Energetics of midvelocity emissions in peripheral heavy ion collisions at Fermi energies

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Peripheral and semi-peripheral collisions have been studied in the system $^{93}$Nb$^+$+$^{93}$Nb at 38 AMeV. The evaporative and midvelocity components of the light charged particle and intermediate mass fragment emissions have been carefully disentangled. In this way it was possible to obtain the average amount not only of charge and mass, but also of energy, pertaining to the midvelocity emission, as a function of an impact parameter estimator. This emission has a very important role in the overall balance of the reaction, as it accounts for a large fraction of the emitted mass and for more than half of the dissipated energy. As such, it may give precious clues on the microscopic mechanism of energy transport from the interaction zone toward the target and projectile remnants.

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In peripheral to mid-central collisions of heavy ions at Fermi energies ($E_{\text{beam}} = 30–50$ AMeV) an intense emission of light charged particles (LCP) and especially of intermediate mass fragments (IMF) at velocities between those of the projectile- and target-like fragments (PLF and TLF) is observed. These so-called “neck-emissions” or “midvelocity emissions” may be seen as an intermediate stage between the fast 3-body processes found at lower energies and the explosion of the “participant zone” at much higher energies.

At low beam energies ($\lesssim 15$ AMeV), the exchange of nucleons between PLF and TLF, whose mean fields merge for a prolonged time, plays a dominant role in the energy dissipation process, but it is very difficult to have experimental access to probes directly connected to the mechanism of matter exchange. At high energies ($\gtrsim 100$ AMeV), because of the small de Broglie wavelength of the nucleons and the reduced Pauli blocking, the energy dissipation mechanism is dominated by direct nucleon-nucleon collisions in the overlap between projectile and target, and the short interaction time does not allow a significant heat transport to the non-overlapping zones. At Fermi energies the energy dissipation is already significantly localized in the midvelocity region – as quantitatively demonstrated in this Letter –, while the interaction time may still be long enough to allow the transfer of a sizable amount of energy to the surrounding nuclear matter thus resulting in an excited PLF and TLF (hereafter indicated with PLF$^*$ and TLF$^*$).

To clarify the mechanism leading to midvelocity emissions, an important aspect is represented by the amount of energy involved in these emissions, as compared with the excitation energy left in the PLF$^*$ or TLF$^*$. This may yield clues about the transition between the low-energy dissipative collisions (where the energy removed from the relative motion is totally converted into excitation of PLF$^*$ and TLF$^*$) and the high-energy participant-spectator regime. We present here, for the first time, a direct simultaneous determination of the energy involved in the midvelocity and in the evaporative emissions.

The results of this Letter refer to the collision $^{93}$Nb$^+$+$^{93}$Nb at 38 AMeV, as a part of a systematic study of heavy ion collisions performed at the Superconducting Cyclotron of the Laboratori Nazionali del Sud of INFN in Catania, with the Fiasco setup. The apparatus consists of gas detectors (measuring heavy products with $E_Z>0.1$ AMeV, in $\approx 70\%$ of the forward hemisphere), $\Delta E - E$ Silicon telescopes (determining charge and mass of PLFs below the grazing angle) and phoswich telescopes (for isotopic identification of LCPs and elemental identification of IMFs with $Z \geq 3$, in about $30\%$ of the forward hemisphere).

This Letter is focused on two-body events, by far prevailing in (semi-)peripheral collisions, where two and only two large reaction remnants are detected by the gas counters (which are fully efficient for heavy fragments with $Z<10–14$). This allows to have as clean as possible kinematics, profiting in the best way of Fiasco’s ability to detect also the TLF, with the aim of studying the energy associated to midvelocity emissions in a situation where their release represents the dominant process.

The setup measures the secondary quantities of PLF and TLF after the sequential evaporation, while primary quantities of the excited PLF$^*$ and TLF$^*$ are estimated from the measured velocities with the kinematic coincidence technique. As an indicator of the centrality of the collision we have chosen a kinematic variable, defined as $\text{TKEL} = E_{\text{c.m.}} - \frac{1}{2} \mu v_{\text{rel}}^2$, where $E_{\text{c.m.}}$ is the center-of-mass (c.m.) energy in the entrance channel, $\mu$ is the reduced mass calculated with the masses of the kinematic reconstruction (forced to add up to the total mass of the system and thus overestimated) and $v_{\text{rel}}^2$ is the reconstructed primary relative velocity between PLF$^*$ and TLF$^*$. While at low incident energies (where reactions are strictly binary), TKEL truly represents the Total Kinetic Energy Loss of the collision, it is important to em-
Dotted line indicates the charge of a Nb projectile, while the arrow on top shows the impact parameter scale estimated from QMD calculations. 

Phasize that in this work, where a sizable midvelocity emission is present, TKEL is used just as an order parameter for classifying the events in bins of different impact parameter. Indeed, the kinetic analysis of events generated by a Quantum Molecular Dynamics (QMD) code shows a strict correlation between TKEL and impact parameter. 

The average multiplicities of charged particles, $\langle \mathcal{M}_{C_i} \rangle$ (henceforth we use the brackets $\langle \rangle$ to indicate averages over events in a given bin of TKEL), were obtained from the distributions of the experimental yields of p, d, t, He and IMFs in the $(v_\parallel,v_\perp)$ plane, after correcting for the finite geometrical coverage of the phoswiches. Here $v_\parallel$ and $v_\perp$ are the velocity components parallel and perpendicular, respectively, to the asymptotic PLF*-TLF* separation axis in the c.m. system; for the TKEL range addressed in this work, the c.m. separation axis lies within about 10° from the beam axis. The advantage of using a symmetric collision is that the forward-going particles (those with $v_\parallel \geq 0$) must have the same average characteristics as the backward-going ones. Therefore, in this paper all multiplicities refer only to forward emitted particles, for which the setup has a much better solid angle coverage and threshold effects do not play any role (all particles having lab-energies larger than $\approx 9.5$ AMeV). In a symmetric system, adding up the charges of forward emitted LCPs and IMFs to the charge of the PLF should reproduce, on average, the projectile charge. The deficit of about half a charge unit shown in Fig. 1 was corrected by slightly rescaling the contribution of all charged reaction products in each TKEL bin. 

Another advantage of a symmetric collision is that the contribution of the free neutrons (unmeasured) can be estimated from mass conservation. In fact the average multiplicity of all the undetected forward-emitted free neutrons is given by $\langle \mathcal{M}_n \rangle = A_{\text{proj}} - \sum_i A_{C_i} \langle \mathcal{M}_{C_i} \rangle - \langle A_{\text{sec}} \rangle$, where $\langle A_{\text{sec}} \rangle$ is the average secondary mass of the PLF (measured with the Silicon telescopes) and $A_{C_i}$ are the mass numbers of the different charged particle species. In doing so, the common assumption $A = 2Z$ was used for estimating the masses of the IMFs, which were not isotopically resolved. This seems reasonable, since experimental data and theoretical arguments (see references therein) suggest the existence of an “isospin fractionation” favoring isospin symmetric IMFs, with a corresponding neutron enrichment of LCPs and free nucleons: indeed, also in the present data, the midvelocity emissions have larger deuteron-to-proton and especially triton-to-proton ratios than the evaporation. In any case, being the IMF multiplicities small ($\lesssim 1$), the uncertainty caused by this assumption is less than one mass unit. Great care was also devoted to determining $A_{\text{sec}}$ via time-of-flight measurements with both gas and Silicon detectors: the obtained secondary masses were always in good agreement with the so-called Evaporation Attractor Line (EAL) except for low TKEL where the excitation is low and the mass of the PLF* close to the stability valley (which is slightly more neutron-rich than the EAL).

It is relatively simple to perform a check of the energy balance of all forward-going reaction products. In fact, the total energy is obtained (for each bin of TKEL) by adding the c.m. kinetic energy of the PLF residue to the energy associated to the emission of all forward-going particles, without distinction of their production mechanism, namely 

$$\langle E_{\text{forw}}^{c.m.} \rangle = \sum_i \frac{\mathcal{C}_{C_i}}{C_{C_i}} \langle \mathcal{M}_{C_i} \rangle + \frac{\mathcal{C}_n}{C_n} \langle \mathcal{M}_n \rangle - Q_{\text{tot}} \quad (1)$$

where $\frac{\mathcal{C}_{C_i}}{C_{C_i}}$ is the average (efficiency corrected) c.m. kinetic energy of the charged particles of the $i$-th species and the sum extends over the different species; $\frac{\mathcal{C}_n}{C_n}$ is the average c.m. kinetic energy of the free neutrons (estimated from the protons after correcting for the lack of Coulomb repulsion); $Q_{\text{tot}}$ is the Q-value for disassembling the projectile into the average secondary PLF, plus as many neutrons, LCPs and IMFs as given by their respective multiplicities. We expect to come close to the c.m. kinetic energy of the incoming projectile (about 885 MeV), having disregarded only the energy of $\gamma$-rays, which are mainly emitted at the end of the evaporation chain. Indeed the sum falls short of the projectile energy by less than 15 MeV at small TKEL values (rising to about 50 MeV at TKEL≈500 MeV), thus giving confidence in the results of the present analysis.

It is much more difficult to separate the energy associated to the midvelocity emissions from that associated to the sequential evaporation from the fully equilibrated PLF*. First it is necessary to estimate the yields of the two components. In peripheral collisions, this is feasible because the PLF can always be safely distinguished from the TLF (on the basis of the phase-space distributions of the heavy remnants) and the most forward part of the LCP and IMF emission can be ascribed to a pure evaporative process. These same considerations advise against extending the study to more central collisions (that is, in the present work, beyond TKEL≈600...
MeV). The procedure is based on the distributions of the emission angle $\theta$ in the PLF frame (see e.g. Fig. 2), taking the PLF*-TLF*-separation axis as polar axis. For pure evaporation and neglecting recoil effects (which are important only at small TKEL), one expects approximately a $\sin(\theta)$-distribution for a source with zero spin and a somewhat flatter shape for non-zero spin (see e.g. Fig. 2). In reality, normalizing the distributions below $30^\circ$, one finds that for all particle species the data have a large excess at backward angles (with a tail extending well below $\theta = 90^\circ$), which is ascribed to midvelocity emissions. Therefore the evaporative multiplicities were extrapolated from the experimental data measured in the range $\theta \leq 30^\circ$ (with the spin of the PLF* deduced from the out-of-plane angular distributions [12]). The multiplicities associated to the midvelocity emissions were then determined from the difference between the total multiplicities and the evaporative ones.

It is now necessary to make also a hypothesis on the subdivision of $\langle M_i \rangle$ between the midvelocity emission, $\langle M_{\text{midv}}^* \rangle$, and the subsequent statistical evaporation of the PLF*, $\langle M_{\text{evap}}^* \rangle$. No firm conclusion has been reached in the literature concerning a possible enhancement of neutrons in the neck matter, however there are indications [12] that globally the N/Z ratio of the neck matter is the same as that of the bulk matter. Therefore, as a working hypothesis, the overall neck emissions (and consequently also the primary PLF*) have been assumed to have the same N/Z ($=2.27$) of the system.

Finally, one needs the average kinetic energy for each particle species. For evaporated particles this is best done in the frame of the emitting PLF, as the value obtained for $\theta \leq 30^\circ$ can be used for the whole distribution.

It is now possible to estimate the total mass evaporated from the excited PLF* and the associated energy (measuring the initial excitation energy) by summing up masses and kinetic energies (the superscript "PLF" reminds that they are not in the c.m. frame) of neutrons, LCPs and IMFs weighted with their evaporative multiplicities.

\[
\langle A_{\text{evap}} \rangle = \sum_i A_i \langle M^\text{evap}_{C_i} \rangle + \langle M^\text{evap}_{n} \rangle \tag{2}
\]

\[
\langle E_{\text{evap}} \rangle = \sum_i \frac{k_{\text{PLF},C_i,\text{evap}}}{k_{\text{n,\text{evap}}}} \langle M^\text{evap}_{C_i} \rangle + \frac{k_{\text{n,\text{evap}}}}{k_{\text{n,\text{evap}}}} \langle M^\text{evap}_{n} \rangle - Q_{\text{evap}} \tag{3}
\]

where $k_{\text{PLF},C_i,\text{evap}}$ is the average (efficiency corrected) kinetic energy of the evaporated charged particles of the $i$-th species (in the PLF frame, evaluated for $\theta \leq 30^\circ$); $k_{\text{n,\text{evap}}}$ is the average kinetic energy of the evaporated neutrons (estimated from that of the protons minus an average Coulomb barrier); $Q_{\text{evap}}$ is the Q-value for disassembling the average primary PLF* into the average secondary PLF, plus as many neutrons, LCPs and IMFs as given by their respective evaporative multiplicities. The obtained results are shown in Fig. 3(a) and (c). Here, as in the other panels, the symbols correspond to the adopted subdivision of the free neutrons, while the dashed and dotted lines correspond to a ±50% variation of $\langle M^\text{evap}_{\text{midv}} \rangle$: the results are not very sensitive to this assumption. The behavior of both $\langle A_{\text{evap}} \rangle$ and $\langle E_{\text{evap}} \rangle$ is very regular, displaying a steady, almost linear increase with increasing TKEL. This suggests that TKEL, even in the presence of a sizable midvelocity emission, remains nevertheless a good indicator of the average excitation energy of the PLF* (and of the TLF* as well) [12]. The obtained average energetic cost per evaporated nucleon is about 9–10.
MeV, in reasonable agreement with results of the statistical code Gemini [20].

By subtracting from the mass and energy of all emitted particles the contribution of the evaporation, one can estimate the part pertaining to the midvelocity emissions

\[ \langle A_{\text{midv}} \rangle = \left( \sum_i A_i \langle \mathcal{M}_i \rangle + \langle \mathcal{M}_n \rangle \right) - \langle A_{\text{evap}} \rangle \]  
\[ \langle E_{\text{midv}} \rangle = \langle E_{\text{forw}}^\text{c.m.} \rangle - \left( \langle E_{\text{evap}} \rangle + \langle K_{\text{transl}} \rangle \right) \]  

As the kinetic energies of \( \langle E_{\text{forw}}^\text{c.m.} \rangle \) are evaluated in the c.m. reference frame and those of \( \langle E_{\text{evap}} \rangle \) in the PLF frame, the translational kinetic energy of the whole pattern of evaporated particles (due to the motion of the source) was taken into account with the term \( \langle K_{\text{transl}} \rangle \approx \frac{1}{2} m_N \langle A_{\text{evap}} \rangle \langle v^2 \rangle \), where \( m_N \) is the nucleon mass, \( A_{\text{evap}} \) the mass number of the total evaporation from PLF* and \( v \) the c.m. velocity of the PLF residue [26].

The results of Eq. (4) and (5) are shown in Fig. 3(b) and (d), respectively. With increasing TKEL, both \( \langle A_{\text{midv}} \rangle \) and \( \langle E_{\text{midv}} \rangle \) first increase almost linearly and then flatten (at values around 16 and 180 MeV, respectively). The origin of this flattening is still an open question and will be the subject of further investigation [30]. The comparison of Fig. 3(c) and (d), shows that, at a given TKEL, up to about half of the energy goes into the midvelocity component, which is really an essential aspect of the reaction and may represent the proemine of the multifragmentation of the whole system, occurring in central collisions.

In short, it can be stated that \( \langle E_{\text{midv}} \rangle \) and \( \langle E_{\text{evap}} \rangle \) are comparable and this statement holds in spite of several systematic uncertainties that affect their evaluation (conservatively, altogether up to 30% of the quoted values). So in the Fermi domain, an important part of the dissipated energy, initially stored in the translational motion of the projectile, is localized in the new midvelocity emission. This mechanism has an important role in the overall balance of the reaction, both in terms of the emitted mass (charge) and energy [22].

Finally, since the amount of dissipated energy localized in the midvelocity matter is comparable to that in the PLF* or TLF*, and the mass of the emitting zone (two sources as schematized in Ref. [11] or more realistically--a whole distribution of sources) is certainly smaller, one may expect for the midvelocity matter a value of \( E^*/A \) (of the order of 7–14 MeV, depending on the assumed size) significantly larger than that of the evaporative source (≤ 2 MeV for the data of this work). It is well known experimentally that with increasing \( E^*/A \) the disassembly properties of nuclear matter radically change, leading to a preferential formation of IMFs [23 24]. A large \( E^*/A \) value is therefore consistent with the observation of a preferential emission of IMFs at midvelocity. Experimental data on the deposition of energy in the midvelocity matter may represent an important benchmark for the most sophisticated microscopic calculations [25 26 27 28]. When such comparisons with the data become available, one may hope to gain some new insight on the mechanism at the basis of the large, strongly localized, energy deposition as well as on the transport of internal energy from the interaction zone to the cold projectile and target remnants.

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