Improved microscopic calculation of initial exciton number

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An improved microscopic calculation of the initial exciton number has been carried out on the basis of the original microscopic model—the so-called phase-space model. In our calculation the Vlasov or Boltzmann-Uehling–Uhlenbeck dynamics is used during the nucleus-nucleus collision instead of a simple dynamical process without friction. Our calculation reproduces the experimental results better than the original microscopic model.

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The continuous part in the energy spectra of emitted particles in light-ion-induced reactions at energies of a few tens of MeV was successfully described by the exciton model [1,2]. According to this model the equilibrium process following a first stage of the projectile-target interaction toward a compound nucleus evolves via two-body nucleon-nucleon collisions. The intermediate states are characterized by the number of particles and holes excited with respect to the Fermi surface and commonly called excitons. At each state with a certain exciton number n there is a probability for particles being in unbound states to escape. The use of an initial exciton number n_0 has been surprisingly effective in fitting the observed energy spectra with remarkable accuracy [3]. Recently, some calculations of n_0 were carried out [4–6]. However, it was found that the model was not very suitable for the heavier projectile-induced reactions [5], or there was a larger numerical deviation in comparison with the experimental extracted n_0 value [6]. In this Brief Report we will improve the later microscopic model by introducing the Vlasov or Boltzmann-Uehling-Uhlenbeck (BUU) dynamics. Better results than Ref. [6] are obtained and the most of the empirically extracted n_0 values from the experimental data on preequilibrium energy spectra [5,7,8] can be reproduced. This is also a first application of Vlasov or BUU dynamics to investigate the initial exciton number of early stages of nucleus-nucleus collisions.

Our calculation is based on the microscopic model presented by Cindro *et al.* [6], which is based on simple geometrical and phase-space considerations with a few straightforward assumption which did not introduce any adjustable parameters. In this passage we describe their model briefly. In momentum phase space, the colliding system is presented by two Fermi spheres, separated from each other by P_P+P_T, where P_T and P_P are the momentum per nucleon of the projectile and the target at the touching point, respectively. After reaching equilibrium the composite system is presented by a third sphere of Fermi radius P_F, whose center is positioned at the center of mass of the colliding system. Cindro *et al.* thought that the particles and holes which are produced at the projectile (target) originate from the nonoverlap region between the Fermi sphere of the composite system and the projectile (target) Fermi sphere, and assumed that the number of particles p_0 is equal to the number of holes h_0. Finally, $n_0=p_0+h_0$. Thus the number of particles and holes is calculated as the geometric overlap of parts of three spheres of equal radii in momentum space. On the other hand, when the geometrical overlap of the two colliding nuclei in the geometrical space is in consideration n_0 should be modified. In the geometrical space, the colliding system is represented by the projectile and target spheres of radii R_P and R_T, respectively. The overlap volume of the two nuclei is calculated by assuming that the relative velocity of the collision partners is not significantly affected by friction. Then the available excitation energy as a function of time is estimated by

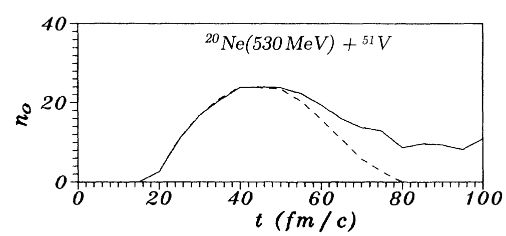

FIG. 1. Time evolution of the initial exciton number within the different dynamics. The full line shows the BUU calculation and the dashed line the Vlasov calculation.

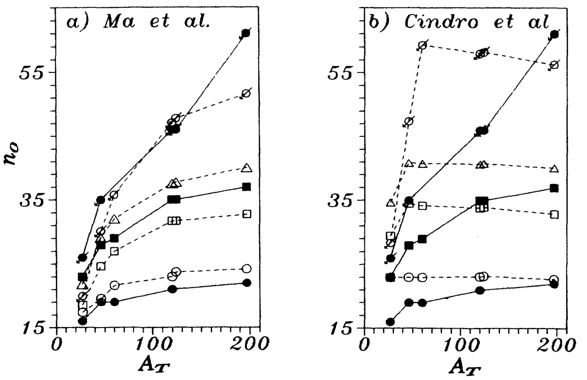

FIG. 2. Dependence of n_0 on the target mass number A_T. The solid symbols show the empirically extracted values from the experimental data of Ref. [18] and the open symbols show the calculated results. The circles, squares, triangles, and circles with an arrow represent ^{16}O (403 MeV)-, ^{32}S(504 MeV)-, ^{32}S (679 MeV)-, and ^{58}Ni (876 MeV)-induced reactions, respectively. Note that the empirically extracted values are the same for ^{32}S (504 MeV)- and ^{32}S (679 MeV)-induced reactions (shown by the solid squares). (a) Our calculations; (b) the calculations of Cindro *et al.* [6].

$$E_0(t) = E_0 \frac{A_T + A_P}{A_T + \Delta A(t)} \frac{\Delta A(t)}{A_P} , \tag{1}$$

where $\Delta A(t)$ is the calculated number of nucleons which is enveloped into the heavier partner from the lighter partner at a given collision time t. Clearly, since E_0 depends on time, all kinematical variables in the momentum phase space, e.g., P_P, P_T, etc. (except P_F), will also depend on t. Finally they took the maximal value of $n_0(t)$ as n_0 without any physical interpretation [6].

In fact, the effect of friction is still important in an energy range of 10–100 MeV/nucleon heavy-ion collisions (HIC's). The overlap volume in the geometrical space relies not only on available kinetic energy but also on the energy dissipation produced by friction, etc., in the other words, $\Delta A(t)$ in Eq. (1); then all kinematical variables are model-dependent quantities. So we rejected their simple dynamical treatment and applied the Vlasov or BUU model which can reveal nuclear friction [10–12] to deal with this collision process. The Vlasov model can be derived as an approximation of the time-dependent Hartree-Fock theory [9] which is very well known in the theory of HIC's at low energy [11]; it mainly includes the mean-field interaction which results in one-body dissipation. The BUU model incorporates both the mean-field interaction and in-medium nucleon-nucleon collision which is extensively applied in the medium energy domain; it introduces the one- and two-body dissipations. Recently, many works demonstrated that the BUU model is also a successful theory at somewhat low energies, such as 10–30 MeV/nucleon [10,12–16]. Thus we could assure the reasonable application of Vlasov or BUU dynamics in this work. Here we used the Vlasov or BUU dynamics to estimate the available excitation energy on the collision time. All the other kinematical quantities in

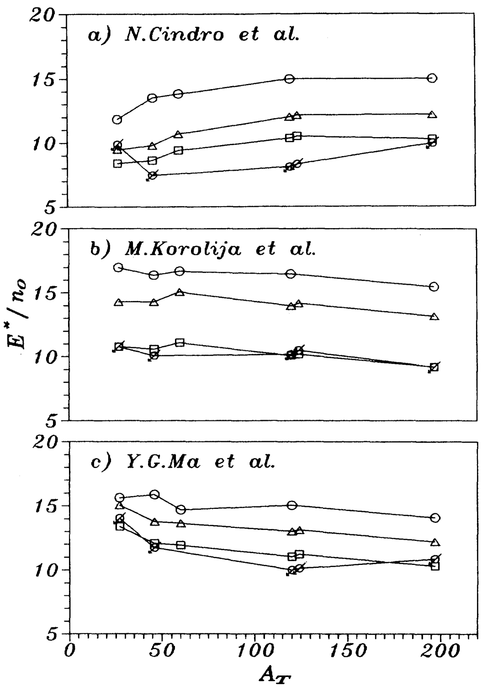

FIG. 3. Plot of E^*/n_0 vs the target mass number A_T for the ^{16}O-, ^{32}S-, and ^{58}Ni-induced reactions. The definition of symbols is the same as Fig. 2. (a) The results of Cindro *et al*; (b) empirical results from Ref. [18]; (c) our calculation.

the phase space were therefore related to the Vlasov or BUU dynamics.

In our numerical simulation, we adopted the test particle method as Ref. [11] where the detail simulation procedure were documented. Test particles per nucleon of 500, a time interval of 0.5 fm/c and cube size of 1 fm^3 were taken. The mean-field potential was chosen as density dependent. A stiff potential of $U(\rho) = -124\rho + 70.5\rho^2$ and in-medium nucleon-nucleon cross section of $\sigma_{nn} = 33$ mb were used. In comparison with the parameter sets of a soft potential and other values of σ_{nn} we found that n_0 is not sensitive to the equation of state (EOS) and σ_{nn}. For both Vlasov and BUU dynamics, the time evolutions of $n_0(t)$ are almost the same at early stages of collision; $n_0(t)$ reaches the same maximum later. After reaching the maximum for Vlasov dynamics, $n_0(t)$ decreases toward to zero value, but for BUU dy-

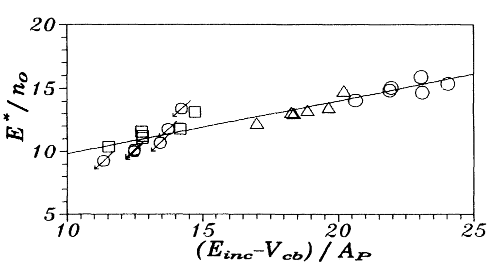

FIG. 4. Dependence of E^*/n_0 on the available incident energy per nucleon. The definition of symbols is the same as Fig. 2. The line shows the linearity of Eqs. (2).

TABLE I. The comparison of the initial exciton number calculated by Eqs. (2) (Calc.) with some empirically extracted n_0 from experimental data [5,7,8].

Energy (MeV)	100	156		300		530	530
Projectile	^{4}He	^{6}Li		^{12}C		^{15}N	^{20}Ne
Target	^{58}Ni	^{40}Ca	^{58}Ni	^{165}Ho	^{197}Au	^{56}Fe	^{51}V
Expt. fit	6	10	17	18	19	23±2	26±2
Calc.	5.97	9.64	16.45	18.54	18.70	21.62	24.31

namics it continues to maintain the maximal value or decreases to a certain value slowly in the following collision process, which depends upon the reaction systems. For example, Fig. 1 shows the time evolution of $n_0(t)$ for the reaction of 530 MeV ^{20}Ne-induced ^{51}V. If we investigate the time evolutions of the calculated exciton number and of the overlap between the projectile and the target, we find that the maximal $n_0(t)$ occurs at the maximal geometrical overlap between the projectile and target nuclei. The latter corresponds to a maximal intrinsic excitation energy (which consists of "cold" internal energy at zero temperature and the excitation energy) and therefore a minimum collective kinetic energy (which includes the kinetic energy carried away by the emitted particles [12,13,17]. The emission before that time should correspond to a preequilibrium emission, after that evaporation emission of light particles takes place and the preequilibrium emission phase is not ended. In addition, in view of Eqs. (1) the maximal available excitation energy is reached when the maximal geometrical overlap occurs. At that time, the maximal separation between the projectile and target Fermi spheres in momentum space appears, and the time-dependent calculated exciton number reaches its maximum which is taken as the initial exciton number. Overall, the initial exciton number is not sensitive to the nucleon-nucleon collision and the EOS. In the following calculation, we only adopted Vlasov dynamics.

Figure 2 shows the dependence of the initial exciton number on the target mass A_T. It is clearly seen that the results of Cindro *et al.* could not reproduce the dependence of n_0 on the target mass A_T and most of them deviate from the empirically extracted values, especially for heavier projectiles. We think that this is mainly because their model cannot incorporate the nuclear friction. Our results not only predict the trend of n_0 with A_T but also reproduce the empirically extracted values from the experimental data [18] rather well. It can be concluded that the correct reproduction of n_0 with A_T stems from Vlasov or BUU dynamics.

The excitation energy per initial exciton, E^*/n_0 [i.e., $(E_{\mathrm{c.m.}}+Q_{\mathrm{fus}})/n_0$], has a dependence on the target masses; it depends mostly on the per-nucleon incident energy of the projectile (Fig. 3). It is clear that the calculation of Cindro *et al* [Fig. 3(a)] gets the converse trend of dependence on the target mass compared with the empirical fit values [Fig. 3(b)]. The incident-energy dependence of E^*/n_0 is shown in Fig. 4. The values of E^*/n_0 increase with the available incident energy per nucleon (in laboratory system), $(E_{\mathrm{inc}}-V_{\mathrm{CB}})/A_P$, following the linear expression

$$\frac{E^*}{n_0}=0.42\left[\frac{E_{\mathrm{inc}}-V_{\mathrm{CB}}}{A_P}\right]+5.61 \qquad (2)$$

(all energies in MeV; V_{CB} represents the projectile-target Coulomb barrier). For a given colliding system we can estimate n_0 from the Eqs. (2). Table I shows our calculations by Eqs. (2); it is obvious that our calculations can reproduce the empirically extracted values from experimental data well [5,7,8].

In conclusion, an improved microscopic calculation of the initial exciton number has been presented on the basis of the original microscopic phase-space model. The Vlasov or BUU dynamics is used during the nucleus-nucleus collision instead of a simple dynamical process without friction. By this improvement, the calculated initial exciton number demonstrates the correct trend of n_0 with A_T and reproduces the empirically extracted values from experimental data rather well. The improved method also reproduces the relation of E^*/n_0 with a different target for a given incident energy of projectile and the linear dependence of E^*/n_0 on the available incident energy per nucleon $(E_{\mathrm{inc}}-V_{\mathrm{CB}})/A_P$. By this linearity we can estimate the initial exciton number n_0 which fits the other empirically extracted values n_0 from experimental data well.

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[1] H. Machner, Phys. Rep. **127**, 311 (1985).
[2] M. Blann, Phys. Rev. C **23**, 205 (1981).
[3] E. Holub, M. Kololija, and N. Cindro, Z. Phys. A **314**, 347 (1983).
[4] S. Yoshida and H. Morinaga, Z. Phys. A **317**, 173 (1984).
[5] H. Machner, Z. Phys. A **321**, 577 (1985).
[6] N. Cindro, M. Korolija, E. Betak, and J. J. Griffin, Phys. Rev. Lett. **66**, 868 (1991).
[7] G. Buhr, H. Machner, M. Nolte, M. Palarczk, and J. Rama Rao, Phys. Rev. C **45**, 705 (1992).
[8] H. Machner, Phys. Rev. C **28**, 2173 (1983).
[9] C. Y. Wong, Phys. Rev. C **25**, 1460 (1981).
[10] C. Gregoire, B. Remaud, F. Sebille, L. Vient, and Y. Raffrary, Nucl. Phys. **A465**, 317 (1987).
[11] G. F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).

[12] W. Cassing, V. Metag, U. Mosel, and K. Niita, Phys. Rep. **188**, 363 (1990).

[13] M. Gonin, L. Cooke, K. Hagel, J. B. Natowitz, R. P. Schmitt, S. Shlomo, B. Strivastava, W. Turmel, H. Utsunomiya, R. Wada, G. Nardelli, G. Nebbia, G. Viesti, R. Zanon, B. Fornal, G. Prete, K. Niita, S. Hannuschke, P. Gonthier, and B. Wilkins, Phys. Rev. C **42**, 2125 (1990).

[14] A. Ohnishi, H. Horiuchi, and T. Wada, Phys. Rev. C **41**, 2147 (1990).

[15] S. Hannuschke, W. Cassing, U. Mosel, and K. Niita, Nucl. Phys. **A535**, 120 (1991).

[16] D. Jouan, B. Borderie, M. F. Rivert, C. Cabot, H. Fuchs, H. Gauvin, C. Gregoire, F. Hanappe, D. Gardes, M. Montoya, B. Remaud, and F. Sebille, Z. Phys. A **340**, 63 (1991).

[17] H. M. Xu, W. G. Lynch, P. Danielewicz, and G. F. Bertsch, Phys. Lett. B **261**, 2420 (1991).

[18] M. Korolija, N. Cindro, and R. Coplar, Phys. Rev. Lett. **60**, 193 (1988).