Inclusive measurements of light charged particles emitted in the reaction $^{40}Ar+^{27}Al$ at 60*A* MeV

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Light charged particles ($p,d,t,^3He,^4He$) emitted in the reaction $^{40}Ar+^{27}Al$ at 60*A* MeV have been studied in a large angular range, $15° < \theta < 112.5°$. The data have been analyzed by supposing light charged particle emission from three equilibrated sources. Although the ''temperatures'' of the three sources as extracted from the slopes of the energy spectra are in agreement with other existing data, they are much higher than those extracted from the isotopic ratios. The anomalous abundance of α particles is also stressed and discussed. [S0556-2813(98)07506-2]

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I. INTRODUCTION

As known, the study of light particles and light fragments emitted in heavy ion nuclear reactions can give some insight on the involved reaction mechanisms. This is certainly true at low energies, where simple spectra are found, characteristic of the emitting source. By increasing the bombarding energy, the experimental particle energy spectra become more complex, suggesting either that a consistent part of the particles are dynamically emitted before thermodynamical equilibrium is reached [1] or that more than one emitting source is present. The renewed interest in this field is witnessed by a recent review article on the formation of light particles at low and intermediate energies nucleus-nucleus collisions [2]. The main information relative to their emission or to the properties of the emitting sources can be extracted from the shape of energy spectra, angular distributions, multiplicity, and their relative abundances [3–7]. However, despite a great amount of work existing in this field, many questions remain open in the intermediate energy domain. The simplest one is the following: can the study of light particles emitted in the reaction give some insight, in an unambiguous way, into the reaction scenario? As is well known at these energies, on one side the fusion mechanism between the two interacting ions vanishes [8], on the other side many experimental data can be accounted for by two different scenarios [9]. In one of them the reaction is thought of as a deep inelastic process with a very short interaction time, so that two highly excited nuclei are expected to emerge from the interaction zone. In the second one an abrasion-ablation mechanism is supposed, so that as a result of the interaction a projectilelike fragment (PLF) and a targetlike fragment (TLF) with low excitation energies are created in the vicinity of the interaction zone that can be thought of as a third source of particles with a broad velocity distribution close to half the beam velocity. We want to stress at this point that many of the results obtained in this intermediate energy regime, either by inclusive or semiexclusive experiments, have been explained successfully in the frame of a participant-spectator mechanism [10–12]. This third source can also be thought of as a source of nonequilibrium particles from the participant zone, or, in the opposite limit, as a highly excited equilibrated source of particles. In principle, the different reaction scenarios described above should lead to different particle energy spectra, so that a detailed analysis of these spectra should help us in the understanding of the underlying reaction mechanism.

In the following, after a short description of the experimental method, the results of a three-source analysis are presented and discussed.

II. EXPERIMENTAL METHOD

The experiment has been performed at GANIL, by bombarding a 100 $\mu g/cm^2$ thick self-supporting ^{27}Al target with a 60*A* MeV ^{40}Ar beam. The light charged particles (LCP) issued from the reaction were detected by means of three composite telescopes, 15° apart, and placed onto a movable arm of the CYRANO scattering chamber. The angular range from 15° to 112.5° was covered during the experiment, by steps of 7.5° taking care to overlap different detectors at the same angle. Each telescope consisted of $2\Delta E$ large area ($300\ mm^2$) silicon detectors, $\simeq 100$ and 2000 μm thick, respectively, followed by an E, 10 cm thick crystal scintillator. One of the crystals was BaF_2, while the other two were NaI (Tl), able to stop, respectively, $\simeq 215$ and 180 MeV protons. A brass collimator, 2 cm thick and with a 15 mm circular aperture, covered by a 50 μm thick Al absorber, defined a solid angle of $\simeq 0.7$ msr. Typical electronic thresholds were 4 MeV for protons and 16 MeV for α particles.

Great care was devoted to the energy calibration of each telescope, as the light output of each crystal depends upon the nature of the light charged particle. After accurate identification of each particle, we have first calibrated by standard methods (α sources and pulse generator) the two silicon detectors of each telescope. Then the calibration of the crystal was made from the knowledge of the energy deposited by the particle in the two silicon detectors. In doing so, by an iterative procedure the incident energy, $E_{\rm inc}$, of the particles was found, such that the total energy, $E_{\rm lost}$, lost by the particles in the aluminum absorber and in the two silicon detectors was reproduced. Before attributing the remaining energy, $E_3 = E_{\rm inc} - E_{\rm lost}$, to the particle entering the crystal, we have carefully evaluated (i) the dead layer of the second silicon detector, (ii) the Al layer in front of the two NaI (Tl), (iii) the electronic threshold of each crystal. In this way we were able to create a correspondence between the light output of each crystal and the particle energy, that we fitted to a polynomial of order 1 or 2.

III. DATA ANALYSIS AND RESULTS

In general, the energy spectra, especially at the most forward angles, are very complex, indicating that more than one emitting source is present in the reaction. By assuming only one or two emitting sources it is not possible to reproduce the energy spectra of a given particle species over the whole measured angular range with a unique set of parameters. At least three sources are required. In the following, after a short presentation of the experimental results, we describe the method used in the data analysis, and then present the results.

Figure 1 shows the energy spectra for p, d, t, ^{3}He, and α particles detected at different angles ranging from 15° up to 112.5°. The energy thresholds ($\simeq 4$ and 16 MeV for protons and α particles, respectively) are essentially given by the thickness of the first silicon element. The ''dip'' apparent in the spectra at $\simeq 20$ MeV for protons and $\simeq 80$ MeV for α particles is due to the dead layer in the second silicon element and the entrance window of the scintillator crystals as discussed in the preceding section. The shape of the spectra depends upon the detection angle. At the most forward angles a consistent part of the spectra is centered at energies corresponding very closely to the beam velocity, with exponential tails extending to higher energies. As the detection angle increases, the high energy part of the spectra becomes less and less important, and its maximum is shifted towards lower energies. The angular distributions, obtained by integrating these spectra over energy, are shown in Fig. 2 for p, d, t, ^{3}He, and α particles. For completeness, experimental data points, mainly at forward angles ($2.8° \leqslant \theta \leqslant 10°$), obtained in a separate measurement [13] on the same system at 58.7A MeV incident energy are also shown on the figure. The two sets of data are in excellent agreement. Due to kinematic focusing, the angular distributions are strongly forward peaked. This focusing effect increases with the mass of the emitted particles and is the strongest for α particles. Such a behavior is expected if all are emitted from sources in thermal equilibrium. In the reference frame of each source, neglecting Coulomb effects, all particles have the same kinetic energy and thus have velocities that decrease as $1/\sqrt{m}$, m being the mass of each particle type. Hence, α particles have half the velocity of protons. Then, in the laboratory frame, this leads to more forward focusing for α particles than for protons. All angular distributions show a change in slope around 30°. Below this angle, the particle yields increase sharply with decreasing detection angle. We have attempted a source analysis, assuming three independent moving sources of emission. In each source reference frame, the particles are emitted isotropically with Maxwell-Boltzmann energy spectra. Thus, in the laboratory frame of reference, the energy spectra measured at a given angle are the superimposition of three distributions of the form [3]

$$\frac{d^2\sigma}{d\Omega\ dE_{\rm lab}} = N(E_{\rm lab} - E_{\rm Coul})^{1/2} \exp\left[-\left(\frac{E_{\rm lab} - E_{\rm Coul} + E_s - 2[(E_{\rm lab} - E_{\rm Coul})E_s]^{1/2}\cos\theta}{T}\right)\right], \tag{1}$$

where $E_{\rm lab}$ and θ are, respectively, the kinetic energy and the angle of emission of the particle in the laboratory. $E_s = 1/2 m v_s^2$ is the laboratory kinetic energy of a particle, of mass m, having the velocity v_s of the source. Here $E_{\rm Coul} = ZE_c$ is a Coulombian repulsion term depending upon the charge Z of the emitted particle. Finally, T is the source temperature and N a normalization constant. Integrating Eq. (1) over energy and angle, the cross section for the emission of a particle species is given by

$$\sigma = 2N(\pi T)^{3/2}. \tag{2}$$

For each source, N, v_s, T, and E_c are treated as free parameters. For a given particle assuming three independent moving sources, the corresponding twelve parameters are determined by a simultaneous χ^2 fit to all energy spectra from 15° to 112.5°. The data points corresponding to the dips in the energy spectra, as well as particles the energy of which exceeds the maximum energy that can be deposited in a given telescope, were excluded from the fits. To overcome the problem of coupling between the parameters, some of them were constrained. Thus the variation of the Coulomb term was limited to the range $2 \leqslant E_c \leqslant 5$ MeV. The initial values of the other parameters were deduced from an abrasion-model calculation [10,14]. Typical initial parameters were a temperature $T = 8$ MeV and a velocity $v_s \simeq 1/2$ of the beam velocity for the intermediate velocity source, a temperature $T = 4$ MeV and a velocity $v_s \simeq$ the projectile velocity for the PLF source, and a temperature $T = 4$ MeV and a velocity $v_s \simeq 0$ for the TLF source. Finally, for the normalization constants N's, relative values of 0.20, 0.30, and 0.50 were used, respectively, for the TLF, PLF, and the intermediate velocity source. These initial parameters were slightly varied, until the final set of parameters yields equally good fits to the experimental data over the whole angular range. As the contribution of each individual source to the observed energy spectra depends strongly upon the detection angle, the whole set of parameters can only be correctly established

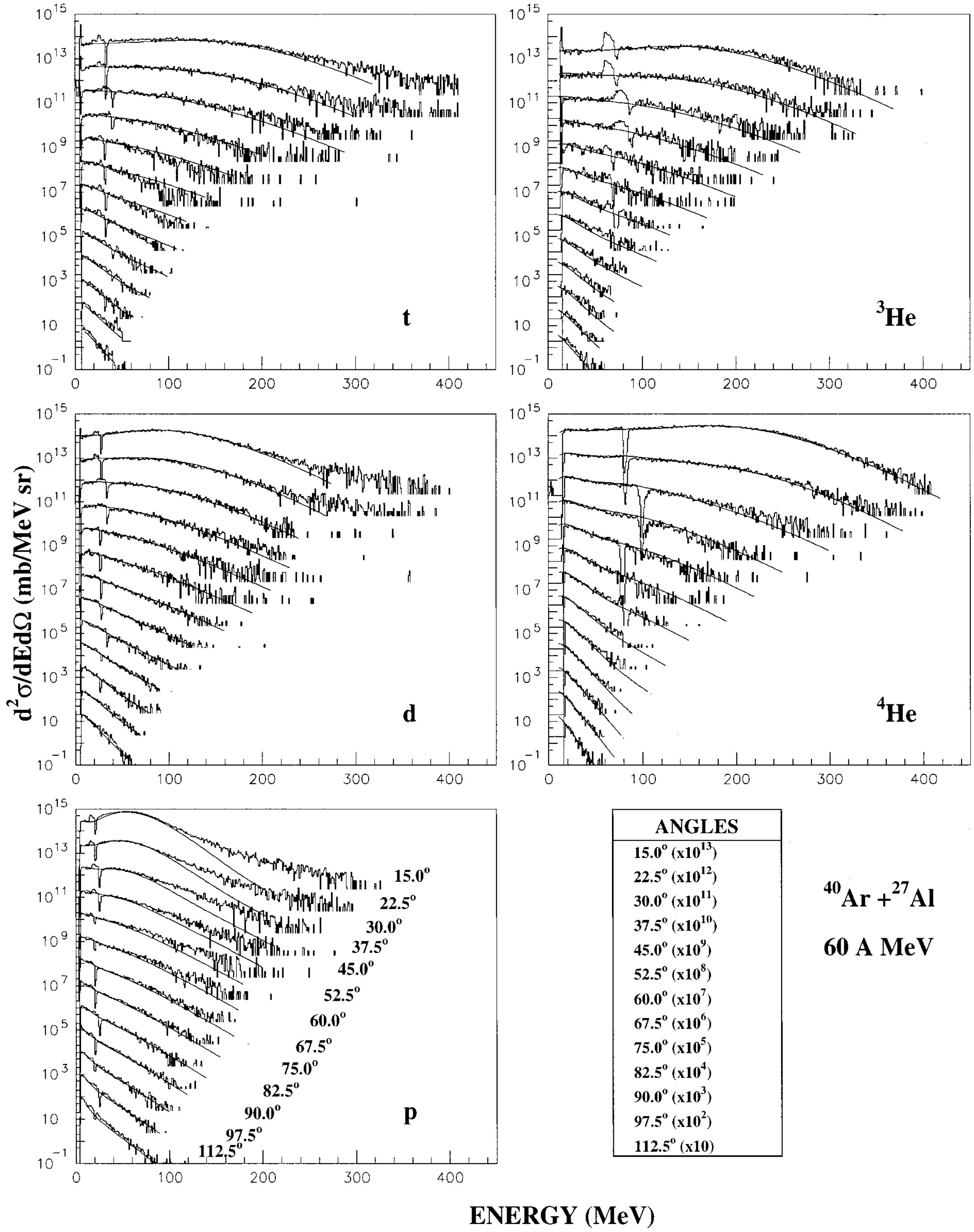

FIG. 1. p, d, t, ^{3}He, and α-particles energy spectra measured in the angular range from $\theta = 15°$ to $\theta = 112.5°$. The dips in the spectra are due to a dead layer in the second element of the telescopes and the entrance window of the NaI and BaF_2 crystals. The lines are the result of a three-equilibrated-sources fit procedure, as explained in the text.

by fitting the spectra over the complete angular range. For each particle species, the parameters extracted from the fits are listed in Table I for the three sources. The energy spectra calculated with these parameters are compared to the experimental data in Fig. 1. The overall agreement is quite good except for protons at forward angles where the experimental spectra show an excess of high energy particles that cannot be reproduced assuming only three sources. After integration over energy, the calculated angular distributions are compared to the experimental ones in Fig. 2. There again, the agreement is quite satisfactory.

Figure 3 shows the contributions of the different sources to the protons and α-particle energy spectra at 15°, 30°, 60°, and 90°. The focusing effect mentioned earlier is clearly apparent. The contribution of the PLF source to the energy spectra extends to much larger angles for protons than for α particles. The same observation is also true for the intermediate velocity source. For the TLF source, the laboratory velocity of which is small ($\sim 0.05c$), its contribution is almost independent of the angle for protons, whereas it decreases by about an order of magnitude for α particles when the detection angle increases from 15° to 90°.

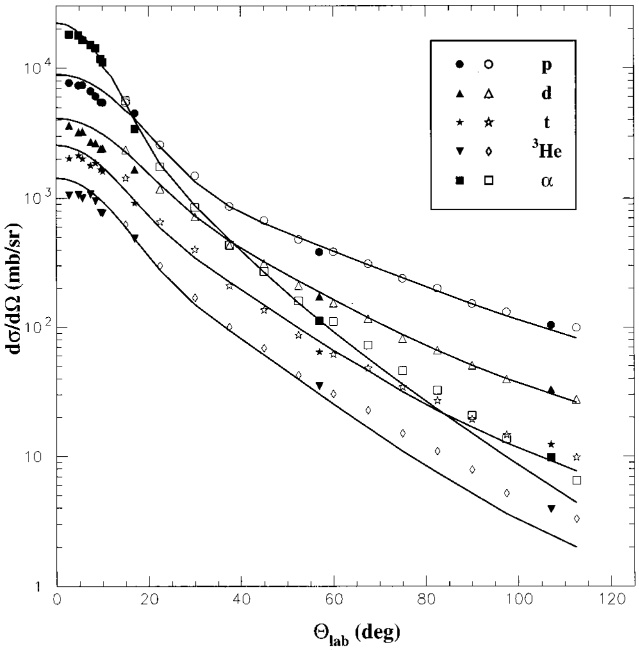

FIG. 2. Experimental angular distributions for p, d, t, ^{3}He, and ^{4}He. Open and full symbols are experimental data from this experiment and from an independent experiment reported in [13], respectively, relative to the same reaction at 58.7A MeV. The lines are the result of a three-equilibrated-sources fit procedure, as explained in the text.

Figures 4(a)–4(e) show for each particle species the contributions of each of the three sources to the total yield as a function of angle. As expected, the faster the source is, the steeper is the associated angular distribution. Thus, the yield at forward angles is dominated by the PLF source, whereas at backward angles it is dominated by the TLF source. At intermediate angles ($\theta \simeq 35°$), the largest contribution comes from the intermediate velocity source. This is illustrated by Fig. 4(f), which shows the fraction of the yield due to the intermediate velocity source as a function of the angle. This fraction reaches a maximum value $\simeq 0.6-0.7$ for $30° \leqslant \theta \leqslant 50°$.

By inspecting more closely Table I, several observations can be made. The quantity of light charged particles emitted in the reaction amounts to a total cross section $\sigma_{tot}=16$ b, to which the TLF, intermediate velocity, and PLF sources contribute, respectively, for $\sigma_{TLF}=4.15$ b, $\sigma_{FB}=5.92$ b, and $\sigma_{PLF}=5.93$ b. Thus, more than one-third of all particles are emitted by the intermediate velocity source, rendering the description of the reaction mechanism in term of a simple two-body dissipative process inadequate. Protons and α particles are produced with almost the same intensity, whereas on the average, the deuteron yield is half that of the protons, the triton's is half that of the deuterons, and the ^{3}He particle's is half that of the tritons. The fact that α particles are so copious in the three different sources cannot go unnoticed. Probably it is connected with the α clusterization of nuclei as light as those of this reaction and/or the reaction mechanism involved. Indeed for ^{20}Ne induced reaction the authors of [15–17] were successful in explaining their experimental results by taking explicitly into account the α structure of the projectile. Furthermore, Hodgson in a recent review [18] speaks about transient α particles formed in a nucleus and of their fate when colliding with another nucleus, stressing the fact that many properties of light nuclei may be simply explained using the concept of α clustering, without explicit reference to the α-particle constituent neutrons and protons. In addition, if the projectile and target fragmentation process is accompanied by the production of light (excited) ions, then their decay by light particles can also contribute to such an increment of α particles. Evidence for this process has recently been observed in the reaction ^{40}Ar+^{27}Al at 44A MeV [19–21], by means of interferometric studies.

The ratio between the number of particles emitted by the TLF source and the PLF one, $\sigma_{TLF}/\sigma_{PLF}=0.68$, is very close to the target to projectile mass ratio. This tends to show that the projectile and the target have reached about the same temperature before to decay by light particle emission. This is substantiated by the fact that the fits to the experimental data yield very similar temperatures for the TLF and PLF sources. For d, t, and ^{3}He, the source parameters are independent of the particle type, suggesting that these particles are emitted from three independent equilibrated sources. It has to be noted, however, that the intermediate velocity source that is associated to the overlap between projectile and target has a temperature $\simeq 16$ MeV, twice as high as the temperature, $\simeq 8$ MeV, of the TLF and PLF sources. For protons and α-particle emission, the source parameters are somewhat different. For protons, the PLF source is faster, whereas the TLF and intermediate velocity sources are

TABLE I. List of the parameters deduced from the fits to the laboratory light particle energy spectra over the angular range $15° \leqslant \theta \leqslant 112.5°$, using three independently moving sources labeled ''Targetlike,'' ''Fireball,'' and ''Projectilelike,'' respectively. For each source, σ, β, T, and E_c are, respectively, the intensity of the source, its velocity (in unit of light speed), its temperature, and the Coulomb repulsion term.

	Targetlike				Fireball				Projectilelike			
Particle	σ_{TLF} (mb)	β	T (MeV)	E_c (MeV)	σ_{FB} (mb)	β	T (MeV)	E_c (MeV)	σ_{PLF} (mb)	β	T (MeV)	E_c (MeV)
p	1497	0.050	4.7	2	2302	0.163	14.5	4	2206	0.328	4.9	3
d	731	0.054	8.4	2	1188	0.174	15.9	4	851	0.315	8.5	3
t	333	0.054	8.4	2	621	0.174	16.9	4	350	0.315	8.5	3
^{3}He	208	0.054	8.4	2	268	0.174	15.9	4	212	0.315	8.5	3
^{4}He	1378	0.060	7.5	3	1539	0.180	12.0	5	2306	0.308	6.9	4

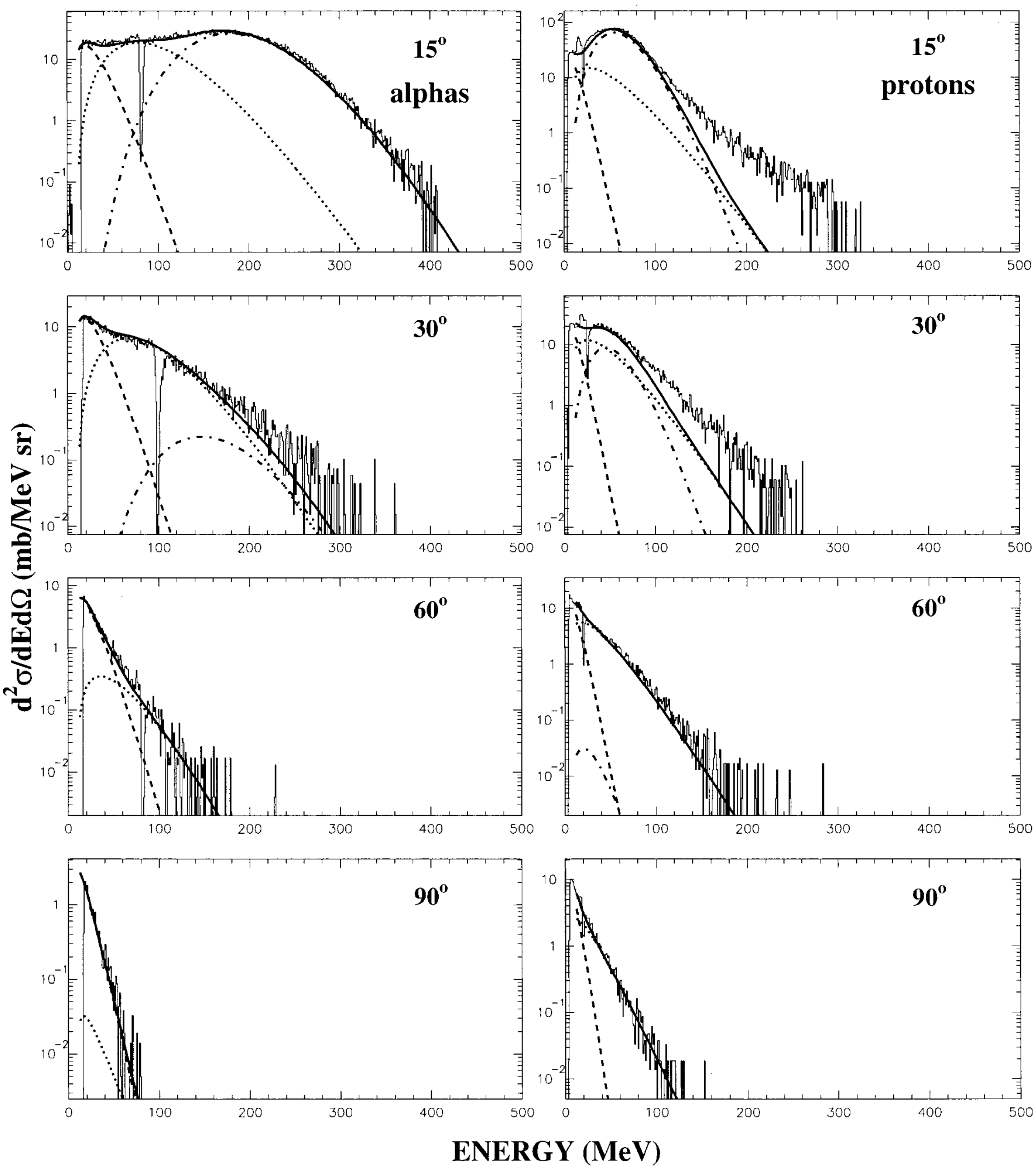

FIG. 3. Contributions of the three sources to the energy spectra of α particles (left panel) and protons (right panel) measured at four different angles from 15° to 90°: TLF source (dashed lines), intermediate velocity source (dotted lines), and PLF source (dot-dashed lines). The solid lines are the sum of the three contributions.

slower than for the other particles. This would suggest that an important fraction of the protons are emitted as the projectile is slowing down. For α particles the inverse is true, suggesting that they are mainly emitted in the final stage of the collision.

The source velocities are in fair agreement with those given by a standard abrasion-ablation model. For a given particle type, the temperatures are the same for TLF as well as for PLF source, ranging from 5 MeV for protons, 7 MeV for α particles, and up to 8.5 MeV for the other particles. There again, the marked difference between the temperatures obtained for proton α particles and the other particles would suggest different production processes. Much higher temperatures are found for particles originating from the intermediate velocity source, ranging from 12 MeV for α particles up to 17 MeV for tritons. These values follow the systematic trends from other data.

Recent analysis [22–31] of the kinetic energy spectra of light particles and fragments produced in nucleus-nucleus collisions at intermediate energy (30–100A MeV) suggests the onset of collective expansion. Studying a system very close to ours, ^{27}Al+^{36}Ar at bombarding energies ranging from 55 to 95A MeV, Jeong *et al.* [29] found that the collective expansion energy is strongly correlated with the energy, E^*, deposited into the system. This radial expansion was found to set in when the deposited energy E^* reached $\simeq 5A$ MeV, increasing linearly with E^* thereafter, to reach a rather small value, $\simeq 1-2A$ MeV for $E^* = 11A$ MeV. In the

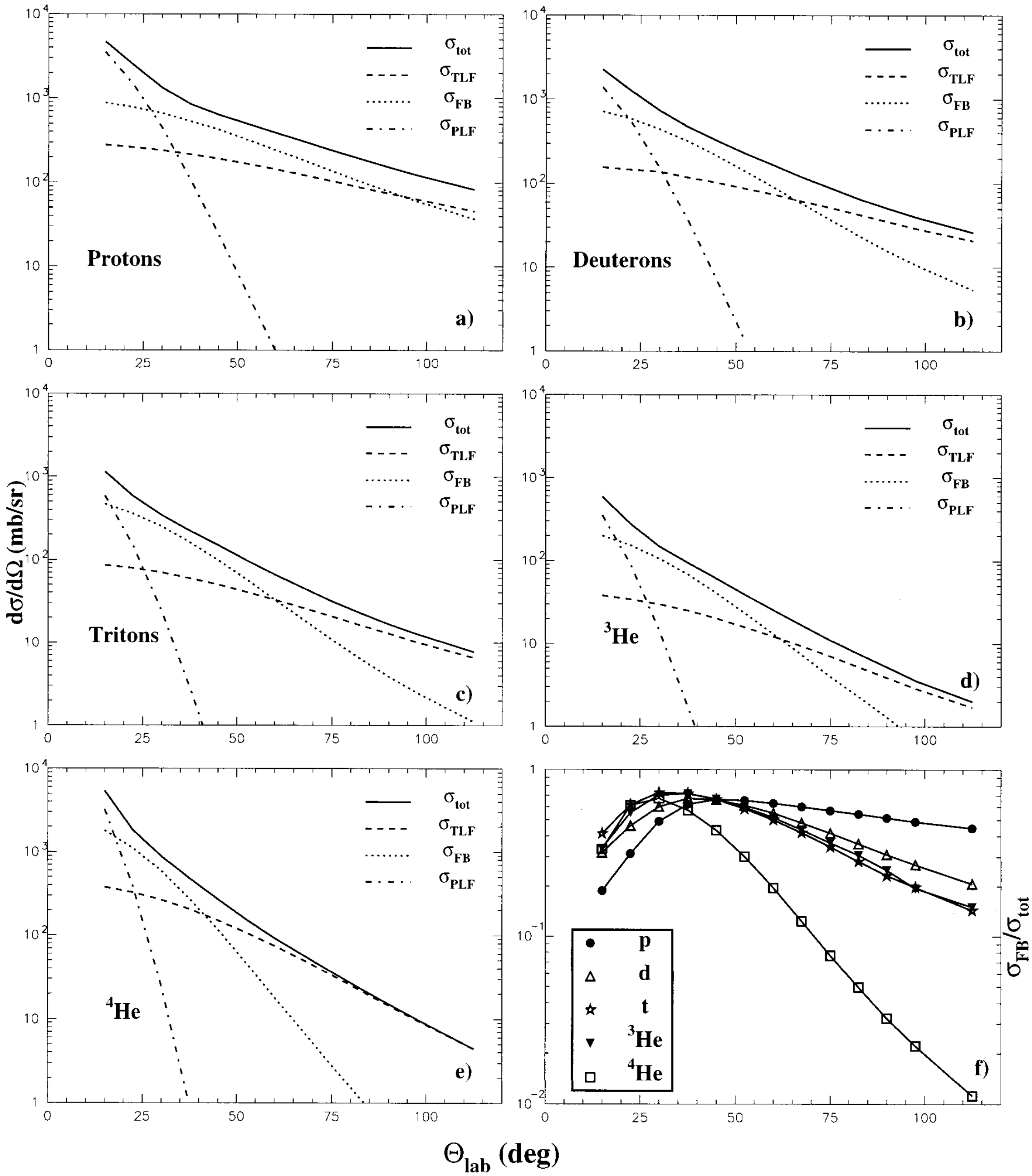

FIG. 4. The total and partial source angular distributions, as obtained by the fit procedure (see text), are displayed for (a) p, (b) d, (c) t, (d) ^{3}He, and (e) ^{4}He. The intermediate source relative intensity is reported as a function of the laboratory angle for p, d, t, ^{3}He, and ^{4}He in (f).

present analysis, we have assumed three isotropic emitting sources with Maxwellian energy spectra. Thus, in the reference frame of each source, the average kinetic energy of particle i is given by

$$\langle E\rangle=\tfrac{3}{2}T+Z_iE_c, \tag{3}$$

where Z_iE_c corresponds to the Coulomb repulsion. Assuming an extra radial expansion energy per nucleon $\epsilon_{\rm rad}$, the average kinetic energy of particle i would be given by [25]

$$\langle E\rangle=\tfrac{3}{2}T+Z_iE_c'+m_i\epsilon_{\rm rad}, \tag{4}$$

where m_i is the mass of the particle. Thus by comparing relations (3) and (4), it is found that the presence of an expansion energy can be simulated in Eq. (3) by an artificial increase of the Coulomb parameter E_c by an amount $(m_i/Z_i)\epsilon_{\rm rad}$, depending on the particle type, without changing the quality of the fits. Assuming that the values of E_c given in Table I are dominated by the radial expansion energy term, an upper limit, $\epsilon_{\rm rad}\simeq 1-2A$ MeV, consistent with Ref. [29] can be estimated. Such a small value will have essentially no effect upon the other fit parameters.

IV. TEMPERATURE MEASUREMENTS

The particle energy spectra have been fitted with a good accuracy assuming three sources of emission. The large difference observed between the temperature (≈ 16 MeV) of

TABLE II. Temperatures of the three sources determined from the isotopic ratios using relations 5 to 7 (see text for details).

Formula	T_{TLF} (MeV)	T_{FB} (MeV)	T_{PLF} (MeV)
(5)	4.5	5.0	3.8
(6)	3.1	3.3	3.4
(7)	4.3	4.5	3.6

the intermediate velocity source and the temperature (≈ 8 MeV) of the projectilelike and targetlike sources indicates that the three sources are not in thermal equilibrium although thermal equilibrium may be achieved inside each individual source. In this latter case, all particle species emitted by the same source should yield the same temperature. However, it is found that protons and α particles yield somewhat lower temperatures than the other particles. Many arguments can be invoked to explain this discrepancy. Some of the particles are emitted before thermal equilibrium is reached. The particles are not emitted in random order. As we are dealing with inclusive spectra, a large range of impact parameters is involved and the extracted source parameters represent only average values. Furthermore, as the PLF velocity depends slightly upon its mass [10], mixing sources with different velocities will tend to produce higher apparent temperatures.

In order to get some insight into the meaning of the temperatures extracted from the source fits, we have attempted to obtain these temperatures by another method, following the approach suggested by Albergo *et al.* [7]. They have made a systematic study of LCP production at intermediate and relativistic energies to test a method for obtaining temperatures from a dilute gas of particles. Assuming thermal and chemical equilibrium inside the gas, the isotopic ratio for different particle species is mainly governed by the temperature of the gas. Using $Z=1$ and 2 isotopes one can derive the following formulas:

$$T=\frac{14.3}{\ln\left[\frac{Y(d)Y(^4\mathrm{He})}{Y(t)Y(^3\mathrm{He})}\times 1.6\right]}\ \mathrm{MeV}, \tag{5}$$

$$T=\frac{4.033}{\ln\left[\frac{Y(d)Y(d)}{Y(p)Y(t)}\times 3.464\right]}\ \mathrm{MeV}, \tag{6}$$

$$T=\frac{18.35}{\ln\left[\frac{Y(p)Y(^4\mathrm{He})}{Y(d)Y(^3\mathrm{He})}\times 5.55\right]}\ \mathrm{MeV}, \tag{7}$$

where $Y(i)$ is the yield for the species i.

Taking for each source the particle yields as given in Table I, the temperatures obtained using relations (5)–(7) are listed in Table II. For a given source, if thermal and chemical equilibrium are reached, formulas (5)–(7) should yield the same temperature, which is not the case. However, as noted previously, an important fraction of the protons may be of preequilibrium origin. Thus, the temperatures deduced from relations (6) and (7) making use of the proton yield may not be reliable. In the following, we will restrict the discussion to the temperatures given by relation (5), which is considered by Albergo *et al.* [7] as the more appropriate. Whereas the moving source fits (Table I) yield equivalent temperatures for the TLF and the PLF sources, relation (5) gives a TLF source temperature, 4.5 MeV, somewhat higher than the PLF source one, 3.8 MeV. These temperature values are only two-thirds of the values deduced from the fits and are also much lower than the value $\simeq 7.3$ MeV found in the systematics established by Albergo *et al.* [7] for various systems at bombarding energies ranging from 50 to 150A MeV on what they call ''fragmentation sources.'' Relation (5) gives a temperature of 5 MeV for the intermediate velocity source, in agreement with the trend they have established for the so-called ''equilibrium component'' in the same bombarding energy range. However, this value is only one-third the value deduced from the source fits. Several effects may affect the validity of relations (5)–(7). The fact that different source parameters are needed to fit the energy spectra according to the particle species calls into question the underlying hypothesis of an emission by sources in statistical equilibrium. Furthermore, as it has been noticed recently [32,33], secondary decay from unbound excited states of heavier fragments may alter the final isotopic yields of light particles. Although corrections for side-feeding have been attempted in the past [34,32], they require a good description of the decay process. Whereas sequential decay may be a good assumption for the PLF and TLF sources, it is certainly not the case for the intermediate velocity source to which direct processes may contribute significantly. Thus, such corrections were not attempted here. Part of the discrepancy between the present results and the systematics of Albergo *et al.* [7] may find its origin in the different ways of unfolding the different emission sources. Looking at Fig. 4, it is not possible to find a region in space where only one source contributes to the yields of all particles. Thus, it seems that besides the delicate problem of side-feeding, the formula of Albergo *et al.*, which may apply at relativistic energies, is difficult to use for a reliable determination of temperature at intermediate energies where the different sources of emission are not well separated in phase space.

V. CONCLUSIONS

Inclusive light particle (p, d, t, ^{3}He, and α) energy spectra produced in the reaction ^{40}Ar+^{27}Al at 60A MeV bombarding energy have been reproduced fairly well over the whole angular range $15° \leqslant \theta \leqslant 112.5°$ assuming three sources of emission (TLF, PLF, and intermediate velocity sources). However, it is not possible to reproduce the spectra of the different particle species with the same set of parameters. In particular, the relative velocity between the TLF and the PLF sources is larger for protons than for α particles, suggesting that a fair amount of the protons are emitted at the beginning of the collision before full energy damping. More than one-third of all particles are emitted at midrapidity, calling into question the description of the reaction mechanism in terms of a simple two-body dissipative process. Although the present analysis does not permit a proper distinction between a collective radial expansion energy and the Coulomb repulsion energy, a collective radial expansion energy of at most

$\simeq 1-2A$ MeV can be accommodated by the present data, in agreement with Ref. [29].

The observed anomalous abundance of α particles could be due to the production in the reaction of excited light ions and/or to the α structure of the two interacting nuclei.

The strong overlap in phase space between particles originating from different sources renders the determination of temperatures by the approach of Albergo *et al.* [7] very difficult to use in the intermediate energy regime.

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