Sharing of the Excitation Energy in the Initial Stages of Nucleus-Nucleus Collisions

M. Korolija, N. Cindro, and R. Čaplar
Rudjer Bošković Institute, 41001 Zagreb, Croatia, Yugoslavia
(Received 28 July 1987)

Inclusive proton spectra from reactions induced by ^{16}O, ^{32}S, and ^{58}Ni projectiles have been decomposed by use of a refined multisource analysis. Yields from centrallike collisions have been extracted and compared with Boltzmann-master-equation predictions. The comparison yields the initial number of degrees of freedom, n_0. The excitation energy per initial degree of freedom, E^*/n_0, is found to be essentially independent of the colliding masses, depending only on the per-nucleon energy of the projectile. An empirical relation connecting E^*/n_0 with the available incident energy is given.

PACS numbers 25.70.Jj, 25.70.Lm

In its early stages, the composite system formed in a nucleus-nucleus collision is far from equilibrium and light-particle emission is expected to be nonisotropic and non-Maxwellian. Conversely, the hard, nonisotropic component of the particle spectra is expected to yield information about the early stages of the collision. With this in mind, we report on a systematic analysis of inclusive proton spectra from an extensive set of heavy-ion collisions. From the analysis we deduce that the excitation energy of the composite system formed in the nucleus-nucleus collision is shared in the early stages in such a way that the quantity E^*/n_0 (excitation energy per degree of freedom) depends only on the per-nucleon energy of the projectile; it depends neither on the projectile mass nor on the target mass.

The data basis for the present analysis are inclusive proton spectra of $^{16}\mathrm{O}+X$, $E(^{16}\mathrm{O})=403.3$ MeV; $^{32}\mathrm{S}+X$, $E(^{32}\mathrm{S})=503.7$ and 678.8 MeV; and $^{58}\mathrm{Ni}+X$, $E(^{58}\mathrm{Ni})=876.5$ MeV; where X stands for targets of ^{27}Al, ^{46}Ti, ^{60}Ni, ^{120}Sn, ^{124}Sn, and ^{197}Au. Details of the measurement and the data are given by Auble *et al.*[1]

The analysis proceeds in several steps. First, the inclusive proton spectra are decomposed into contributions from centrallike and noncentral collisions. This is done with use of a refined analysis with four moving sources, associated, respectively, with (i) equilibrium emission from the compound system, (ii) preequilibrium emission from the composite system, and emissions from (iii) a fast projectilelike and (iv) a slow targetlike source. The parameters for these sources are obtained by our fitting the proton emission spectra measured at seven angles from $\theta_{\mathrm{lab}}=10°$ to 144°. This procedure has been described by Korolija *et al.*[2,3] Sources (i) and (ii) simulate emission from centrallike collisions. Their contributions are singled out and summed up to form angle-integrated spectra consisting of protons emitted from the composite system before and during the equilibration stage. These spectra are then analyzed in terms of a Boltzmann-master-equation approach. We follow the approach introduced by Blann,[4] who extended the Harp-Miller-Berne equilibration model[5] to heavy-ion-induced reactions.

The Boltzmann-master-equation approach describes the time evolution of the composite system. It contains two types of parameters: One determines the initial conditions and the other the transition rates between the various stages that the system goes through during its evolution. The first set is represented by n_0, the initial number of degrees of freedom that share the excitation energy of the composite system in its early stages. For the second set, we take the transition rates for a stochastic system of colliding nucleons in nuclear matter.[6] In order to fit the absolute values of the experimental multiplicities, these transition rates are scaled by a variable factor k. Recent analyses[7-9] adopt $k=\frac{1}{4}$ (arbitrary increase of the calculated nucleon mean free path by a factor of 4); we have also used $k=\frac{1}{4}$ throughout the analysis. The value of k, however, does not influence the slope of the calculated spectra (see Fig. 4 of Ref. 8). Thus, the experimental feature directly connected with n_0 being the slope of the high-energy component of the spectra, using k in a reasonable range (e.g., $k=1$ or $\frac{1}{2}$) would not modify the obtained best-fit values of n_0.

The transition rates having been thus fixed, the only remaining fit parameter in the analysis is n_0. Because of the sensitivity of n_0 to the slope of the spectra, it is of utmost importance to determine accurately the preequilibrium component in the decomposition of the spectra. We have achieved this by introducing a new *Ansatz*[2] which explicitly takes into account the anisotropy of the emitted preequilibrium particles already in the source frame (c.m. system):

$$\left(\frac{1}{p}\right)\left(\frac{d^2\sigma}{dE\,d\Omega}\right)=AE^{1/2}e^{-E/T}e^{-\theta/\Delta\theta}. \qquad (1)$$

The anisotropy parameter $\Delta\theta$ depends on the energy of the emitted particles through the relation $R\,\Delta\theta\geq 2\pi/K$,[10] with K the nucleon wave number and R the radius of the compound system. For charged emitted particles,

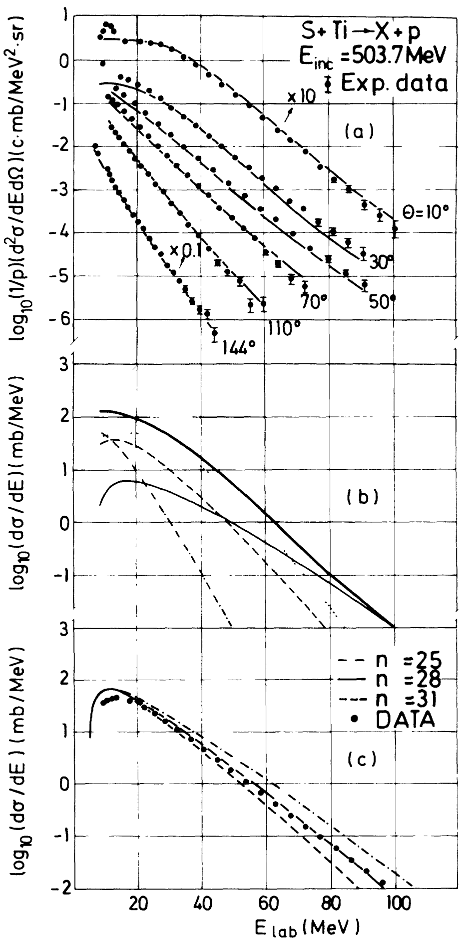

FIG. 1. (a) Best fits to experimental proton spectra. (b) Angle-integrated spectra from the multisource analysis; yields from the equilibrium (dashed line), preequilibrium (thin solid line), projectilelike (dotted line), and targetlike (dash-dotted line) sources. The thick solid line is the sum of the four components. (c) Comparison of angle-integrated spectra from centrallike collisions (full dots) with Boltzmann-master-equation calculations for three different values of n_0.

Eq. (1) is modified by our taking particle-source Coulomb repulsion into account.

Figures 1(a)–1(c) give an example of the analysis described above. We estimate the uncertainty in the deduced centrallike spectra to be at most a factor of 2, which is roughly twice the size of the dots in Fig. 1(c). The sensitivity to the value of n_0 is illustrated by our plotting the calculated spectra for three different values of n_0 [Fig. 1(c)].

The best-fit values of n_0 for all the analyzed systems are collected in Table I. The main feature of their behavior is the dependence of n_0 on the entrance channel: The obtained values are grouped around the mass number of the projectile (A_P), viz., for collisions induced by the heavy ^{58}Ni projectile, around that of the lighter partner. Furthermore, the values of n_0 show an increase with the mass of the system (i.e., with the target mass A_T for a given projectile). Since the excitation energy $E^* = E_{c.m.} + Q_{fus}$ of the system tends to increase in the same way, plotting the values of E^*/n_0 vs A_T and/or the available incident energy seems a natural way of representing the obtained results (Figs. 2 and 3).

TABLE I. Best-fit values of n_0, composite-system excitation energies E^*, and E^*/n_0 for the analyzed projectile+target systems.

Target	n_0	E^* (MeV)	E^*/n_0 (MeV)
	^{16}O projectile, E_{inc} = 403.3MeV		
^{27}Al	16	272	17.0
^{46}Ti	19	311	16.4
^{60}Ni	19	318	16.7
^{120}Sn	21	346	16.5
^{197}Au	22	341	15.5
	^{32}S projectile, E_{inc} = 503.7 MeV		
^{27}Al	23	248	10.8
^{46}Ti	28	298	10.6
^{60}Ni	29	322	11.1
^{120}Sn	35	350	10.0
^{124}Sn	35	356	10.2
^{197}Au	37	338	9.2
	^{32}S projectile, E_{inc} = 678.8 MeV		
^{27}Al	23	329	14.3
^{46}Ti	28	401	14.3
^{60}Ni	29	436	15.1
^{120}Sn	35	489	14.0
^{124}Sn	35	496	14.2
^{197}Au	37	489	13.2
	^{58}Ni projectile, E_{inc} = 876.5 MeV		
^{27}Al	26	280	10.8
^{46}Ti	35	354	10.1
^{120}Sn	46	471	10.2
^{124}Sn	46	484	10.5
^{197}Au	61	561	9.2

Figure 2 demonstrates the striking feature that the excitation energy per initial degree of freedom, E^*/n_0, depends only on the per-nucleon energy of the incident projectile. It is in fact constant for a given projectile at a given energy and also for two different projectiles (^{32}S and ^{58}Ni) having the same per-nucleon energies.

The incident-energy dependence of E^*/n_0 is shown in Fig. 3. The values of E^*/n_0 increase with the available incident energy per nucleon, $(E_{inc} - V_{CB})/A_P$, following the linear expression

$$E^*/n_0 = 0.74(E_{inc} - V_{CB})/A_P \quad (2)$$

(all energies in megaelectronvolts; V_{CB} represents the projectile-target Coulomb barrier).

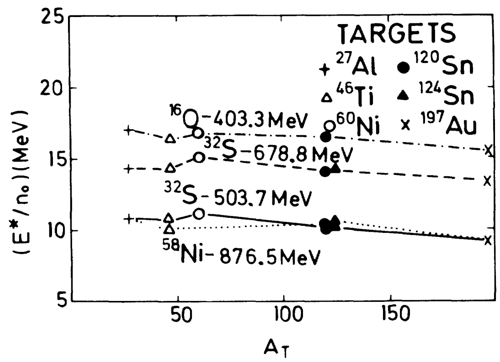

FIG. 2. Plot of E^*/n_0 vs the target mass number A_T for the ^{16}O-, ^{32}Si-, and ^{58}Ni-induced reactions.

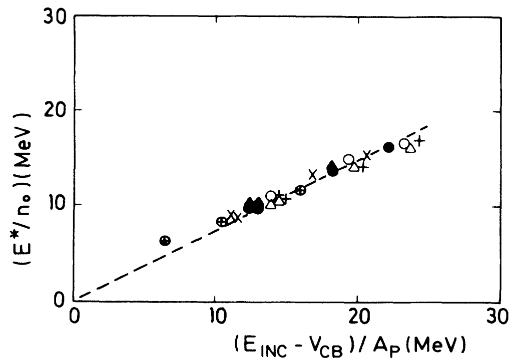

FIG. 3. Dependence of E^*/n_0 on the available incident energy per nucleon. The dashed line is the empirical relation (2), obtained by a χ^2 fit through all the points. Symbols are as in Fig. 2.

The closeness of n_0 to the mass number of the lighter partner in the collision, $A_{\rm light}$ ($=A_P$ in most cases), is consistent with a picture where this reaction partner breaks up first, which behavior may, for instance, be due to its unfavorable ratio of surface to volume energies. Such a picture is corroborated by recent calculations,[11] showing that at energies below the Fermi energy very few nucleons are abraded in nucleus-nucleus collisions.

The hitherto unreported behavior of E^*/n_0 presented in Figs. 2 and 3, and analytically by Eq. (2), deserves some comments. Relating such behavior to a given physical picture or model is not quite obvious at first glance. A uniform sharing of the excitation energy E^* into the various degrees of freedom involved (all nucleons, for instance) would indeed be expected for a thermally equilibrated, fully relaxed system. In such a system, E^* is related to the temperature T by the expression $E^*=aT^2$. The information on the constancy of E^*/n_0 shown in Fig. 2 is, however, extracted from the system in its very early stages, and hence far from equilibrium, and the above relation between E^* and T cannot be applied. Therefore, we have to turn to other possible explanations of the reported behavior of E^*/n_0. To do so, we introduce a quantity $T_{\rm PE}$ which, for the nonequilibrated (preequilibrium) system, will play the role that the temperature T plays for the equilibrated system. For this purpose, we use the statistical definition of the temperature,

$$T^{-1}=d\ln\rho(E^*)/dE^*, \tag{3}$$

with, however, $\rho(E^*)$ taken as the exciton state density at the appropriate excitation energy E^*,[12]

$$\rho(E^*;p,h)=\frac{g_0^{p+h}(E^*)^{p+h-1}}{p!h!(p+h-1)!}. \tag{4}$$

It can be easily shown that the quantity $T_{\rm PE}$, defined by Eqs. (3) and (4), depends linearly on E^*. In fact, combining these two equations, one gets

$$E^*=(p+h-1)T_{\rm PE}=(n-1)T_{\rm PE}. \tag{5a}$$

Hence,

$$E^*/n\propto T_{\rm PE}. \tag{5b}$$

Equation (5b) has the form of the empirical expression (2). In analogy with the thermodynamic temperature, related to the average energy per degree of freedom, $T_{\rm PE}$ is related to the average energy per initial degree of freedom. Our results show that such a "temperature" is determined essentially by the size of the projectile and the total available energy.

Taken at face value, Eq. (2) has predictive power and could be used to predict n_0 for any specific nucleus-nucleus colliding system, at least at low and intermediate energies. In fact, the values of E^*/n_0 from an earlier analysis[8] of ^{20}Ne induced reactions fit well with the curve (crossed circles in Fig. 3).

To conclude, by using a refined multisource analysis of inclusive proton spectra from collisions induced by ^{16}O, ^{32}S, and ^{58}Ni projectiles, we have extracted angle-integrated spectra of protons originating from centrallike collisions. These spectra have been analyzed with use of a Boltzmann-master-equation approach. The relevant parameter for this approach, the initial number of degrees of freedom, n_0, has been deduced and its dependence on various physical quantities (energy and mass of the system) studied. The quantity E^*/n_0, showing the sharing of the excitation energy E^* into the early-stage degrees of freedom, has been found to depend only on the energy per nucleon brought in by the projectile. Such behavior is reported for the first time.

This paper is part of a study under the U.S.-Yugoslav collaboration project JFP 554 DOE/IRB. It was initiated during the stay of one of us (N.C.) at the Joint Institute for Heavy Ion Research at Oak Ridge, Tennessee, whose hospitality is gratefully acknowledged.

[1]R. L. Auble *et al.*, Phys. Rev. C **37**, 390 (1988).
[2]M. Korolija *et al.*, Z. Phys. A **327**, 237 (1987).
[3]M. Korolija *et al.*, to be published.
[4]M. Blann, Phys. Rev. C **23**, 205 (1981).
[5]G. D. Harp, J. M. Miller, and B. J. Berne, Phys. Rev. **165**, 1166 (1968).
[6]K. Kikuchi and M. Kawai, *Nuclear Matter and Nuclear Reactions* (North-Holland, Amsterdam, 1968).
[7]E. Holub *et al.*, Phys. Rev. C **28**, 252 (1983).
[8]E. Holub, M. Korolija, and N. Cindro, Z. Phys. A **314**, 347 (1983).
[9]E. Holub *et al.*, Phys. Rev. C **33**, 143 (1987).
[10]G. Mantzouranis, H. A. Weidenmüller, and D. Agassi, Z. Phys. A **276**, 145 (1976).
[11]C. Gregoire, in Proceedings of the Enrico Fermi School of Nuclear Physics, Course 103, Varenna, Italy, June 23–July 3, 1987 (to be published).
[12]T. Ericson, Adv. Phys. **9**, 425 (1960).