{\mathrm{lab}}>200$ MeV, are like the clusters observed in natural cluster radioactivity. The IMFs arise mainly due to the macroscopic liquid drop energies (since the shell effects are almost zero at the excitation energies involved), favoring $N=Z$ α nuclei. In particular, the ^{12}C (or ^{104}Sn) decay is intersting. Such a result could be taken as the possible signature for ^{12}C or Sn radioactivity from the excited ^{116}Ba* nucleus, that was first expected from its ground-state decay [20,21]. At still higher energies (where pure liquid drop energies enter the calculations), the multiple light-particle ($Z<2$) production (other than the promptly emitted ones) also becomes equally probable and one should perhaps use the T-dependent V_{LDM}.

The measured cross sections [1] are available only for non-α-decays, which are easily explained here with a reasonable choice of the total kinetic energies (TKE) or total excitation energies (TXE) of the fragments. Hence, this additional information on TKE is very much needed from experiments for an actual test of the model proposed.

An extension of our calculations to still higher energies shows that for light-particle emission one requires much higher TKE values than are shown involved for the experiments of Ref. [1]. Note that only the higher-mass fragments were actually measured in Ref. [1].

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