Fast light particles in Kr + Au collisions at 27 and 60 MeV/u

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Abstract

Coincident light particles and fragments produced in Kr + Au reactions at 27 and 60 MeV/u have been measured with the four charged-particle multi-detectors of Nautilus. The mechanism is basically a two-body damping collision in which up to 1.6 GeV kinetic energy can be dissipated. Multiplicities of particles sequentially emitted by the slowed-down projectile-like nucleus follow the energy loss and are nearly independent on the bombarding energy, confirming that this emission is equilibrated. However, the energy spectra are reproduced by a sum of an evaporation and a fragmentation component, the latter increasing strongly with energy loss.

The mechanism of peripheral collisions between heavy nuclei such as Kr + Au has been shown to be strongly dissipative and essentially of two-body nature even at bombarding energies as high as 43 MeV/u [1]. On the other hand, growing evidence for multifragmentation has been found in central collisions for such systems [2]. Are statistical models valid even when the nucleus approaches the limit of stability ? It has recently been shown [3] that the energy spectra of light particles emitted by the projectile-like nucleus in Kr + Au collisions at 27, 44 and 60 MeV/u deviate from the classical maxwellian shape and exhibit an evolution toward a fragmentation pattern. We shall review here the 27 and 60 MeV/u data and introduce TKEL, the total kinetic energy loss calculated event by event. At both energies and up to TKEL=1.6 GeV, the mechanism of the reaction is basically a two-body dissipative collision. Almost independently from the bombarding energy, the fragmentation component increases as a function of TKEL.

The experiment presented here was performed with the four multidetectors of Nautilus at GANIL: XYZt [4] and DELF [5] which measure fragments at forward angles and around the target, respectively, and the MUR [6] and the TONNEAU [7] which detect light particles in the same angular ranges (Fig.1).

The binary character of the mechanism is illustrated in Fig.2. This plot concerns triple coincidences between fragments (Z>8) detected in XYZt or DELF. Shown here is the total kinetic energy TKE as a function of the longitudinal velocities of the fragments. The calculation has been performed in a frame bound to the c.m. system of the detected fragments. The orientation is determined by the long axis of the ellipsoid representing the momentum tensor of the event. Two components appear in $V_{//c.m.}$. In each event, two

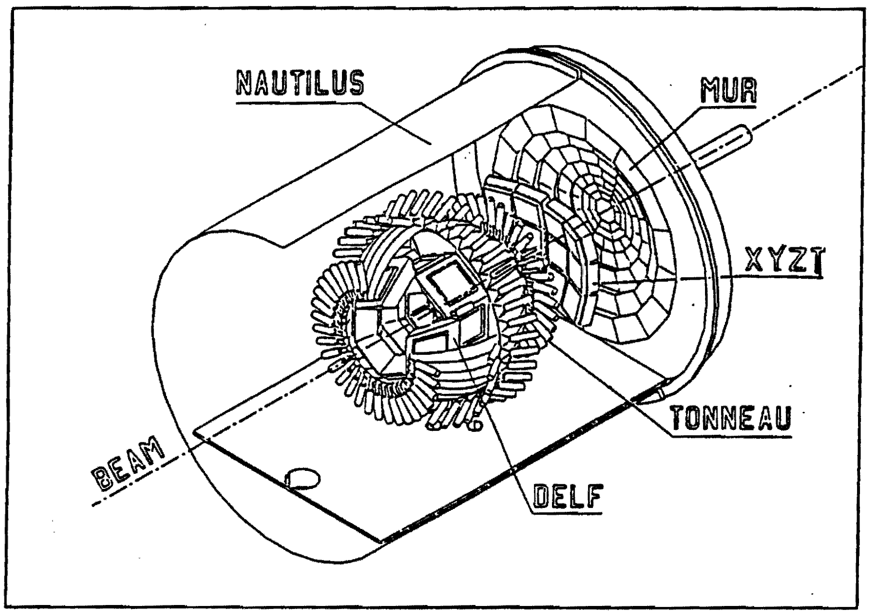

Figure 1: The experimental set-up

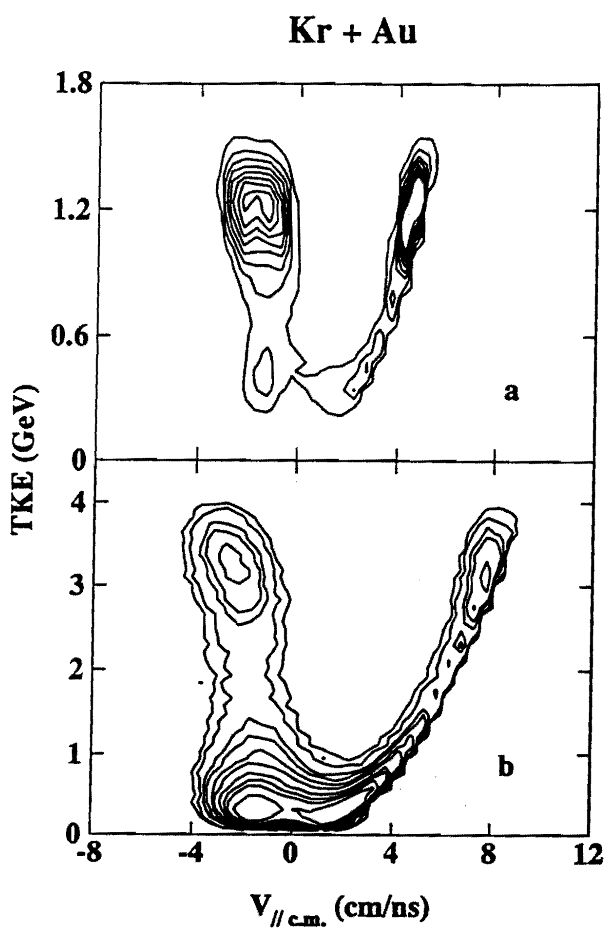

Figure 2: Kinematical characteristics of triple coincidences between fragments at a) 27 MeV/u and, b) 60 MeV/u

fragments contribute to the component at $V_{//c.m.} < 0$. Their relative velocity close to 2.4 cm/ns shows that they are fission fragments from the target. The fragment at $V_{//c.m.} > 0$ is the projectile-like nucleus (PLF). Thus TKE has been calculated by adding the kinetic energies of the PLF and of the reconstructed target-like nucleus. The two components are well separated down to the complete energy damping at 27 MeV/u, and to TKE=2.0 GeV at 60 MeV/u. If this kinetic energy is entirely converted into excitation energy, the system reaches a mean excitation energy of about 7 MeV per nucleon in a two-body reaction.

To investigate the deexcitation of nuclei under such extreme conditions, we have studied charged particle emission by the PLF. The spectra measured in MUR and TONNEAU were incremented event by event not in the laboratory system as usual for inclusive data [8], but in a system bound to the fragment at $V_{//c.m.} > 0$. The energy, velocity and angle in this system are E_{sys}, V_{sys} and θ_{sys}. Isotropic decay into a light particle-fast fragment pair is demonstrated at both energies by the comparison between the data and a reference spectrum (Fig. 3) which has been calculated with an arbitrary maxwellian shape and the assumption of isotropic emission. It fits the data up to about $\theta_{sys}=60^{o}$. A significant non-isotropic component appears only at larger θ_{sys} and may be due to emission from the target or to pre-equilibrium particles produced by nucleon-nucleon collisions.

The energy spectra corresponding to the isotropic component at 27 MeV/u are shown in Fig.4 for consecutive windows on TKEL. The slope of these spectra becomes less and less steep, indicating a higher and higher temperature when TKEL increases. This is the expected trend. However, a fit with a

$$dM / dE_{sys} = M_e \, [(E_{sys}-B) / T^2] \, . \exp[-(E_{sys}-B) / T] \qquad (1)$$

formula yields unreasonably high values for T (Fig. 4). Since the maximum of eq. 1 is for $E_{sys} = B + T$, this explains the vanishing values obtained for B. In order to improve the fit, as in ref. [3], we have temptatively reproduced the multiplicities by adding an evaporation term having the general form given by eq. 1, and a fragmentation term:

$$dM / dE_{sys} = dM_e / dE_{sys} + dM_f / dE_{sys} \qquad (2)$$

The fragmentation component has been calculated by supposing that the particles are emitted with a Gauss-shaped momentum distribution having a mean value p_0 and a variance σ^2:

$$dM_f / dE_{sys} = M_f \, C_0 \, E_{sys}^{1/2} \exp[-(p-p_0)^2 / 2\sigma^2] \qquad (3)$$

where:

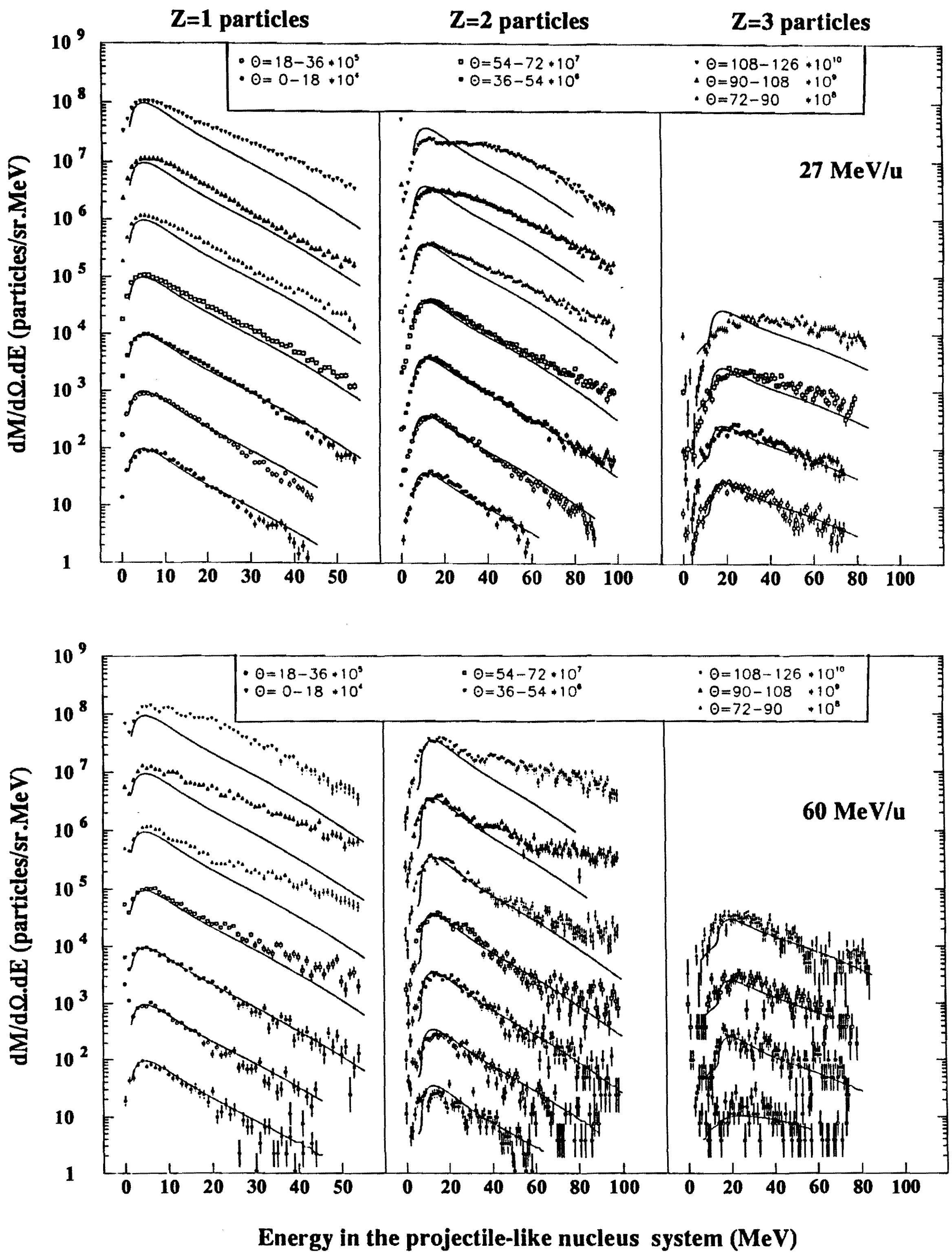

Figure 3: Energy spectra in consecutive bins on the angle θ_{sys}

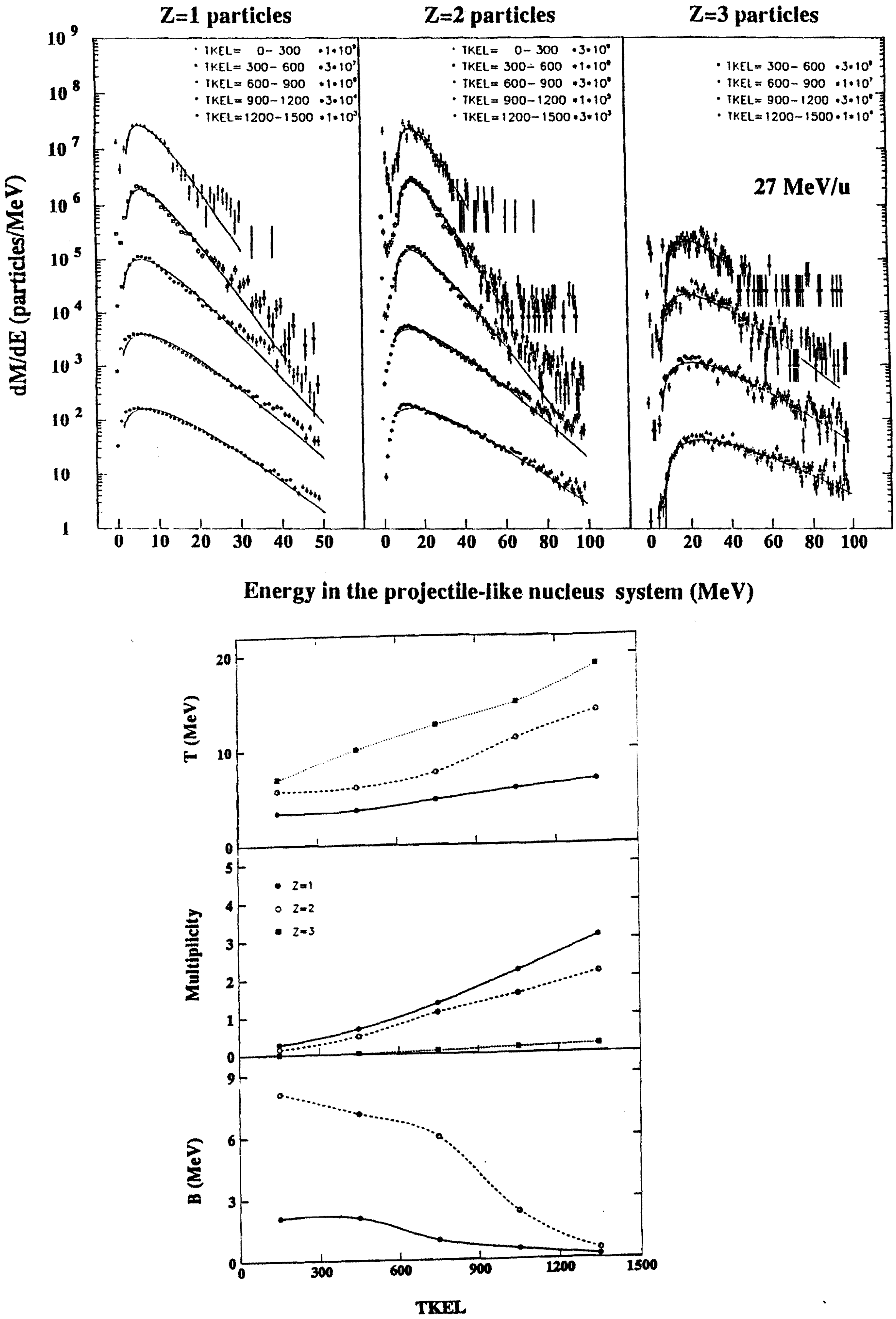

Figure 4: Energy spectra in consecutive bins on TKEL (top) and parameters of the Maxwellian fits to these spectra (bottom).

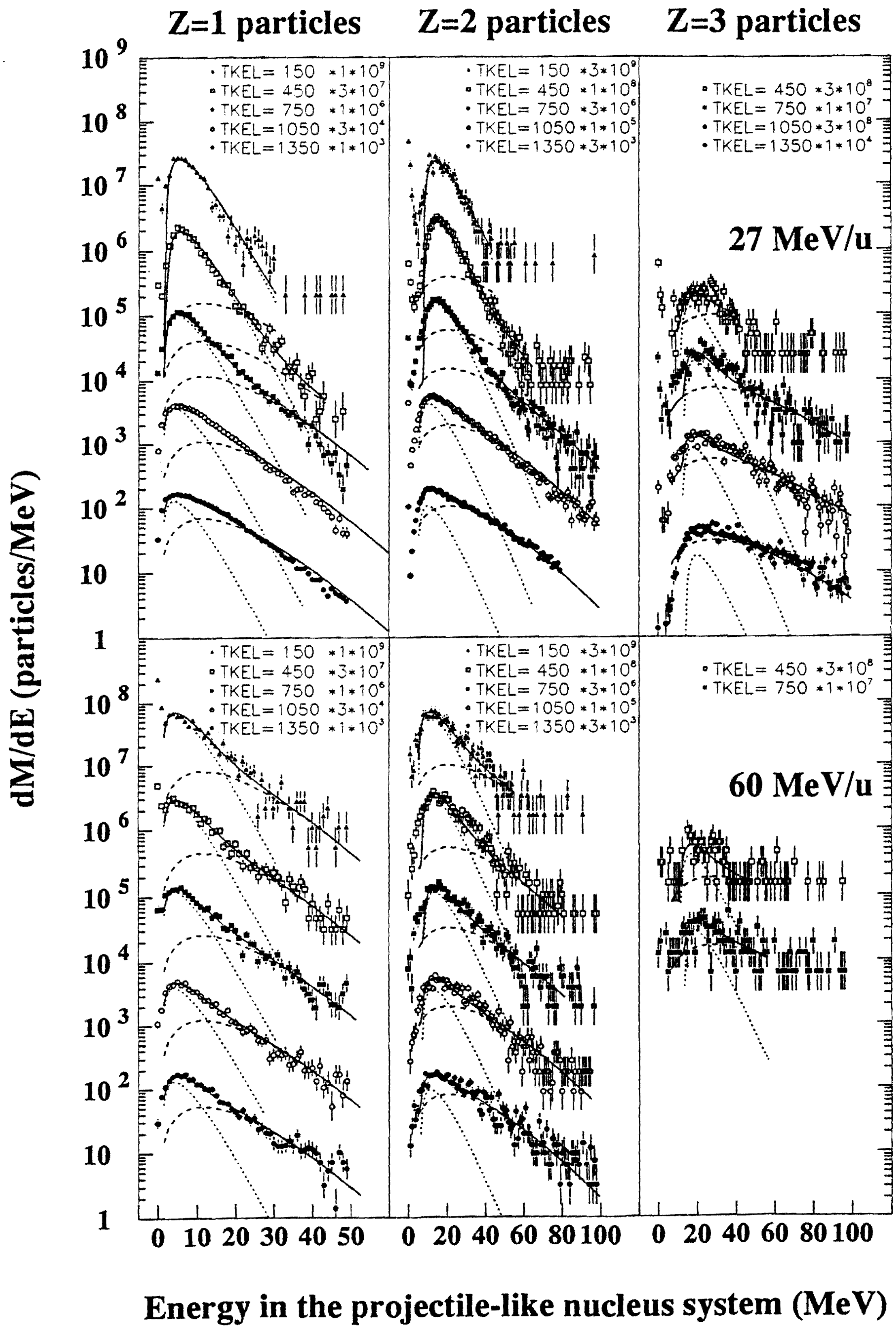

Figure 5: Energy spectra in consecutive bins on TKEL (the values are given in MeV). The evaporation component is indicated by the dotted line, the fragmentation component by the dashed line and the sum by the full line

$$\sigma^2 = A_{part}\,(A_p - A_{part})\,\sigma_0^2/(A_p-1)$$
$$p = A_{part}\, m_N\, V/c$$
$$p_0 = A_{part}\, m_N\, V_0/c$$
$$V = (A_p - A_{part})\, V_{sys} / A_p$$
$$E_{sys} = 1/2\, A_{part}\, m_N\, V_{sys}^2$$

and C_0 is a normalisation factor, A_{part} is the mass number of the particle, A_p that of the beam, c the velocity of light and m_N the nucleon mass. The fitting procedure consisted in minimising χ^2 for each energy distribution. In a first step, all 6 parameters in eq. 2 were approximatively optimized. However, best values for some of them were found to vary little from one spectrum to the other, and were therefore fixed: T is equal to 3.55 MeV for Z=1 particles and 5.6 MeV for Z=2 and 3 particles, V_0 is given by the Coulomb repulsion (3.57, 2.45 and 2.40 cm/ns for Z=1,2 and 3 particles, respectively) and σ_0 is equal to 70, 90 and 100 MeV/c for the same Z values. In the final procedure, the parameters fitted for each spectrum are therefore B, M_e and M_f.

The result is shown in Fig.5: the dotted curves show the evaporation component, the dashed ones the fragmentation component and the full curves their sum. The agreement is quite satisfactory. The fragmentation component increases with TKEL and with the Z value. The best-fit parameters indicate that the corresponding particles have a mean velocity determined by Coulomb repulsion from the PLF, and that the width of the distribution seems determined by Fermi motion.

It should be stressed once more that the fragmentation as well as the evaporation components are isotropic in the frame of the slowed down PLF, and correspond therefore to sequential emission after the dissipation step. The data in Fig. 5 show even that the corresponding multiplicities depend little on the bombarding energy, and almost only on TKEL, suggesting that this emission is equilibrated to some extend. This, together with the constant value obtained for T, seems to show that the onset of the fragmentation term is due to some saturation in the deexcitation process.

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