Limiting excitation energy in fusion-evaporation reactions?

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The systematics of fusion-evaporation reactions in the mass-symmetric system ^{40}Ar+^{40}Ca are studied for incident energies of 5–30 MeV/nucleon. The measurement of the resulting evaporation residues in coincidence with emitted neutrons permits a clear identification of central collisions and a separation of equilibrium and preequilibrium contributions. The total neutron multiplicities and the total average mass loss of the system both show a tendency of soft saturation. Above about 20 MeV/nucleon the increase of the energy removal is entirely due to preequilibrium emission of light particles. The total excitation energy of the evaporation residues approaches a maximum value, but the excitation energy per nucleon rises linearly without any sign of saturation. At even higher projectile energies the production of evaporation residues is dramatically reduced and they become indistinguishable from spectatorlike fragments resulting from less central collisions. Thus, the long-standing question of a limiting excitation energy in hot nuclei can probably not be solved by experimental studies of fusion-evaporation reactions. [S0556-2813(97)04304-5]

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I. INTRODUCTION

Central heavy-ion collisions at intermediate energies (10–100 MeV/nucleon) offer an excellent tool to produce and obtain information about hot, i.e., highly excited, nuclei. This energy range covers the Fermi energy of nucleons in nuclei, about 30 MeV/nucleon, where the transition from mean-field-dominated dynamics of low-energy reactions to two-body collision dynamics of high-energy reactions is expected. The relative influence of these two mechanisms dominates the formation of hot nuclei. Fundamental quantities are, e.g., thermalization time scales and the decay time of the highly excited finite nuclear matter (for a review see [1]). Furthermore, a relevant and still open question concerns the maximum excitation energy (or maximum temperature) a fused system can sustain. Does a maximum total excitation energy $E^*_{\rm max}$ exist or a maximum excitation energy per nucleon $\mathcal{E}^*_{\rm max}(=E^*_{\rm max}/\text{nucleon})$? Obviously the maximum excitation energy should not exceed the total binding energy of the system.

With increasing relative velocity of projectile and target, all dissipative processes in intermediate-energy heavy-ion reactions become increasingly ''incomplete'' due to nonequilibrium phenomena in a fast first step of the reaction. We restrict ourselves in the present work to central or near-central collisions. In this case, the scenario in the earliest stage of the reaction is usually described by preequilibrium (PE) emission of nucleons and light clusters. The energy and momentum carried away by these particles prevent the system from converting the total available center-of-mass energy into excitation energy [''incomplete fusion'' (IF)]. At the end of the PE stage (which is of the order of 10^{-22} s or even less [2]) thermalization [or equilibration (EQ)] is reached in the compound nucleus $\widetilde{\rm CN}$ (the tilde indicates the *reduced* compound nucleus *actually* formed). This means as well that PE emission accelerates the equilibration process. For light- and medium-mass composite systems ($A<100$) the highly excited $\widetilde{\rm CN}$ mainly decays further by evaporative emission of neutrons and charged light particles (LP's), leading to evaporation residue (ER) formation. Heavy systems which mostly decay by fission are not considered here.

Among a variety of theoretical approaches, the most successful PE models are a quantal phase-space model [3] and the nucleon exchange transport model [4]. Both theories allow for a parameter-free prediction of PE nucleon (especially neutron) energy spectra *and* angular distributions (i.e., PE multiplicities as well). Energy spectra of nucleons and light clusters emitted in PE reactions can also be reproduced within the Boltzmann master equation approach [5,6], provided that certain input parameters are set properly.

In the present work, excitation energies and temperatures are derived from kinetic energy spectra, multiplicities, and angular distributions of light ejectiles (preferentially neutrons which yield more reliable temperatures) coincident with ER's. This method should be less model dependent and therefore more reliable than the derivation of these quantities from recoil velocities and residual masses alone. A lot of effort has been devoted in the near past to experimental investigations of LP emission related to ER formation, especially at incident energies close to 30 MeV/nucleon. Very recent examples, among many others, are studies performed with neutrons [7,8] or charged LP's [9–16]. While most of these studies were conducted in asymmetric systems, the symmetric reactions ^{40}Ar+^{40}Ca [8], ^{40}Ar+^{45}Sc [9], and ^{28}Si+^{28}Si [10,11] were also investigated.

In producing hot nuclei, symmetric collision systems offer the advantage that at a given projectile velocity the total kinetic energy in the center-of-mass (c.m.) system and thus the maximum available excitation energy are highest. Morgenstern *et al.* [17] have shown that in this case IF is less

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likely for a mass-symmetric system than for an asymmetric one. Moreover, symmetric systems allow for a more stringent separation of the PE component since all particle-emitting sources rest in the overall c.m. system, thus avoiding possible ambiguities in fitting moving-source velocities.

We report here on an analysis of experiments which focus on central collisions between equal-mass nuclei in which an ER is formed. Events were selected where, besides detection of an ER, only light particles are emitted in the PE and in the subsequent evaporative stage. With these severe restrictions we are looking, at the highest energies, for only a tiny fraction of the reaction cross section leading to very hot nuclei. But a clear isolation of a particular class of events is indispensable for a quantitative understanding of the production mechanisms or deexcitation properties of such nuclei. The results allow us to establish especially in the $^{40}Ar+^{40}Ca$ system in the bombarding energy range 5–30 MeV/nucleon stringent systematics concerning LP multiplicities, temperatures (PE and EQ), mass balances and average excitation energies. A brief account of this work already appeared elsewhere [18].

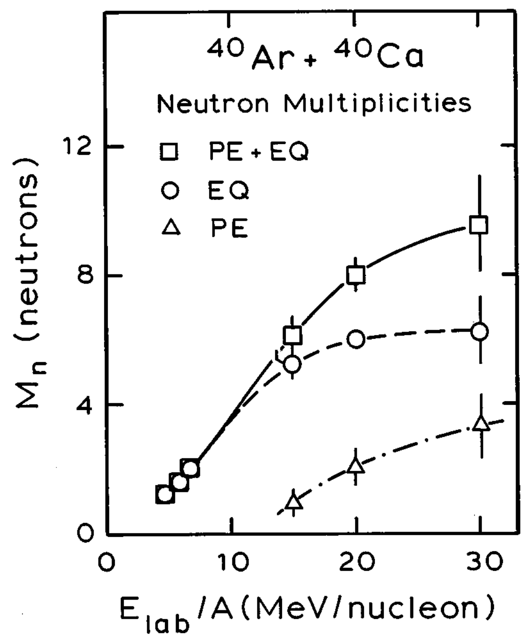

FIG. 1. Neutron multiplicities as derived from the measured neutron angular correlations. PE and EQ denote the preequilibrium and equilibrium components, respectively. The curves are only to guide the eye.

II. EXPERIMENTS AND TRENDS IN NEUTRON RESULTS

As a detailed description of the experimental techniques and data evaluation procedures used can be found in Refs. [19,20], only the salient features will be briefly mentioned here. The experiments were performed at UNILAC/GSI Darmstadt [19–21], SARA/ISN Grenoble [8], and VICKSI/HMI Berlin [21,22]. The relevant quantities of the compound nuclei ($\widetilde{CN}$) formed (masses, temperatures, average excitation energies) were obtained exclusively from correlations between neutrons (partly also protons and deuterons [19–21]) and heavy residues. Neutrons were detected with position-sensitive liquid scintillation counters [23] covering almost the complete in-plane angular range. For all neutron detectors, n/γ pulse-shape discrimination was employed. The neutron energies were determined by time of flight (TOF) relative to the beam pulse. Thin plastic scintillator paddles in front of the neutron detectors vetoed energetic charged LP's and enabled, at 20 MeV/nucleon incident energy, also the identification of fast protons and deuterons.

Coincident fusion residues were detected at forward angles ($3°$–$10°$) either with solid-state ΔE-E telescopes for element separation or with single E detectors which, together with the TOF signal, allowed for mass determination. Separation of ER's from more peripheral reaction products was accomplished from the velocity spectra, after preselection of the data via appropriate window settings in the mass- and element-energy distributions, respectively.

All PE neutron data (energy-spectra *and* angular correlations) can be understood very well and on an absolute scale within the framework of a quantal phase-space model [3] which, in addition to the mean field, takes nucleon-nucleon collisions properly into account. The agreement between experiment and theory convincingly indicates that these energetic neutrons are emitted in the first two-body encounters and thus probe the phase-phase configuration in the earliest stages of the collision.

Neutron multiplicities (multiplicities refer to the number of neutrons emitted per ER event) as obtained by integration of the measured angular correlations are displayed in Fig. 1 for the system $^{40}Ar+^{40}Ca$ at different incident energies. While in the energy range 15–30 MeV/nucleon the EQ multiplicity only increases by about 20% (and essentially keeps constant between 20 and 30 MeV/nucleon) the PE multiplicity increases drastically in the same energy interval, roughly by a factor of 4.

Similar trends can be seen from the neutron temperatures. Equilibrium (T_{EQ}) temperatures extracted from the measured energy spectra, using a Maxwellian shape parametrization $\sqrt{E}\exp(-E/T)$, are depicted in Fig. 2. Again the EQ temperature varies with clearly decreasing slope in the energy interval 15–30 MeV/nucleon whereas the preequilibrium temperature parameter increases monotonically from 8 to 11 MeV/nucleon [8,20,21]. We conclude from the neutron data that the equilibrium component tends to a soft saturation, whereas the preequilibrium component steadily increases with bombarding energy. These trends provide strong evidence that *the additional available energy is mainly removed by preequilibrium emission from the system.*

III. MASS BALANCES

In the presented experiments we find a striking interrelation between ER distributions and the total number (PE plus EQ) of emitted light particles. Whereas neutrons were detected completely, charged LP's have been measured only at 20 MeV/nucleon bombarding energy. In cases where charged LP data are not available, we proceeded by means of a simple statistical model. The idea is the following: If incomplete fusion is due to PE light-particle emission, there should be little difference in LP emission in complete fusion and IF. Therefore we consider both processes as evaporation at different energies and angular momenta. Then global

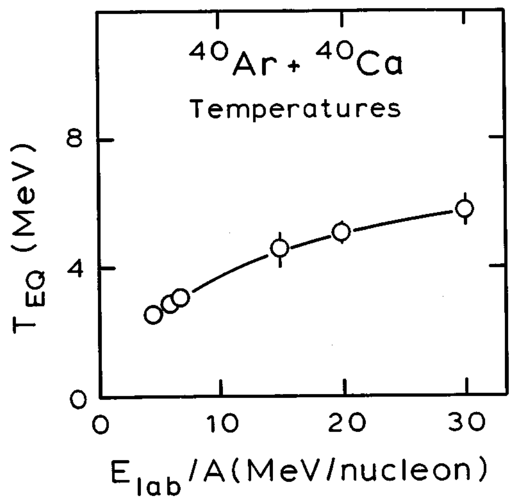

FIG. 2. Neutron temperatures (EQ). All values are extracted from the measured neutron kinetic energy spectra, using a Maxwellian shape parametrized as $\sqrt{E}\,\exp(-E/T)$. The curves are only to guide the eye.

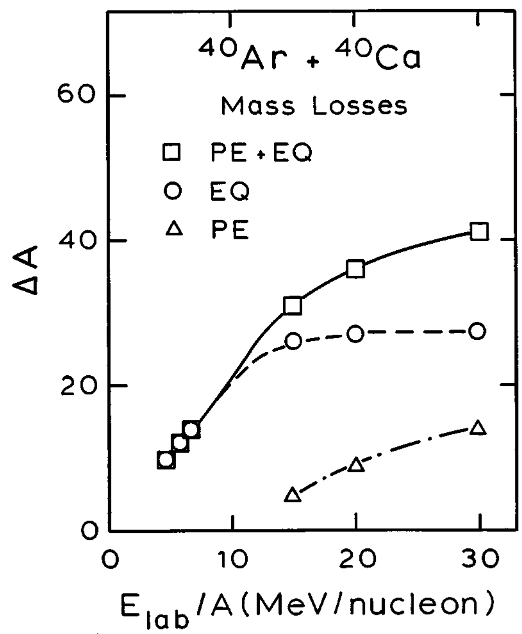

FIG. 3. Mass losses (number of nucleons) due to preequilibrium (PE) and equilibrium (EQ) light-particle emission and their sum. The curves are only to guide the eye.

quantities like LP multiplicities or residue distributions $\sigma_{ER}(A,Z)$ can be described in a common way for PE and EQ emission.

A simple method [20,24] to model an evaporation cascade is to assume that the probability for producing a given residue is proportional to the number of different evaporation chains leading to this residue. In this context, the chain (n,p,α) is different from the chain (p,n,α), etc. Measured ER mass and/or element distributions and LP multiplicities served as input for the model: in all cases M_n, if measured, also M_p; otherwise, $M_p = M_n$ was assumed. For deuterons, the ratio of multiplicities, M_p/M_d, was taken from the measurements at 20 MeV/nucleon. As output, the model yields optimized LP multiplicities (including M_α) from fits to the measured ER distributions (emission of t and ^{3}He was not taken into account explicitly). In all cases the agreement between measured and calculated ER mass and element distributions, respectively, is very good [8,20,21]. For the present system the centroids of the distributions reasonably fulfill well the relation $A_{ER} = 2Z_{ER}$.

Thus obtained mass losses ΔA due to light-particle emission in the different stages of the reaction are shown in Fig. 3 for the ^{40}Ar+^{40}Ca system. The indicated ΔA values comprise neutrons, protons, deuterons, and α particles. The separation of ΔA^{PE} and ΔA^{EQ} relies upon the assumption that the relation $M_i^{PE}/M_i^{tot} = M_n^{PE}/M_n^{tot}$ (the latter ratio having always been determined experimentally) holds for all $i = p,d,\alpha$. Here, the superscript ''tot ''stands for PE+EQ. The average masses of the actually formed compound nuclei, $A_{\widetilde{CN}}$, and evaporation residues, A_{ER}, are consequently obtained by the relations $A_{\widetilde{CN}} = A_{CN} - \Delta A^{PE}$ and $A_{ER} = A_{CN} - \Delta A^{tot}$, respectively. Furthermore, $A_{\widetilde{CN}} - A_{ER} = \Delta A^{tot} - \Delta A^{PE} = \Delta A^{EQ}$ holds.

The trends in the energy dependence of mass losses in Fig. 3 are akin to those of neutron multiplicities (cf. Fig. 1). Whereas ΔA^{EQ} levels off at about 15 MeV/nucleon bombarding energy, the PE component continuously increases in the energy range indicated. The total mass loss ΔA^{tot} tends to a soft saturation, exhausting about half of the full CN mass at the highest energy. We conclude from the mass balances that the ''missing'' mass, i.e., the mass difference between the full compound and the observed ER's, can be fully accounted for by the emission of only light particles with $Z \leqslant 2$ in both the preequilibrium and equilibrium stages. The emission of fragments heavier than α particles is, if any, weak in this class of events.

IV. LIMITING EXCITATION ENERGY FOR FUSION-EVAPORATION?

Having separated the PE and EQ components, we proceed to the quantitative determination of the excitation energy $E^*_{\widetilde{CN}}$ of the compound nucleus actually formed. We derive here $E^*_{\widetilde{CN}}$ from the balance between the maximum available energy $E_{c.m.}$ and the sum of the kinetic energies of all ejectiles, $\Sigma(E_{kin}^{EQ} + E_{kin}^{PE})$, taking into account the total separation energy S which can be calculated from binding energies [25]

$$\sum (E_{kin}^{EQ} + E_{kin}^{PE}) = E_{c.m.} - S(\mathrm{CN} \rightarrow \mathrm{ER}) \quad . \tag{1}$$

The kinetic energies of light charged particles are not known explicitely from all our measurements. Therefore, we have to estimate the sharing of the kinetic energy between the PE and EQ components for these particles. On the assumption that the ratio $E_{kin}^{EQ}/(E_{kin}^{EQ} + E_{kin}^{PE})$ shall be the same for all particles (p,d,α) and equal to that for neutrons, one obtains

$$\frac{E_{kin}^{EQ}}{E_{kin}^{EQ} + E_{kin}^{PE}} = \frac{\langle E_{kin}^{EQ}\rangle_n}{\langle E_{kin}^{EQ}\rangle_n + \langle E_{kin}^{PE}\rangle_n} = \frac{M_n^{EQ} T_{EQ}}{M_n^{EQ} T_{EQ} + M_n^{PE} T_{PE}} \quad , \tag{2}$$

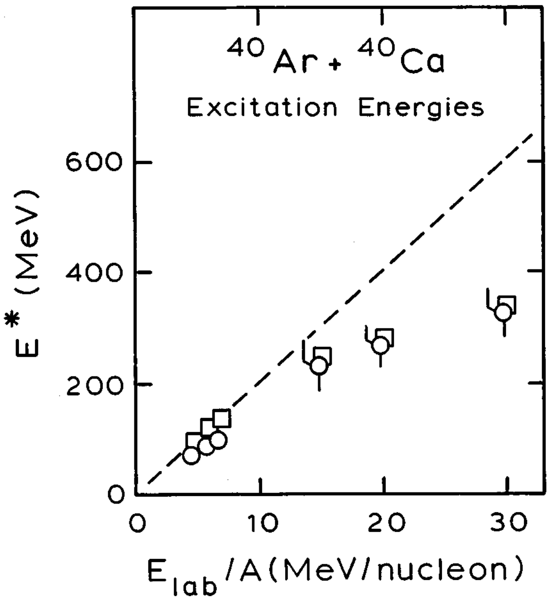

FIG. 4. Total excitation energies derived according to Eqs. (3) and (4) shown as squares and circles, respectively. The squares at about 5 MeV/nucleon incident energy were calculated with the evaporation code CASCADE. The error bars consider uncertainties of the measured temperature values only. The dashed straight line indicates the maximum available energy in the system, $E_{c.m.}$. Excitation energies refer to the compound nuclei actually formed, $\widetilde{CN}$.

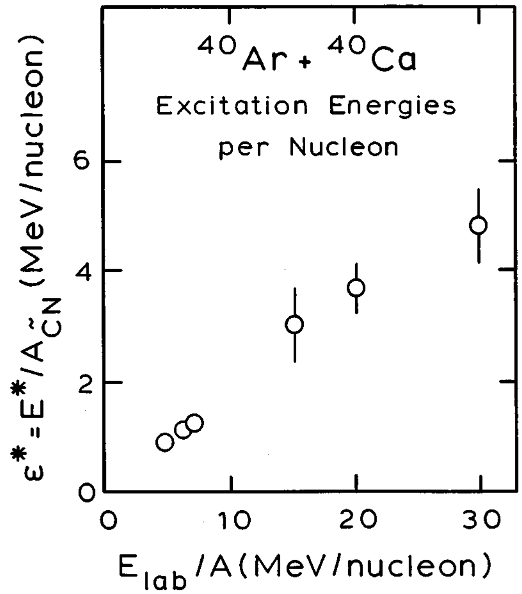

FIG. 5. Excitation energies per nucleon. Same as circles in Fig. 4, but now related to the average masses $\overline{A_{\widetilde{CN}}}$ of the respective compound nuclei $\widetilde{CN}$ actually formed.

where the latter quantities are from experiment and the relation $\langle E_{kin}\rangle = 1.5$ T has been used for neutrons according to a Maxwellian preexponential of $E^{1/2}$. Here one should keep in mind that only the neutron kinetic energy spectra (and temperatures derived) do not depend on Coulomb effects due to deformations of the source. Using Eq. (2) one arrives at

$$E^*_{\widetilde{CN}} = \sum_{n,p,d,\alpha} E^{EQ}_{kin} + S(\widetilde{CN} \to ER) \quad , \qquad (3)$$

where S denotes the separation energy for the decay indicated in the brackets. In the energy balance, Eq. (3), the kinetic energy of the evaporation residue is not included since residues are the result of isotropic light-particle emission from the equilibrated compound nuclei and, therefore, can be assumed to rest in the frame of the respective emitter.

A widely used method to determine excitation energies is the derivation from the well-known relation $E^* = aT^2$, where a is the level density parameter. For $A_{\widetilde{CN}} \approx 90$ it has been shown that a is close to $A_{\widetilde{CN}}/8$ (as known from lower excitation energies) also up to temperatures T of about 7 MeV [26]. This covers reasonably well the mass and temperature ranges considered here. The measured neutron equilibrium temperatures T_{EQ} are mean temperatures of the whole respective neutron cascades. For the initial temperature in a neutron cascade, $\frac{12}{11}T_{EQ}$ was obtained [27]. Since the equilibrium cascade starts from the (equilibrated) reduced compound nucleus with average mass $\overline{A_{\widetilde{CN}}}$, we end up with

$$E^*_{\widetilde{CN}} = \frac{\overline{A_{\widetilde{CN}}}}{8} \frac{12}{11} T_{EQ} \quad . \qquad (4)$$

Total excitation energies are shown in Fig. 4 for different bombarding energies. The agreement between the values derived from Eqs. (3) and (4) is remarkably good which *a posteriori* might also reflect the validity of the assumptions made in Eq. (4) for the present case. Nevertheless, we believe that the first method yields the most reliable results since here excitation energies have been determined from a direct measurement of decay particle multiplicities and energy removal by them in the preequilibrium and equilibrium stages, respectively.

As can be seen from Fig. 4, the total excitation energy increases with incident energy, but much less than the maximum available energy. We again interpret this behavior as due to the increasing emission of PE particles having ever increasing kinetic energies (cf. Figs. 1 and 2), which remove an increasing amount of the total available energy from the system: E^* tends to a soft saturation, approaching a value of about 350 MeV.

Owing to the combined measurement of heavy residues and light decay particles the average mass of the actual compound nuclei is known from experiment. This enables a reliable determination of excitation energies per nucleon, $\mathcal{E}^* = E^*/\overline{A_{\widetilde{CN}}}$, from the total values E^*. As is shown in Fig. 5, $\mathcal{E}^*$ behaves quite different from E^* with increasing bombarding energy. While total excitation energies clearly tend to saturate, excitation energies per nucleon monotonically increase up to the highest energy measured, 30 MeV/nucleon. This behavior reflects the fact that in addition to energy also an ever-increasing amount of mass is removed by the PE ejectiles: The residual available excitation energy is thus shared among accordingly lighter reduced compound nuclei $\widetilde{CN}$. The slightly decreasing slope in Fig. 5 might indicate tendencies for a saturation at higher energies but maximum values of $\mathcal{E}^*$ have obviously not yet been reached in the bombarding energy range explored. We feel strongly that $\mathcal{E}^*$ (or T), rather than E^*, is favored as the more rel-

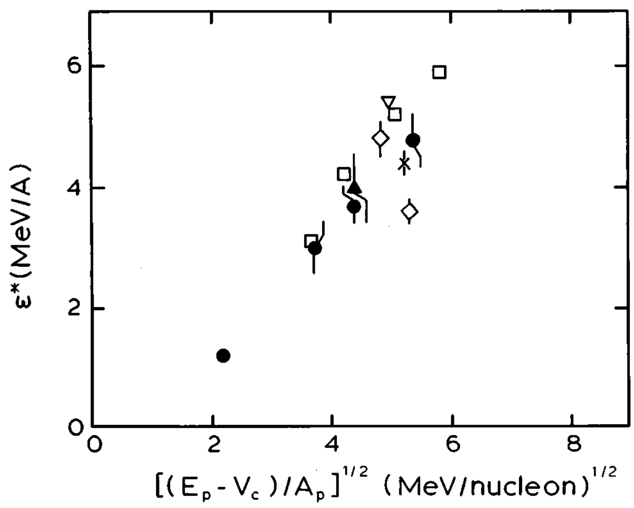

FIG. 6. Excitation energies per nucleon. Our work: solid circles ($^{40}Ar+^{40}Ca$) and solid triangle ($^{28}Si+^{28}Si$, Ref. [21]). Squares and the inverted triangle represent ^{40}Ar-induced reactions on ^{68}Zn [28] and Ni [7], and diamonds and the cross ^{32}S on ^{58}Ni [15,29] and Ag [14], respectively.

evant quantity when looking for a limiting excitation energy in CN formation since it reflects both energy *and* mass removal from the system during the PE stage.

Our data are compared in Fig. 6 with various Ar- and S-induced reactions having fairly comparable compound masses and energies per projectile nucleon. The excitation energies are plotted versus projectile velocity above the barrier which is related to the amount of energy deposited in the system. Only a few results have been selected which, in our opinion, comply with criteria which ensure a rather good confidence in the measured excitation energies. With one exception [28] all data displayed in Fig. 6 originate from experiments where heavy-residue–light-ejectile correlations explicitly have been measured. The scattering of the data at least partly reflects different selection criteria used in the evaluation procedures and different impact parameters involved. The obvious discrepancy between the two data points from the $^{32}S+^{58}Ni$ measurements at close-lying values of the bombarding energy is discussed in Ref. [29].

The excitation energies per nucleon depicted in Fig. 6 steadily increase with incident energy up to 35 MeV/nucleon (highest data point). However, no definite conclusions can be drawn from these results as to a saturation of $\mathcal{E}^*$ in incomplete fusion-evaporation reactions in such systems. This especially holds in those cases where systematics in one system have been established over a large range of bombarding energies: $^{40}Ar+^{40}Ca$ (present work) and $^{40}Ar+^{68}Zn$ [28].

Similar trends have been observed at still higher bombarding energies. In a recent investigation, incomplete fusion evaporation has been studied in $^{40}Ar+^{27}Al$ collisions at incident energies of 36–65 MeV/nucleon [30]. Although the production of heavy residues drastically decreases above 36 MeV/nucleon, equilibrated very incomplete fusion nuclei, corresponding to our $\widetilde{\mathrm{CN}}$, and accordingly lighter ER's persist up to 65 MeV/nucleon. For the most central collisions (impact parameters <2 fm), excitation energies increase slowly with bombarding energy, ranging from $\mathcal{E}^*=3.2$ MeV/nucleon at 36 MeV/nucleon to 5.5 MeV/nucleon at 65 MeV/nucleon. On the other hand, due to difficulties in the separation of the PE and EQ components, also values being systematically larger than those quoted above by about 1.5 MeV/nucleon can be derived as upper limits for $\mathcal{E}^*$. These higher values, reaching 7 MeV/nucleon at 65 MeV/nucleon incident beam energy, would follow the trend shown in Fig. 6, whereas the authors of [30] favor the lower ones. Likewise in a similar investigation in the $^{40}Ar+Ag$ reaction [31], an increase in excitation energy per nucleon between 50 and 70 MeV/nucleon bombarding energy is reported, reaching values above 6 MeV/nucleon for the hottest incomplete fusion nuclei.

V. CONCLUSIONS

We have discussed the systematics of ER formation in $^{40}Ar+^{40}Ca$ reactions for an incident energy range of 5–30 MeV/nucleon. In coincidence measurements with emitted light particles a clear extraction of central collisions was possible. Furthermore, for the neutron emission channel a separation of EQ and PE contributions could be achieved. The choice of a mass-symmetric system led to the highest possible ER excitation energy for a given incident energy.

The results indicate a soft saturation of the total neutron multiplicities and the total average mass loss of the full compound system. If EQ and PE parts are further distinguished, one finds in both cases that the former is essentially constant for incident energies above about 20 MeV/nucleon. The increasing mass loss for higher projectile energies is solely due to PE emission. Very similar trends are shown by the EQ and PE temperature parameters derived from the neutron spectra.

The excitation energy of the actually formed compound nuclei was determined with two independent methods. The results obtained from the energy-temperature relation with a standard level density of $a=A/8$ and those from a calculation based on the measured kinetic energies of the ejected particles are in very good agreement. Studying the incident energy dependence one seems to approach a saturation value $E^*\approx 350$ MeV for the maximum energy which can be pumped into the compound nucleus formed in $^{40}Ar+^{40}Ca$ fusion. However, a more relevant quantity for the question of a limiting excitation energy in CN formation is provided by the energy per nucleon, $\mathcal{E}^*$. Because of the ever-increasing mass removal, an almost linear increase of $\mathcal{E}^*$ over the whole range of projectile energies with no sign of saturation is observed. This finding is corroborated by other experimental studies with not too asymmetric mass systems.

The values $\mathcal{E}^* \approx$ 5–6 MeV/nucleon at the maximum projectile velocities studied are already rather close to the separation energy which provides a natural upper bound. However, it cannot be excluded that a limiting value might be reached at even higher velocities. Experimental searches for ER formation in the energy regime $E>35$ MeV/nucleon face severe problems. The ER production cross sections are dramatically reduced, since multifragmentation becomes the dominant reaction mode [32]. Even worse, in the case of collision partners with roughly equal masses (needed to reach the highest possible energies), the average mass of the actually formed compound nucleus will drop below the projectile mass (cf. Fig. 3). This makes central collisions indistinguishable from reactions at larger impact parameters where spectator fragments with comparable mass distribution and kinematics can be produced. We thus conclude that it will probably not be possible to solve the long-standing problem of a limiting excitation energy in hot nuclei by experimental investigations of evaporation residues formed in fusion reactions.

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