C.E. SACLAY
DSM

SERVICE DE PHYSIQUE NUCLEAIRE

DAPNIA/SPhN 94 06 03/1994

EQUILIBRIUM VERSUS NON-EQUILIBRIUM EMISSION IN PROJECTILE FRAGMENTATION FOR ^{40}Ar + ^{nat}Ag SYSTEM AT 58.7 A.MeV

J.E. Sauvestre, J.L. Charvet, R. Dayras,
C. Volant, B. Berthier, R. Legrain,
R. Lucas, E.C. Pollacco, E. de Filippo,
G. Lanzano, A. Pagano, C. Beck, B. Djerroud

DAPNIA

Le DAPNIA (**D**épartement d'**A**strophysique, de physique des **P**articules, de physique **N**ucléaire et de l'**I**nstrumentation **A**ssociée) regroupe les activités du Service d'Astrophysique (SAp), du Département de Physique des Particules Elémentaires (DPhPE) et du Département de Physique Nucléaire (DPhN).

Adresse : DAPNIA, Bâtiment 141
CEA Saclay
F - 91191 Gif-sur-Yvette Cedex

soumis pour publication dans

Physics Letters B

Equilibrium versus non-equilibrium emission in projectile fragmentation for the ^{40}Ar + ^{nat}Ag system at 58.7 A.MeV*

J.E. Sauvestre†, J-L. Charvet, R. Dayras, C. Volant,

B. Berthier‡, R. Legrain, R. Lucas, E.C. Pollacco

DAPNIA/SPhN, CE Saclay, F-91191 Gif-sur-Yvette Cedex, France

E. De Filippo§, G. Lanzanó, A. Pagano

Istituto Naz. Fisica Nucleare and Dipartimento di Fisica

Corso Italia 57, 95129 Catania, Italy

C. Beck, B. Djerroud**

Centre de Recherches Nucléaires,

IN2P3-CNRS/Université Louis Pasteur F-67037 Strasbourg Cedex 2, France

(March 4, 1994)

Abstract

Coincidences between light-charged particles and projectile-like fragments were measured at forward angles. An analysis of the data based on a kinematical reconstruction of the emitter evidences a thermalized emission for protons and a large non-equilibrium α emission. From the slope of the equilibrated component of the particle energy spectra in the emitter frame, high temperatures in the primary projectile, up to ~4.5 MeV, have been extracted and are found to increase as the atomic number of the projectile-like fragment decreases.

---

*Experiment performed at GANIL, Caen

†Present address: CE Bruyères-le-Châtel, Service PTN, BP 12,

F-91680 Bruyères-le-Châtel, France

‡Present address: DRECAM/Laboratoire Pierre Sue, CE Saclay,

F-91191 Gif-sur-Yvette Cedex, France

§Present address: DAPNIA/SPhN, CE Saclay, F-91191 Gif-sur-Yvette Cedex, France

**Present address: Laboratoire de Physique Nucléaire, Université Laval,

Ste-Foy, Québec, Canada GIK 7P4

The excitation energies imparted to the two colliding partners in peripheral collisions remain an open problem in the physics of heavy ions induced reactions at intermediate energies (E = 20-100 A.MeV) [1,2]. In principle, these excitation energies can be determined by a measurement of the energies carried out by the light charged particles (LCP) [3] or neutrons associated with the decays of the two colliding ions. Such studies are rather sparse and are mainly limited to light projectiles ($Z \leq 10$) for which structure effects may play an important role [5–11]. However such a procedure is valid only if the particles are emitted by primary nuclei in thermal equilibrium. In fact, preequilibrium emission was observed [1–4,12] in these peripheral reactions and to establish the energies imparted to the primary fragments a deconvolution of the thermal component is necessary. On the other hand, preequilibrium emission offers the opportunity to test dynamical models for reaction mechanisms between complex ions at the early stage of the collisions.

In this letter, new results are presented on the characteristics of LCP emitted in coincidence with projectile-like fragments (PLF) for the ^{40}Ar + ^{nat}Ag system at 58.7 A.MeV. The emphasis is placed on the complete identification of LCP and on precise measurements of their velocities and angles relative to the detected PLF. These data are to be compared to earlier results obtained at 60 A.MeV [12]. The present experiment attempted to solve ambiguities in interpreting the results of coincidence measurements between projectile-like and target-like fragments (TLF) [13–15]. These data could be described using two different hypotheses : i) An abrasion-ablation mechanism leading to barely excited primary fragments [16] ii) A binary reaction mechanism reminiscent of deep inelastic collisions, where large amount of excitation energy are borne by the two partners [17].

A 58.7 A.MeV ^{40}Ar beam from the GANIL facility bombarded a self-supported 487 μg/cm^2 thick natural silver target. PLF were detected in six ΔE-E telescopes each consisting of two silicon solid state detectors, ~300 μm and ~5000 μm thick respectively of sufficient depth to stop all fragments with Z>6 having the beam velocity. These telescopes were placed in an horizontal plane symmetrically on each side of the beam at polar angles of 2.8°, 4.8°, and 11.4°. They were energy calibrated using α-sources and ^{40}Ar elastic scattering. PLF were identified by their atomic number through the usual ΔE-E method. The LCP were detected in an hodoscope of 22 BaF_2 crystals located on one side of the beam at ~120 cm from the target and covering polar angles from 2.8° to 10° and azimuthal angles from 90° to 270°. Solid angles were defined by brass collimators placed in front of each crystal. Their sizes were chosen in order to make uniform the counting rates in each element of the array. Times of flight were measured relative to the RF signal of the cyclotrons, yielding an overall time resolution of Δt ~800 ps. Using time-of-flight information and pulse shape discrimination in the BaF_2 crystals [18], LCP were unambiguously identified by their atomic number and their mass up to α particles, with an energy threshold of ~5 A.MeV. Single and coincident events were registered during the measurements.

The single PLF energy spectra have approximately gaussian shapes and present the usual characteristics [16]. They are peaked at an energy slightly lower than the energy corresponding to the incident beam velocity with a low energy tail which increases as the mass of the fragment decreases. The angular distributions are strongly forward peaked, decreasing exponentially with angle.

The single LCP energy spectra are very broad, extending from the detection threshold to well above an energy corresponding to the beam velocity. At the most forward angles, they exhibit two bumps almost symmetrically around the associated PLF mean velocity. This feature is characteristic of forward and backward emissions by a source having a velocity close to the beam velocity [5–10,12]. The LCP inclusive energy spectra were simultaneously fitted assuming two moving sources. The best fit to the data was obtained with a source having the beam velocity and a low apparent temperature ~2.5 MeV, whereas the other source had about two third of the beam velocity and a high temperature ~25 MeV. Regardless of its physical meaning this parametrization leads to values consistent with systematics [4].

From the LCP-PLF coincidence data, it was possible to extract the average LCP multiplicities as a function of the Z of the detected PLF and they are in excellent agreement with the previous measurement of ref. [12]. The total average LCP multiplicity is close to zero for Z=18 and reaches ~3.8 (0.95, 0.65, 0.3 and 1.9 for p, d, t and α particles respectively) for Z=9 fragments. This trend suggests that the lightest detected PLF are issued from primary fragments carrying the highest excitation energy. However, in order to determine the thermal excitation energy of the primary fragments, beyond the number and the energy of the emitted particles, one has to assess which fraction of these particles are really evaporated from a nucleus in thermal equilibrium. To do so, the LCP-PLF coincidence data were converted, event by event, into the frame of the emitter where the z-axis is chosen to lie along the recoil velocity of the emitter. In this frame, thermally emitted particles should display angular distributions symmetrical around 90° and the shape of their energy spectra in particular their temperature, should be independant of angles. As several particles may be emitted, this change of frame can be only approximately made. For each coincident event, the recoil velocity vector of the emitter is obtained by combining the velocity vectors of the PLF and of the associated LCP. Thus, recoil effects due to non-detected particles are not taken into account. For a given detection angle of the PLF, data from the right and left telescopes were combined together.

In order to assess recoil effects as well as the effect of the limited angular coverage of our experimental set-up for LCP, Monte-Carlo simulations were performed following as closely as possible the experimental situation. The following hypotheses were made : i) The primary emitter was ^{40}Ar and was given an excitation energy adjusted to yield preferentially the detected PLF (180 MeV for $Z_{PLF} = 9$, 80 MeV for $Z_{PLF} = 14$). ii) Its velocity distribution was taken to be that of the inclusive PLF spectra. iii) Its angular distribution was exponentially decreasing with angles with parameters adjusted to yield the angular distribution of the detected PLF. iv) At each step along the decay chain the competition between the emission of LCP of different types is governed by the ratio of the observed multiplicities, assuming the neutron and proton multiplicities to be equal. v) In the frame of the primary fragments, the LCP were emitted isotropically (no angular momentum), their energy spectra had Maxwellian distributions, the corresponding temperature was adjusted at each step of the desexcitation process assuming a level density parameter equal to $A/8$, A being the emitter mass. The Coulomb barrier parameters were those used to fit the single LCP energy spectra. At each step of the decay process, the excitation energy of the residual nucleus was determined taking into account binding energies. After each evaporation sequence, the laboratory velocities, energies and emission angles (θ, ϕ) of the PLF and of the associated LCP as well as their atomic number and mass were registered. The simulated data were then analyzed in the same way as the experimental ones.

Assuming full angular coverage for the LCP, the simulated angular distributions, $d\sigma/d\theta_{cm}$, of the LCP, in the emitter frame show the expected $\sin\theta_{cm}$ dependence. This is illustrated by the histograms of Fig. 1a and Fig. 1c for α particles and protons respectively in coincidence with a Z=9 PLF emitted between 2.5° and 3.5° in the laboratory. Our experimental set-up drastically filters the angular distributions as shown by the smooth curves of Fig. 1a and Fig. 1c. As a consequence, the angular distributions now exhibit two bumps, at forward and backward angles. The forward bump is enhanced relative to the backward one because of a Jacobian effect resulting from the strong focussing in the laboratory of the forward emitted particles. Because of their higher center-of-mass velocity, this enhancement is more pronounced for the protons than for the α particles.

Comparisons with data are made in Fig. 1b for α particles and Fig. 1d for protons. The simulation was normalized to the data on the forward angle bump. The experimental proton angular distribution agrees well with the simulation, suggesting that these protons are emitted by a system in thermal equilibrium. In contrast, the experimental α particle angular distributions show a large excess of backward emitted particles when compared to the simulation. This excess could be attributed to some non-equilibrium emission process. Similar results are obtained for all PLF. However, the fraction of non-equilibrium emitted particles decreases when the Z of the PLF increases. This fraction appears to increase with the mass of the LCP, for Z_{PLF}=9 it rises from 15% for protons to 45% for α particles. Reasonable variations of the parameters entering the simulation (recoil velocity, excitation energy, angular distribution, angular momentum of the emitter) do not change the above conclusion. However, through a close inspection of the experimental data, it was found that the calculated ratios between equilibrium and non-equilibrium components depended critically upon an accurate energy calibration of the LCP to which great care was devoted [18,19] in the present work.

For the same system at the same energy, by comparing the calculated angular correlations to the experimental ones in the laboratory frame, the authors of ref. [12] have found than 2/3 of the protons and only 15% of the α particles are of non-equilibrium origin. However, in this analysis no distinction was made between particles emitted in the forward or backward hemispheres in the primary PLF reference frame, and all Z=1 particles were considered to be protons whereas in the present experiment it was found that 50% of the Z=1 particles are in fact deuterons and tritons. Finally in this type of analysis, the ratio between the non-equilibrium and equilibrium components is sensitive to the way the calculated angular correlations are normalized to the data. Through an analysis very similar to ours, the authors of ref. [8] conclude that α particles from the fragmentation of a 32.5 A.MeV ^{16}O projectile on a gold target result mainly from the sequential emission by an excited projectile in thermal equilibrium. However, inspection of their Fig. 9, suggests that, in the primary PLF frame, the backward angle emission is slightly enhanced relative to the forward angle emission. The much lower energy (32.5 vs. 58.7 A.MeV) may explain that the non-equilibrium emission is negligible in their case.

To test further the nature of the emitted particles, the experimental distributions of the relative velocities between $Z_{PLF} = 9$ and α particles (protons) emitted at forward and backward angles are shown in Fig. 2a (Fig. 2c) and Fig. 2b (Fig. 2d) respectively. They exhibit maxima close to the velocities expected from the Coulomb repulsion between these LCP and a PLF of Z near the projectile and decrease towards higher velocities. These spectra are closely related to the LCP energy spectra in their emitter frame, the slopes of which are analysed later on. As expected from an isotropical emission, the proton experimental relative velocity spectra are similar at backward and forward angles as also predicted by the simulation for both protons and α particles. However, the experimental backward velocity distribution for the α particles is flatter than the forward angle distribution, exhibiting a clear departure from the emission by a system in thermal equilibrium.

The presence of a non-equilibrium contribution is a challenge to the calculations of the collision dynamics between complex nuclei. Indeed most preequilibrium calculations do not include composite particle emissions which are found here to be the most important. Rather promising features were generated in preliminary Landau-Vlasov calculations performed using the formalism of [20]. The evolution in time of the density profiles exhibits a concentration of matter backward to the projectile after the interaction with the target which may be the source of the preequilibrium particles found experimentally. This has to be compared with the recent findings of a preferential emission of intermediate mass fragments between projectile and target in Kr + Au collisions at 43 A.MeV [21].

The preequilibrium emission being rather important, the determination of the primary excitation energy is a difficult task since the primary mass is unknown. However the slope parameters of the energy spectra can be determined for the LCP emitted at forward angles in the recoiling frame where equilibrium is essentially achieved and they can be related to the imparted excitation energies. The apparent temperatures deduced from the LCP energy spectra are shown as open symbols in Fig. 3 and plotted versus the detected Z_{PLF} for protons (stars) and α particles (circles). In order to correct the measured temperatures for cooling down along the decay chain, the simulation was used to generate the energy spectra of the LCP associated to the most populated PLF as a function of the excitation energy (temperature) of the primary argon. The ratios of the initial temperature in the primary argon to the one deduced from the calculated energy spectra were then used to correct the measured temperatures associated to a given PLF. These corrected values are shown as full symbols in Fig. 3. After correction, the temperatures deduced from the proton spectra are consistent with those from the α particle spectra, conforting a common source for both particles. These temperatures increase from $\sim$1.5 MeV for Z_{PLF} = 17 to $\sim$4.5 MeV for Z_{PLF} = 9. Thus, contrary to what was initially thought, peripheral reactions are able to transfer a large amount of excitation energy to the collision partners. This questions the ability of the simple abrasion-ablation picture [16] to describe projectile fragmentation. A scenario reminiscent from deep inelastic collisions with stochastic exchange of nucleons between projectile and target which leads to high excitation energies is more plausible [17]. However a proper treatment of non-equilibrium effects has still to be worked out. PLF-TLF coincidence measurements [13–15], as well as calculations in the framework of the stochastic exchange model [17], indicate that there is little net mass exchange between projectile and target in the course of the collision and that the mass of the primary PLF remains close to the one of the projectile, independently of the detected PLF. Thus, the dependence of the initial temperature upon the Z of the detected PLF (Fig. 3) simply indicates that lighter PLF result from higher excitation energies in the primary PLF as expected from sequential decay.

Clearly more theoretical work is needed in order to fully explain the experimental results. The present data show the strong influence of preequilibrium emission of rather massive fragments from the projectile in peripheral collisions. Despite this non-thermalized contribution, one is able to infer that large amount of excitation energies are imparted to the partners of heavy ion peripheral reactions at intermediate energies.

ACKNOWLEDGMENTS

We wish to thank C. Mazur, J.P. Passérieux, V. Sparti and S. Urso for their help during the experiment and the GANIL staff for delivering a beam of excellent quality.

REFERENCES

[1] B. Borderie, M.F. Rivet and L. Tassan-Got, Ann. Phys. Fr. (1990) 287.

[2] H. Fuchs and K. Möhring, Rep. on Prog. in. Phys. (1994) in press.

[3] D. Guerreau, Proceedings of the International School of Physics Enrico Fermi, Course CXII, Ed. by C. Détraz and P. Kienle, North Holland (1991) p37 .

[4] C.K. Gelbke and D.H. Boal, Prog. Part. Nucl. Phys. 19 (1987) 33.

[5] R. Ost et al., Phys. Rev. C32 (1985) 1927.

[6] C. Pruneau et al., Nucl. Phys. A500(1989) 168.

[7] P.L. Gonthier et al., Phy. Rev. C41 (1990) 2635.

[8] J. Pouliot et al., Phys. Rev. C43(1991) 735.

[9] J. Pouliot et al., Phys. Lett. B263(1991) 18.

[10] E. Chavez-Lomeli et al., Phys. Rev. C48(1993) 699.

[11] M. Stern et al., Nucl. Phys. A559(1993) 401.

[12] J.C. Steckmeyer et al., Nucl. Phys. A500 (1989) 372.

[13] R. Dayras et al., Phys. Rev. Lett. 62 (1989) 1017.

[14] F. Gadi-Dayras, thesis, Université d'Orsay, June 1988.

[15] J.L. Charvet et al., Proceedings of the XXVIII International Winter Meeting on Nuclear Physics (Bormio 1990) p351.

[16] R. Dayras et al., Nucl. Phys. A460(1986) 299.

[17] L. Tassan-Got and C. Stéphan, Nucl. Phys. A524 (1991) 121.

[18] G. Lanzanó et al., Nucl. Instrum. and Methods A312 (1992) 515.

[19] J.E. Sauvestre, thesis, Université de Caen, April 1992.

[20] C. Grégoire et al., Nucl. Phys. A465(1987) 317.

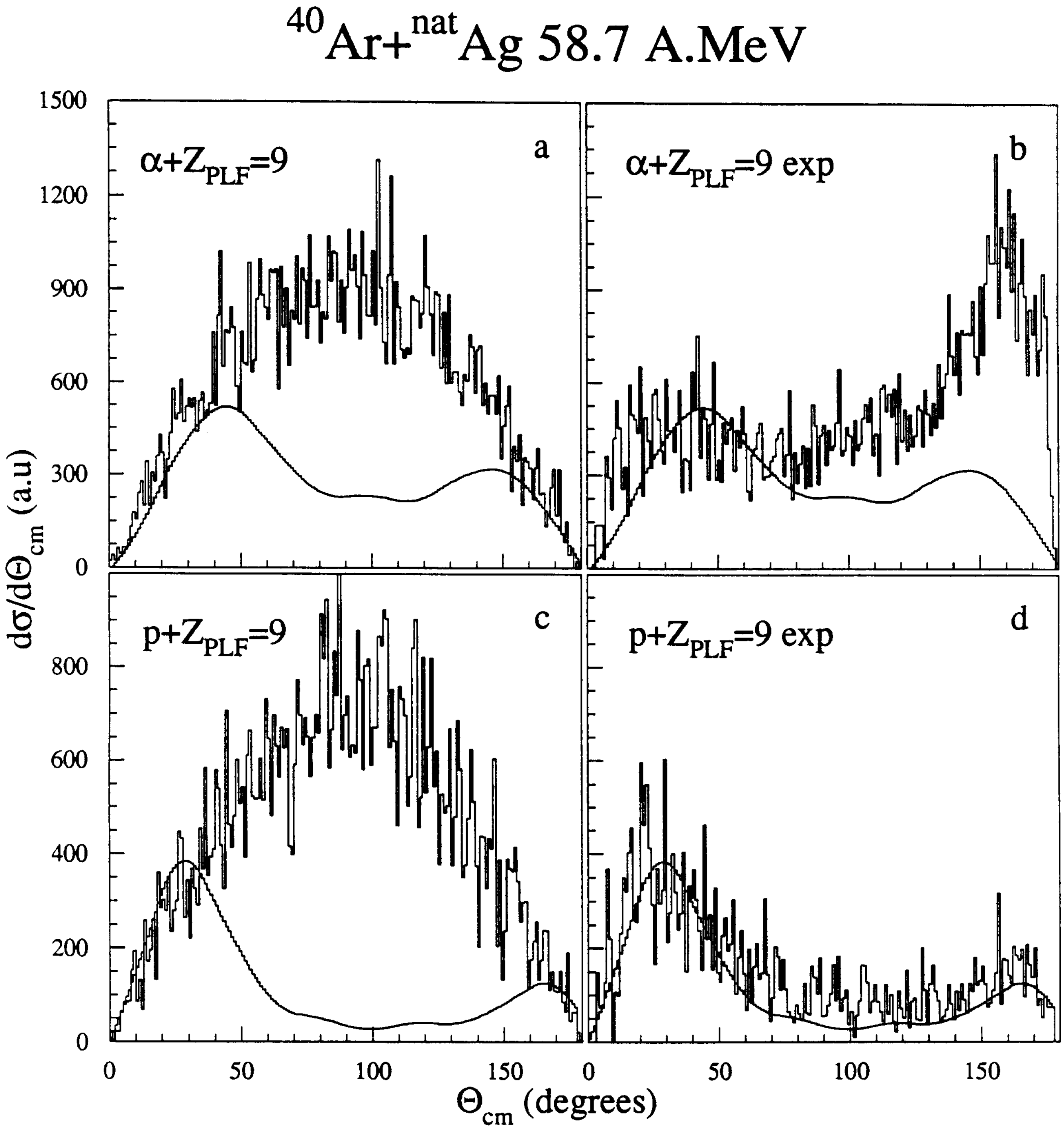
[21] L. Stuttgé et al., Nucl. Phys. A539(1992) 511.

FIGURES

FIG. 1. Monte-Carlo simulations of the angular distributions in the center-of-mass system for the α particles (1a) and protons (1c) in coincidence with a PLF of Z=9 detected between 2.5° and 3.5°. $\Theta_{cm}=0°$ corresponds to the direction of the emitter. Histograms are the results from the simulation whereas the smooth curves represent the results filtered by the BaF_2 hodoscope. Comparisons between experimental data and simulations for α particles (1b) and protons (1d). Simulated results have been normalized to the experimental data at forward angles ($\Theta_{cm}<90°$).

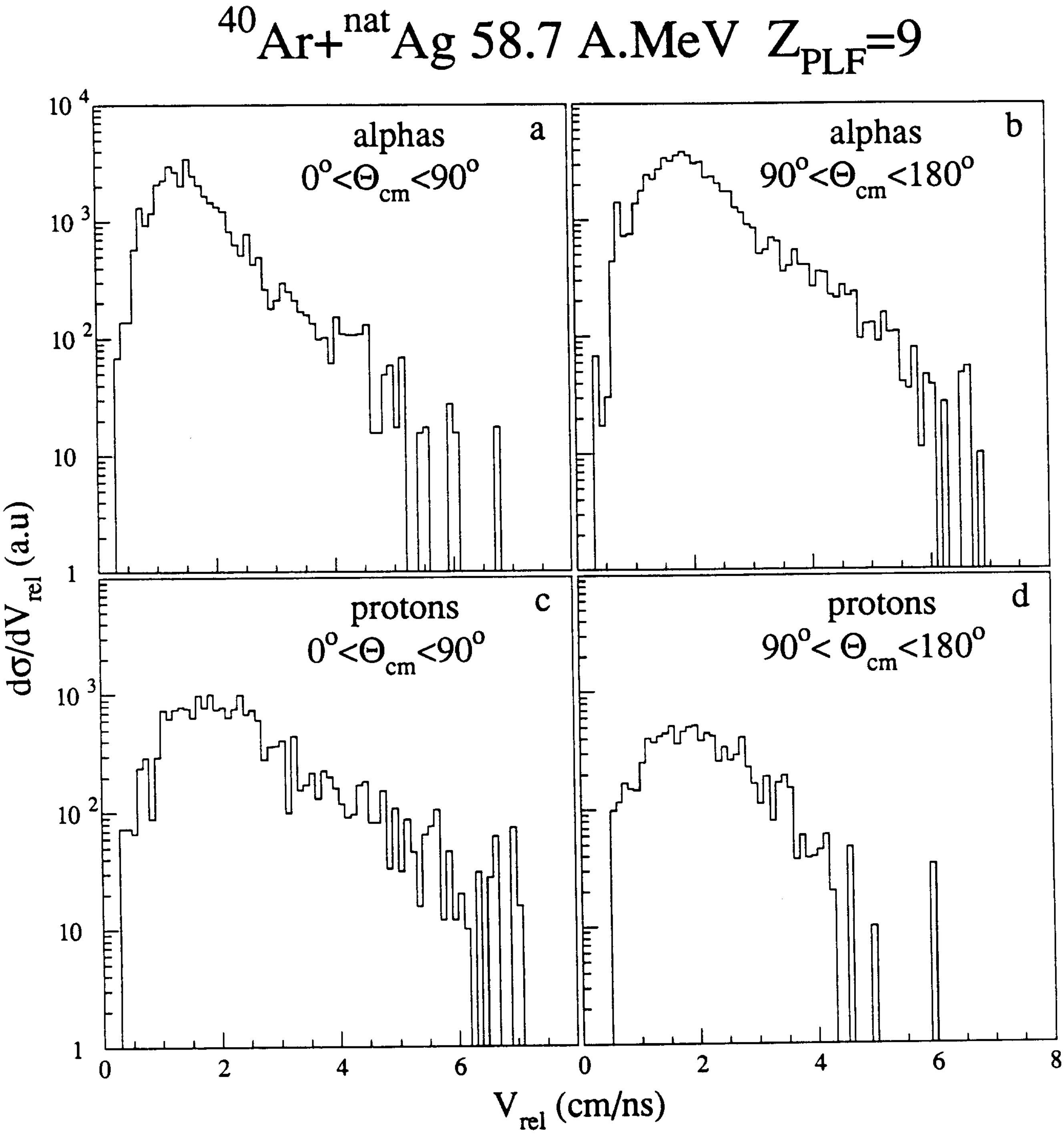
FIG. 2. Experimental spectra of the relative velocity between LCP and PLF for the forward (left) and backward emission (right) in the emitter reference frame of α particles (upper part) and protons (lower part) in coincidence with a PLF of Z=9 detected at 2.8°.

FIG. 3. Temperatures deduced from the forward emitted protons (open stars) and α particles (open circles) energy spectra, in the emitter frame, as a function of the Z of the PLF detected in coincidence. After correction for cooling down along the decay chain (see text), proton and α particle energy spectra yield the same temperature for the primary PLF (full symbols).



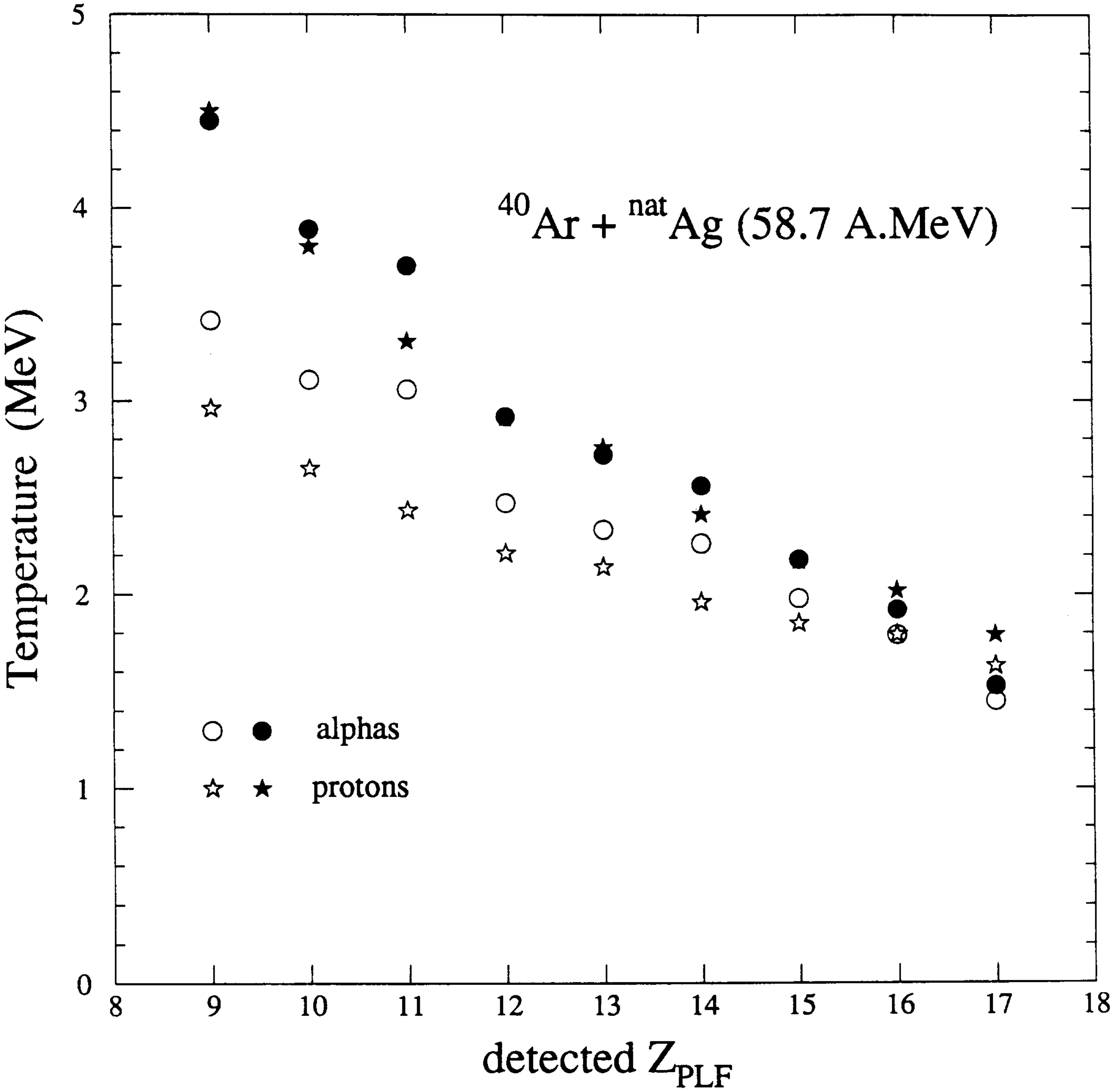
40Ar+natAg 58.7 A.MeV
α+ZPLF=9
a
α+ZPLF=9 exp
b
p+ZPLF=9
c
p+ZPLF=9 exp
d
dσ/dΘcm (a.u)
Θcm (degrees)
1500
1200
900
600
300
0
800
600
400
200
0
50
100
150

fig. 1



40Ar+natAg 58.7 A.MeV Z_PLF=9
alphas
0°<Θcm<90°
a
alphas
90°<Θcm<180°
b
protons
0°<Θcm<90°
c
protons
90°< Θcm<180°
d
dσ/dVrel (a.u)
Vrel (cm/ns)
10 4
10 3
10 2
10
1
0
2
4
6
8

fig 2



^{40}Ar + ^{nat}Ag (58.7 A.MeV)
alphas
protons
Temperature (MeV)
detected Z_{PLF}
0
1
2
3
4
5
8
9
10
11
12
13
14
15
16
17
18

fig. 3