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Excitation energy sharing in binary peripheral heavy ion reactions at Fermi energies

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Evidence for the dependence of excitation energy sharing between two heavy remnants on the difference in the lost mass in two-body peripheral heavy ion reactions at Fermi energy is presented, based on experimental results for the reactions ^{93}Nb + ^{116}Sn, ^{116}Sn + ^{93}Nb, and ^{93}Nb + ^{93}Nb at 38A MeV. An observable based on the experimental velocities of the heavy residues is used to select reactions with equal preevaporative masses of projectile-like fragments and target-like fragments. The excitation energy, evaluated by means of a complete average calorimetry, is found to be larger for the nucleus that finally retains a larger part of the hot interaction region.

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I. INTRODUCTION

In the 80s and 90s many experimental and theoretical studies were devoted to the investigation of the degree of equilibration attained by projectile-like fragments (PLF) and target-like fragments (TLF) in deep inelastic collisions, first at low and then at intermediate beam energies. In particular, by means of asymmetric collisions, it was possible to put into evidence that the evaporation [1–4] and the sequential fission [5] decay processes are affected by some memory of the entrance channel. Both findings were attributed to a dependence of excitation energy sharing on the net mass transfer between PLF and TLF, possibly due to the reaction time becoming too short for the attainment of full equilibration in the internal degrees of freedom. For example, in the rather asymmetric reaction ^{74}Ge + ^{165}Ho at 8.5A MeV, the fraction of excitation energy gained by the PLF was shown to be linearly correlated with its net mass transfer [1]. Likewise, in the reaction ^{100}Mo + ^{120}Sn at 14.1 and 19.1A MeV, it was found that, for a given primary mass, both the total amount of evaporated mass and the fission probability were larger when that value of the primary mass had been reached by a net gain of nucleons [3,5]. Moreover, in the reaction ^{93}Nb + ^{116}Sn at 25A MeV, the different evolution of the multiplicities of hydrogen and helium particles gave support to the hypothesis that not only the excitation energy sharing but also the angular momentum transfer actually depends on the net mass transfer [4]. In these older works, the evaporated masses were estimated from the difference between the primary masses (obtained with kinematic methods, see, e.g., Ref. [6]) and the secondary masses (measured with silicon detectors by means of the energy–time-of-flight technique). Good information on both reaction partners was obtained by measuring the PLF characteristics of a given collision, both in direct and reverse kinematics.

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With the rise of the bombarding energies into the Fermi energy domain (20–50A MeV), it was realized (see, for example, Refs. [7–13]) that in peripheral and semiperipheral collisions increasing amounts of light charged particles (LCP) and intermediate mass fragments (IMF) are emitted at midvelocity, i.e., with velocities intermediate between those of the PLF and TLF. Although the origin of these reaction products is still not fully settled, their peculiar emission pattern indicates that they are produced (from the contact region and on a rather short timescale) either during the interaction of the colliding nuclei or immediately after their reseparation. The midvelocity emissions leave two rather hot primary fragments (indicated henceforth with PLF* and TLF*), which then decay via a chain of evaporative steps and become the cold secondary residues (PLF and TLF) that finally reach the detectors. Thus, an appreciable amount of mass and energy is emitted on a rather short timescale (of the order of 100 fm/c or less, see Refs. [14,15]) while the two main reaction products are still rather hot and possibly not fully equilibrated.

At Fermi energies, because of the midvelocity emissions, the basic assumption of kinematic methods, namely, that the reaction is strictly binary and that the primary masses of PLF* and TLF* add up to the total mass of the system, is no longer fulfilled. The presence of a sizable midvelocity emission would cause an overestimation of the kinematically reconstructed masses of PLF* and TLF*, which therefore can be used neither for reliably estimating the total amount of evaporated mass nor for sorting the data in bins of primary mass (as it was done at lower energies [3,4]); a different approach—which takes into account the midvelocity contribution—is presented in this work. Also the variable TKEL, defined as (TKEL = $E_{\rm in}^{\rm c.m.} - \frac{1}{2}\tilde{\mu} v_{\rm rel}^2$) (where $E_{\rm in}^{\rm c.m.}$ is the center-of-mass energy in the entrance channel, $v_{\rm rel}$ the PLF–TLF relative velocity, and $\tilde{\mu}$ the reduced mass assuming an exactly binary reaction), no longer represents a good estimate of the true "total kinetic energy loss" of the collision. However, as argued in Ref. [13], TKEL can still be used as an *ordering parameter* for sorting the events in bins of increasing centrality. Since the relationship between the impact parameter and its experimental estimators is somewhat model dependent, in this article we prefer to present the results as a function of the experimental quantity TKEL; a detailed discussion on this point can be found, for similar reactions, in Appendix A of Ref. [13].

II. EXPERIMENTAL SETUP AND ANALYSIS METHODS

The experimental data presented in this article refer to the collision ^{93}Nb + ^{116}Sn at 38A MeV, which was studied, in direct and reverse kinematics, with the FIASCO setup (for details, see Refs. [13,14,16]) at the Superconducting Cyclotron of the Laboratori Nazionali del Sud of INFN in Catania; for comparison, the symmetric collision ^{93}Nb + ^{93}Nb also was investigated, at the same beam energy.

The FIASCO setup was specifically designed for the investigation of peripheral and semiperipheral collisions. It includes 24 position-sensitive Parallel Plate Avalanche Detectors (PPAD) that cover a large fraction of the relevant solid angle (about 70% of the forward hemisphere) and measure the velocity vectors of heavy ($Z \gtrsim 10$) fragments with very low detection thresholds ($\approx$0.1A MeV), so that they can detect also the low energetic TLF of very peripheral collisions. LCPs and IMFs are detected in 182 three-layer phoswich telescopes, located behind most of the PPADs and covering about 30% of the forward hemisphere: they identify protons, deuterons, tritons, and light elements ($2 \leqslant Z \lesssim$ 15–20), measuring also their time-of-flight. Finally, the charge and energy of the PLF are measured with 96ΔE(200-μm-thick)–$E_{\rm res}$ (500-μm-thick) silicon telescopes located behind the most forward PPADs; in conjunction with the time-of-flight of the coincident PPAD, one can thus obtain the secondary mass of the PLF.

The presented analysis concerns two-body events, which at these energies still represent more than 50% of the total reaction cross section [13]: they were selected by requiring that only two heavy fragments (with $Z \gtrsim 10$) be detected by the PPADs. The background of incompletely detected three-body events (which becomes appreciable only for large TKEL values) was estimated and subtracted [13]. In this article the attention is focused on peripheral and semiperipheral collisions, where the PLF and TLF can be unambiguously distinguished and their emission patterns of LCPs and IMFs do not get too intermixed. A good determination of the secondary mass of the heavy fragment and of its evaporated particles was possible only for the PLF, while it was impractical for the TLF because of severe threshold effects and the reduced geometric coverage of the setup at larger angles. Therefore, as in previous experiments [3,4], information on the TLF was obtained just by reversing the collision (with exactly the same relative velocity) and matching the results for the PLFs in the two cases (direct and reverse kinematics) for the same TKEL window.

The experimental yields of LCPs and IMFs were corrected for the geometrical coverage of the setup and for the detection thresholds (for more details, see Ref. [13]). Midvelocity emissions, although mainly populating the region between PLF* and TLF*, have long tails that may appreciably extend into the forward hemisphere in the PLF* rest system. Therefore, to reduce such a contamination, the evaporative multiplicities of the PLF (and the following estimate of the total evaporated charge, or mass) were obtained by selecting particles in the forward cone $\theta^{\rm em} \leqslant 45^\circ$ (in the PLF reference frame) and extrapolating the result to the whole angular range [13]. The measured velocities of the PLF* were also corrected for the effect of the correlated recoil of the emitter (see Ref. [13] for a detailed discussion of this point).

The above-mentioned procedure allows one to obtain the evaporative multiplicities, in bins of TKEL, directly from the measured evaporated particles, instead of deducing them as the difference between primary and secondary masses (we note here that primary is the mass *after* midvelocity emission and *prior* to evaporative emission). To estimate the relative size of the evaporating PLF* and TLF*, we build event-by-event the ratio P_v, defined as

$$P_v = \frac{v_{\rm TLF}^{\rm c.m.}}{v_{\rm PLF}^{\rm c.m.} + v_{\rm TLF}^{\rm c.m.}},$$

where $v_{\rm PLF(TLF)}^{\rm c.m.}$ is the experimental length of the velocity vector of the PLF(TLF), transformed into the c.m. reference system.

In a binary reaction, P_v would represent the fraction of primary mass residing in the PLF*, as sequential evaporation does not change, on average, the velocity vectors of the emitters. The midvelocity emissions might indeed displace the c.m. origin of the (PLF* + TLF*) subsystem with respect to the c.m. of the whole system. However, the displacement is small (midvelocity emissions are a small fraction of the total mass of the system) and mainly transversal (particle emission is preferentially orthogonal to the PLF–TLF separation axis, as shown by data [13] and confirmed also by Coulomb trajectory calculations [14]), so the lengths of the velocity vectors depend only marginally on which of the two c.m. systems is used. Therefore, we assume that P_v can still be used to approximately estimate the mass ratio of the two primary fragments.

Indeed the experimental values of P_v are strictly correlated to the average primary charge $Z_{\rm prim}$ of the PLF*, obtained by summing up its secondary charge $Z_{\rm sec}$ with all the evaporated charges $Z_{\rm evap}$ (a similar estimation of the primary mass would be less reliable, because of the undetected free neutrons). As an example, Fig. 1 presents the average primary charge of the PLF* in the asymmetric collisions ^{93}Nb + ^{116}Sn and ^{116}Sn + ^{93}Nb at 38A MeV (solid and open circles, respectively), as a function of P_v for a bin of TKEL (550–650 MeV). The most important result is that there is a clear, almost linear, correlation between $Z_{\rm prim}$ and P_v and that the correlations for the two kinematics nicely match at $P_v = 0.5$, where the primary charges of the PLF* in the two cases are equal. On the contrary, the secondary charges $Z_{\rm sec}$ of the PLFs in the direct and reverse kinematics (solid and open triangles, respectively) have a weak dependence on P_v, as they vary by just a couple of charge units over a rather wide range of P_v and do not match at $P_v = 0.5$. All this demonstrates that, within a window of TKEL, the variable P_v effectively selects samples of events with different average primary charges, thus corroborating our assumption that P_v can be used to estimate the primary mass asymmetry. Similar results are obtained also for the other bins of TKEL, the main difference simply being that the accessible range of P_v values becomes narrower with decreasing TKEL.

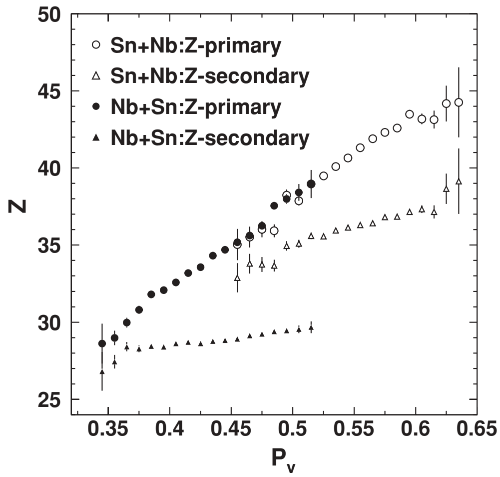

FIG. 1. Primary and secondary average charges (circles and triangles, respectively) of the PLF for the systems ^{93}Nb + ^{116}Sn and ^{116}Sn + ^{93}Nb (solid and open symbols, respectively) at 38A MeV as a function of P_v for the bin 550 ⩽ TKEL ⩽ 650 MeV. Bars are for statistical errors only.

Indeed, the statistics of the event samples are largest around values of P_v corresponding to the projectile asymmetry of the entrance channel (0.445 and 0.555 for the two kinematics) and decrease more or less steeply when moving away from these values.

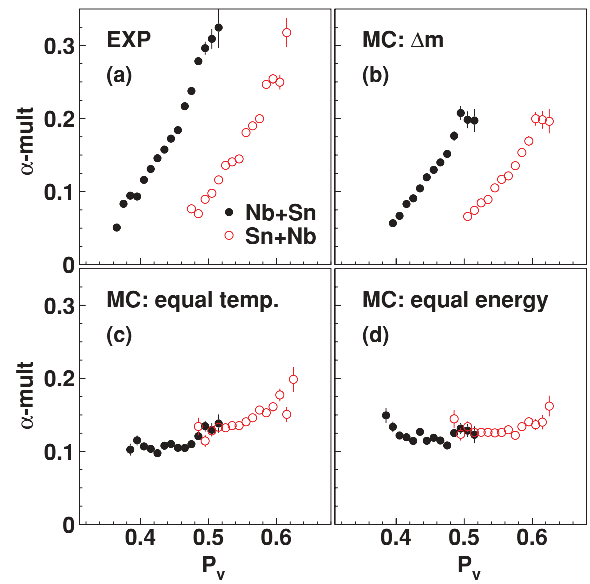

FIG. 2. (Color online) Average multiplicities of α particles evaporated by the PLF* in the cone $\theta^{em} \leqslant 45^\circ$, plotted as a function of P_v, for TKEL = 450–550 MeV in the direct and reverse kinematics (solid and open circles, respectively). The panels refer to experimental data (a) and, for a qualitative comparison, to Monte Carlo simulations of evaporative decay with different assumptions on the PLF–TLF excitation energy sharing: dependent on the net mass transfer (b), of the equal-temperature type (c), and of the equal-energy type (d).

III. RESULTS

Figure 2(a) presents an example, for one bin of TKEL, of the direct comparison of the experimental evaporative multiplicities in the collision ^{93}Nb + ^{116}Sn, studied with direct (solid circles) and reverse kinematics (open circles). The data are plotted as a function of P_v and refer to the multiplicities of α particles emitted from the PLF in the cone $\theta^{em} \leqslant 45^\circ$. A similar behavior is found for all kinds of light particles and in all TKEL bins: for a given P_v, the PLF multiplicities in the direct kinematics are systematically higher than those in the reverse kinematics.

In the following, for the sake of clarity, instead of referring to the PLF* in direct and reverse kinematics, we rather use PLF* and TLF*, respectively, as if the two nuclei were the partners of the collision in *direct* kinematics, at a given TKEL; in this way PLF* (TLF*) assumes the more physical meaning of that reaction partner that was originally the lighter (heavier) reactant in the asymmetric entrance channel of the reaction.

In general, the multiplicities are larger when the initial mass is lighter (i.e., in the direct reaction) and this is particularly evident at $P_v = 0.5$, corresponding to PLF* and TLF* with equal primary masses. As higher evaporative multiplicities are expected to correspond to higher excitation energies, the result of Fig. 2(a) indicates that the excitation energy sharing depends not on the relative mass asymmetry of the exit channel,[1] but on the relative change in mass of PLF* and TLF*. Being that the exact nature of the midvelocity mechanism is not yet fully ascertained and lacking a complete characterization of its emissions, it is not easy to realistically include the effects of midvelocity emissions in a simulation. However, it is already instructive to consider the outcome of a Monte Carlo simulation which, using the GEMINI statistical code [17], describes the decay of the excited PLF* and TLF* of a binary reaction, under different assumptions for the energy sharing. Indeed, for what concerns the secondary decay, the main effect of the preceding midvelocity emissions is just to remove some mass and energy from the system, but the qualitative outcome of the simulation does not appreciably depend on this fact. In Fig. 2 the lower panels show the results for the two most commonly used energy-sharing recipes, which, by definition, depend only on the final masses of the heavy residues and not on the initial ones. In the equal-temperature hypothesis [Fig. 2(c)], larger masses (i.e., higher values of P_v) imply higher excitation energies and hence larger multiplicities: however, the particle multiplicities of PLF* and TLF* nicely match at $P_v = 0.5$, forming a single straight (and less steep) line, at variance with the behavior of the experimental data. In the equal-energy hypothesis [Fig. 2(d)], the particle multiplicities of PLF* and TLF* are approximately equal, independently of the mass asymmetry. As shown in Fig. 2(b), a behavior qualitatively similar to that of the experimental data is obtained only when introducing in the energy sharing the dependence of Ref. [3] on the change of mass asymmetry for PLF* and TLF* (with respect to the value in the entrance channel).

[1] Henceforth in this article, "exit channel" always refers to the primary exit channel, before sequential evaporation.

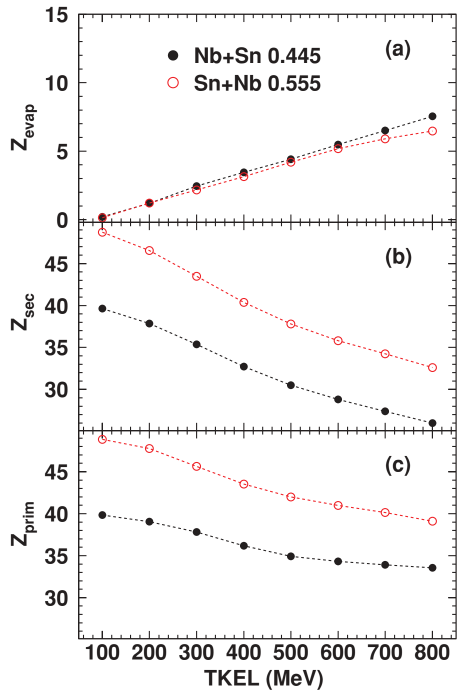

FIG. 3. (Color online) Average charge of all evaporated particles (a), final residue (b), and primary nucleus (c) as a function of TKEL, for ^{93}Nb + ^{116}Sn at 38*A* MeV. Solid (open) circles refer to the PLF (TLF), for events with $P_v = 0.435$–0.455 (0.545–0.565), corresponding to values appropriate to the entrance channel of the direct (reverse) kinematics. Lines are guides to the eye. The presented TKEL values are estimated to correspond approximately to the outmost 4 fm of impact parameter.

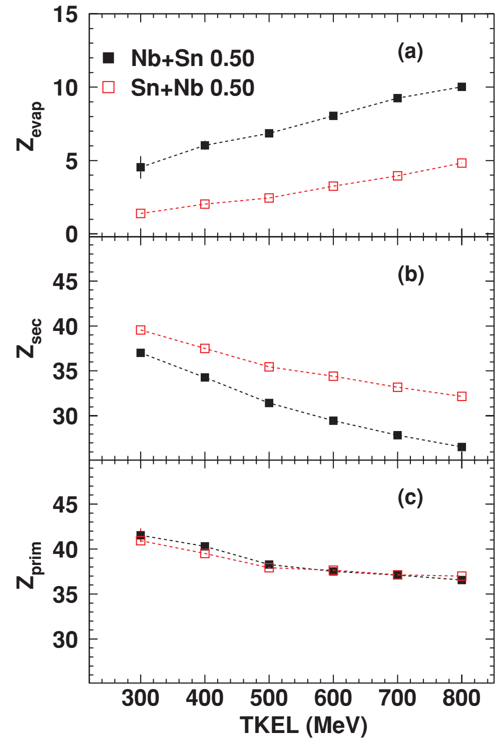

FIG. 4. (Color online) Same as in Fig. 3, but for events with $P_v = 0.49$–0.51, corresponding to symmetric exit channels for both kinematics.

The total evaporated charge $Z_{\rm evap}$ of the asymmetric reaction ^{93}Nb + ^{116}Sn at 38*A* MeV is presented, as a function of TKEL, in Figs. 3(a) and 4(a), where the solid and open symbols refer to the PLF⋆ and TLF⋆, respectively. In Fig. 3, solid (open) circles refer to a selection of P_v around 0.445 (0.555), which corresponds to the entrance channel asymmetry of the direct (reverse) kinematics. This means that, although both the PLF⋆ and the TLF⋆ are allowed to become lighter (because of the midvelocity emissions), the original mass ratio is preserved. This selection well represents the average behavior of the collision, as the experiment shows that the bulk of the events stays peaked at about the initial asymmetry. It is worth noting that the two nuclei practically evaporate the same total number of charges, thus suggesting that they have similar excitation energies; actually, to make a stronger statement in this respect, one would need some information, or some assumption, also on the evaporation of free neutrons. The average secondary charges $Z_{\rm sec}$ of the PLF and TLF residues, shown in Fig. 3(b), differ by about 7–8 units almost at all TKEL. For completeness, Fig. 3(c) shows the primary charges $Z_{\rm prim}$ of the PLF⋆ and TLF⋆ simply obtained by adding $Z_{\rm sec}$ and $Z_{\rm evap}$.

Let us now look at what happens when we select reaction partners with approximately equal primary masses in the exit channel. This selection is accomplished by requiring $P_v \approx 0.5$ and the results are displayed in Fig. 4. Again, Figs. 4(a), 4(b), and 4(c) show the average total evaporated charge, the charge of the residue and the primary charge, respectively, as a function of TKEL. (Note that, being that the asymmetry is different from that of the entrance channel, the selected events are in the tails of the distributions and the statistics become too scarce below TKEL = 300 MeV.) This time, the situation is quite different with respect to that of Fig. 3. First of all, Fig. 4(c) shows that the PLF⋆ and TLF⋆ have practically the same primary charge $Z_{\rm prim}$ at all TKEL, thus confirming that P_v is indeed a good estimator of the charge (and presumably mass) ratio in the exit channel. One should also note that, to reach the symmetry in the exit channel, neither nucleus undergoes a net increase of charge: indeed, not only the primary charge $Z_{\rm prim}$ of the TLF⋆ (the former heavier ^{116}Sn nucleus) always remains well below 50 but also that of the PLF⋆ (the former lighter ^{93}Nb nucleus) always stays around 41 or below. This, together with the $P_v \approx 0.5$ selection, results in the TLF⋆ having lost the larger amount of charge with respect to the entrance channel. However, the most important feature to be stressed here is the remarkable difference in the evaporation of light particles shown in Fig. 4(a): the TLF⋆ definitely presents a smaller evaporation of light charged particles than the PLF⋆.

For comparison, Fig. 5 shows the results of the symmetric collision ^{93}Nb + ^{93}Nb at 38*A* MeV. Once more, Figs. 5(a), 5(b), and 5(c) present the average total evaporated charge, the charge of the residue and the primary charge, respectively. The upward and downward triangles refer to the asymmetric exit channels with values 0.445 and 0.555 for P_v, respectively (corresponding to the entrance-channel asymmetry of the two partners of the Nb + Sn system). Therefore the upward

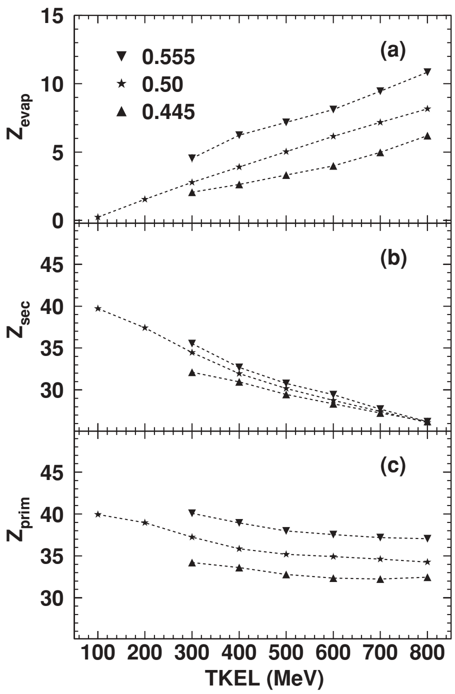

FIG. 5. Same as in Figs. 3 and 4, but for the symmetric collision ^{93}Nb + ^{93}Nb at 38A MeV. Upward and downward triangles refer to events with $P_v = 0.435$–0.455 and 0.545–0.565, respectively (i.e., values appropriate for the entrance channel of the Nb + Sn system). For comparison, the stars show the results for the symmetric exit channel, $P_v = 0.49$–0.51.

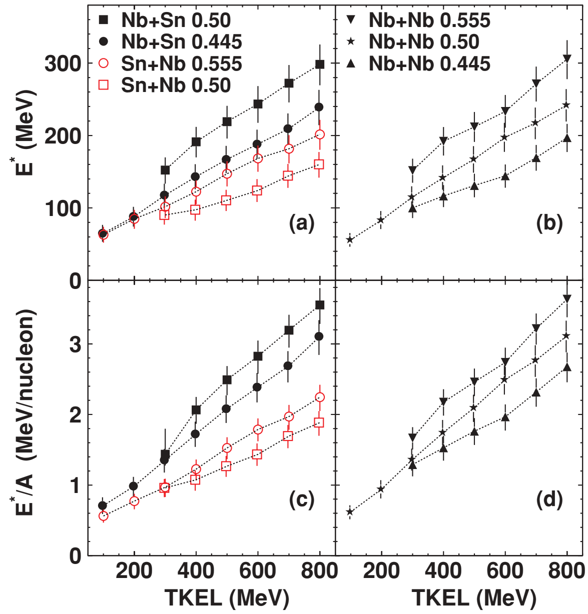

FIG. 6. (Color online) Average excitation energy of the primary nuclei, estimated from a calorimetric measurement. Part (a) corresponds, with the same meaning of symbols, to the data shown in Figs. 3(a) and 4(a); part (b) corresponds to those of Fig. 5(a). Error bars indicate the uncertainties in the estimation of $E^\star$.

(downward) triangles display the behavior of nuclei that have decreased (increased) their P_v value with respect to the entrance channel: as such, they should be compared to the open (solid) squares in Fig. 4. What is physically significant is the strong similarity of the data in Figs. 4(a) and 5(a): in both cases, PLF*s, which have reduced their fraction of the total mass, present a definitely smaller evaporation of light charged particles at all TKEL values. For panels (b) and (c), at first sight the data of Figs. 4 and 5 seem quite different, but this is trivially due to the fact that the Nb + Sn and Nb + Nb systems have different total charges and different asymmetries in the entrance channel.

The stars of Fig. 5 refer to the symmetric exit channel ($P_v = 0.5$). Their behavior can hardly be distinguished from that of the PLF* in the reaction ^{93}Nb + ^{116}Sn, shown by the solid circles in Fig. 3. Thus, provided that the selected asymmetry remains that of the entrance channel, the behavior of the former Nb nucleus seems to scarcely depend on whether it collided with another Nb or with a Sn nucleus.

As described in Ref. [18], from an average calorimetry of the evaporated particles it is possible to obtain an experimental estimate of the excitation energy of the PLF* and TLF*. The main uncertainty of the procedure resides in the guess for the multiplicity and the kinetic energies of the undetected free neutrons, as discussed at length in Refs. [13] and [18]. The temperatures deduced (with a Fermi-gas formula) from these excitation energies agree within 10–20% with those obtained from the slope of the kinetic energy spectra of protons and α particles and this fact gives confidence in the results of the implemented calorimetric method.

The values (and the relative uncertainties) of $E^\star$ and $E^\star/A$ shown in the upper and lower panels of Fig. 6, respectively, were obtained from the same experimental data displayed in Figs. 3(a), 4(a), and 5(a), using the recipe of Ref. [18]. If an equal-temperature (equal-energy) picture were correct, one would expect the data in the upper (lower) panels of Fig. 6 to collapse into a single correlation with TKEL, independently of mass asymmetry, but this is not the case. For an asymmetric system, when the asymmetry of the exit channel is the same as in the entrance channel [circles in Figs. 6(a) and 6(c)], the estimated values of $E^\star$ for the PLF* and TLF* appear to be quite similar, while those of $E^\star/A$ are more separated; this suggests that we are nearer to an equal-energy partition. On the other hand, when, in the same asymmetric collision, a symmetric exit channel is selected [squares in the same Figs. 6(a) and 6(c)], the excitation energy of the PLF* (the former Nb nucleus, solid squares) increases and that of the TLF* (former Sn nucleus, open squares) decreases, the net result being that the PLF* is considerably more excited and has also a considerably higher $E^\star/A$, than the TLF*. This behavior contrasts with both the equal-energy and the equal-temperature pictures, thus confirming the relevance of the mass-asymmetry change. Figures 6(b) and 6(d) refer to the symmetric system Nb + Nb and the strong similarity with Figs. 6(a) and 6(c) confirms the results obtained for the asymmetric systems. Here the stars represent the average $E^\star$ or $E^\star/A$ of each of the two collision partners for the exit channel which is symmetric ($P_v = 0.5$), just like the entrance one. When a value of P_v higher than 0.5 is selected, i.e., when the PLF* is heavier than the TLF*, both its excitation energy and its excitation energy per nucleon become larger than in the symmetric case. The opposite happens for a value of P_v lower than 0.5. Thus, quite independently of the initial mass asymmetry of the collision, when there is a change in the mass partition between the two reaction partners, the one that increases its fraction of the total primary mass is, on average, more excited and has also a higher $E^\star/A$.

IV. DISCUSSION

At low bombarding energy, it was proposed [3] to study the dependence of the excitation energy sharing on the net mass transfer in mass-asymmetric colliding systems. This was done by means of an excitation energy asymmetry parameter, R, defined as $R = (E^{\star l}_{\rm sym} - E^{\star h}_{\rm sym})/(E^{\star l}_{\rm sym} + E^{\star h}_{\rm sym})$, where $E^{\star l}_{\rm sym}$ and $E^{\star h}_{\rm sym}$ indicate the excitation energies of the two primary nuclei of a mass-symmetric exit channel, which were the former light and heavy collision partner in the entrance channel, respectively. Actually, this parameter was estimated by means of the experimental ratio $R = (\Delta A^{l}_{\rm sym} - \Delta A^{h}_{\rm sym})/(\Delta A^{l}_{\rm sym} + \Delta A^{h}_{\rm sym})$, where $\Delta A^{l}_{\rm sym}$ and $\Delta A^{h}_{\rm sym}$ are the total masses evaporated by the two above-mentioned primary nuclei, under the assumption that the energy removed per evaporated nucleon is the same, on average, for all nuclei in the mass region of interest.

At equilibrium, the energy sharing of the two reaction partners was expected to depend only on the macroscopic variables characterizing the selected exit channel, and not on their past history. According to the two most common assumptions of energy sharing (equal-energy and equal-temperature), one expected a value of R compatible with zero, at all TKEL, for the mass-symmetric exit channel. On the contrary, R was found to be positive [3], starting with values around 0.4 in peripheral collisions and decreasing with increasing TKEL. Such a behavior was taken as an indication [4] that with increasing bombarding energy the interaction time becomes too short to allow the exchange of enough nucleons to reach equilibrium: hence, the heavy fragment that gains nucleons gets, on average, also a larger share of the total excitation energy.

At Fermi energies, the midvelocity emissions make the determination of the primary masses unreliable, but the ratio R can be evaluated either from the measured average multiplicities of Fig. 4(a) or from the estimated excitation energies of Fig. 6(a). In both cases a positive value of R of about 0.3–0.4 is obtained and this value is quite independent of TKEL; i.e., it does not display any decreasing tendency. At intermediate bombarding energies, the idea of a too short contact time for reaching equilibrium becomes even more plausible and a possible emerging picture is the following. As shown in Ref. [18], the excitation energy is initially localized in the contact region between the interacting nuclei. Part of this excited nuclear matter is emitted at midvelocity on a rather short time scale [14], while the remaining part is shared between PLF* and TLF*. Shortly after reseparation, a strongly anisotropic emission of particles is observed [19], but with passing time the excitation becomes more and more distributed among all the internal degrees of freedom of the two fragments, which finally deexcite by sequential evaporation. Due to fluctuations in the mass sharing during the separation phase, the fragment that retains a larger fraction of the excited nuclear matter of the contact region obtains also a larger share of the excitation energy and consequently it evaporates a larger number of charged particles.

This schematic picture can explain the features observed in the previous Figs. 3, 4, and 5. The primary nuclei selected in Fig. 3 have almost the same mass asymmetry as in the entrance channel, because they have retained comparable fractions of the interaction zone, thus ending up with similar excitation energies and similar evaporative emissions. On the contrary, the nuclei selected in Fig. 4 have equal primary masses, with the initially lighter one having retained, on average, a larger fraction of the interaction zone. Therefore, it is hotter and evaporates a larger number of particles, leaving a lighter final secondary residue. Concerning the symmetric collision of Fig. 5, the selection of an asymmetric exit channel implies that the heavier (lighter) primary nucleus retained a larger (smaller) share of the interaction zone with respect to the other reaction partner: it was therefore more (less) excited and evaporated more (less) particles. Thus there is a kind of compensation and in the two cases the final residues end up with secondary charges (and masses) rather close to each other and also close to those of the symmetric exit channel (which represents the average behavior of the whole collision).

V. SUMMARY AND CONCLUSIONS

In this work experimental evidence for the dependence of the excitation energy sharing between the hot PLF* and TLF* on their relative change in mass is presented for two-body heavy ion collisions at Fermi energies. This work extends to higher energies the investigations performed at lower beam energies [3,4], modifying the adopted experimental technique to take into account the new peculiar phenomena, such as the midvelocity emissions, emerging at Fermi energies. Midvelocity emissions remove part of the mass and excitation energy from the interaction region on a rather short time scale [14]. Being that the direction of these emissions is mainly perpendicular to the PLF–TLF separation axis, little perturbation is given to the magnitudes of the c.m. velocities of the two primary fragments, which can be used to estimate the mass asymmetry of PLF* and TLF*. As shown by the average values of the primary charges, moving along the mass-asymmetry coordinate never implies that either of the two primary nuclei becomes on average heavier than it was originally in the entrance channel: at all TKEL values, both partners contribute with charge (and mass) to the midvelocity emissions, although not always with an equal share. Indeed, the varying mass asymmetry of the primary nuclei in the exit channel seems to be due more to the fact that they retain a different amount of charge (and mass) from the hot interaction region than to a real transfer of nucleons from one to the other. As shown by the present analysis of the experimental data, the partner that finally retains a smaller (larger) part of the hot interaction region appears to be less (more) excited and hence it evaporates less (more) light particles.

A comparison of the presented data with theoretical predictions would be very interesting and probably also very challenging for the model (which, for peripheral collisions, should be some kind of transport code). In our opinion, for an accurate comparison the code should include the fermionic features of the system and take realistically into account the interplay between one-body (Fermi momentum) and two-body (nucleon-nucleon collisions) effects. To our knowledge, presently a good candidate for an accurate comparison would be the AMD code [20,21].

The observed phenomena are similar to those already known at low bombarding energy (where they were interpreted in terms of an exchange of nucleons through a window): it is surprising that they persist also at Fermi energies although here we are in the presence of a nonnegligible preceding midvelocity emission. This fact may suggest we look back at the low-energy behavior also from a different perspective.

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