сообщения
объединенного
института
ядерных
исследований
дубна

E2-85-748

V.V.Avdeichikov *

EXCITATION OF TARGET RESIDUES IN THE FIRESTREAK MODEL

* Permanent address: V.G.Khlopin Radium Institute, Leningrad 197022

1985

There are two extreme concepts of the mechanism of interaction between high-energy heavy ions and nuclei. In both cases the interaction proceeds, as a rule, via two distinct stages.

In the intranuclear-cascade model (INC) [1,2] each nucleon from the projectile and target interacts as a single particle. The collision is governed by the properties of nucleon-nucleon collision. A detailed review of different approaches and many generalizations of the INC model can be found in Ref. [3]. After the first fast stage of the reactions the target remnant becomes excited. This residual nucleus is de-excited at the second (evaporation) stage by the emission of low-energy secondaries.

In the case of nucleus-nucleus collisions INC calculations are very complicated and contain some obscurities [4,11]. Besides, there are experimental arguments that a relativistic heavy ion may interact with the target nucleus as a single entity [5].

An alternative concept of the fast stage mechanism and the calculation of the excitation energy of the residual nucleus is proposed by abrasion-ablation model [6]. In this model both projectile and target nuclei are assumed to be hard spheres. At the first fast abrasion stage the interaction is localized in the overlapping region of the target and projectile forming a fireball [7] from participating nucleons. The fireball moves forward in the direction of the collision of primary nuclei and decays by emitting fast secondaries [8]. The excess of the surface area of the "spectator" (target or projectile) nucleus immediately after the abrasion step and its equilibrium (spherical) shape defines its excitation energy. The primary residues are de-excited through the statistical evaporation cascade - ablation process. This idealized picture of nuclear interaction is often used to describe the target residues distributions in heavy-ion-induced reactions [5,9].

In further generalizations of the abrasion-ablation model it is assumed that the spectator nuclei can obtain an additional excitation energy other than the extra surface one. Hüfner et al. [10] have introduced the final state interaction mechanism as an additional one for the energy deposition to the spectator nucleus. At the abrasion stage the recoil target nucleons are directed towards the target spectator, and so they deposit a part of their energy to the spectator piece. The average energy deposited by recoil nucleons is a function of the lab.energy/nucleon and the type of projectile [10].

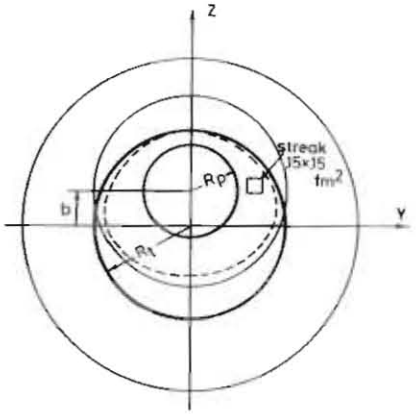

Fig.1. Collision of two nuclei in the firestreak geometry. $R_{p,t} = 1.2 A_{p,t}^{1/3}$. *The thin solid lines denote region with* $\rho(r) = 0.005\rho(0)$. *The dashed line defines the area of contact at some impact parameter* b, *projected onto the y-z-plane.*

There is a significant difference in the value of excitation energy calculated in both above-mentioned models. The ratio is $\approx 10/1$ for the average excitation energy in the reaction ^{40}Ar + + Pb [4,6] calculated in the INC and abrasion-ablation models. The calculation of nucleus-nucleus interaction in the INC model presents significant difficulties [4,11].

This paper is to a certain degree the generalization of the abrasion-ablation model. We use a geometrical picture of the firestreak model [12] to calculate the abrasion stage of the reaction. The model incorporates a real nuclear density distribution for both colliding nuclei. Unlike the fireball model the firestreak model assumes that the interaction proceeds via collinear streaks of nuclear matter from the target and the projectile. A relative success of this model [13] in the description of the yield of fast secondaries and their distribution functions has initiated the question: what can we say about the abraded nucleus?

A schematic representation of the collision of two nuclei in the firestreak geometry is shown in fig.1. The square denotes a streak of $0.15 \cdot 0.15$ fm^2 taken in our numerical calculations. Each of the streaks is characterized by the value $\nu = n_p/(n_p + n_t)$, where $n_p(n_t)$ are the numbers of the contributing nucleons from the projectile (target). The nuclear matter in the firestreak model is treated as a thermodynamical system in equilibrium. The velocity of a streak is defined by the geometry and relativistic kinematics of collision. The temperature T of a streak is completely defined by thermodynamical and chemical equilibrium. As interactions are assumed to occur independently between the collinear streaks, there are $v(\nu)$ and $T(\nu)$ gradients in a fireball composed of the streaks. $\nu = \nu(T_{kin/nucleon}\,proj.)$. The streaks with $T(\nu) \geq 10$ MeV were included in calculations as participants. We found that the variation of $T_{min}(\nu)$ within reasonable limits, say 10 ± 3 MeV, did not change the results.

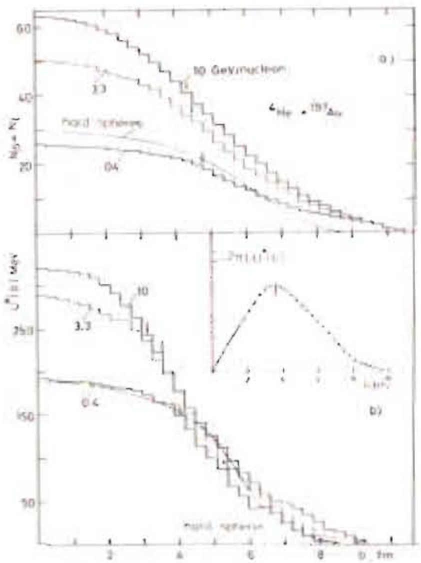

Fig.2. Calculated geometrical quantities as a function of impact parameter b. *The arrows indicate the impact parameter with the maximum weight. a)* $N_p + N_t$ *is the number of participant nucleons. The histograms represent our numerical calculation for various incident kinetic energy/nucleon of* ^4He: *the solid line is the analytical calculation* [6,8] *for hard spheres collisions. b) Extra surface excitation energy. The solid line is the same as a). The insert shows the* $2\pi b U^*(b)$ *distribution.*

The temperature of the streaks $T(\nu)$ was defined by the method proposed in [14].

Figure 2a presents the results of a numerical calculation of the number of participant nucleons in the reaction $^4He + {}^{197}Au$ for various energy/nucleon as a function of impact parameter b. We have used in our calculation a Fermi type nuclear density distribution $\rho(r)$ for both colliding nuclei (soft spheres). Parameters for $\rho(r)$ are taken as compiled in [15]. (We have found that a Yukawa type distribution used by other authors [13] represents not adequately the experimental behaviour of $\rho(r)$, particilarly for A_p or $A_t \leq 12$). The solid line is an analytical calculation for the case of collision of hard spheres, $\rho(r) = const(r) = 0.17$ fm^{-3}. Here we have used the formulas proposed in [6] and published in [8]. A striking difference between the cases of collisions of hard and soft spheres is seen.

Further we concentrate our attention on target excitation. The target residue is assumed to have an excitation energy given by multiplying the extra surface by ≈ 0.95 MeV fm^{-2}. The surface of the nucleus has a meaning only for a hard sphere. So in the calculation of extra surface energy of the target nucleus the condition was added: only streaks inside $r_t \leq 1.2 A_t^{1/3}$ were included. The result is displayed in fig.2b. The solid line is an analytical calculation for hard colliding spheres. The excitation energy U^* for impact parameter with maximum weight $2\pi b U^*(b)$ is shown in fig.3a. We present the value $\bar{U}^*/[(197 - \Delta A)/10] = T^2$(MeV^2) obtained from the relation between the excitation energy of the nucleus (as a Fermi gas) and its

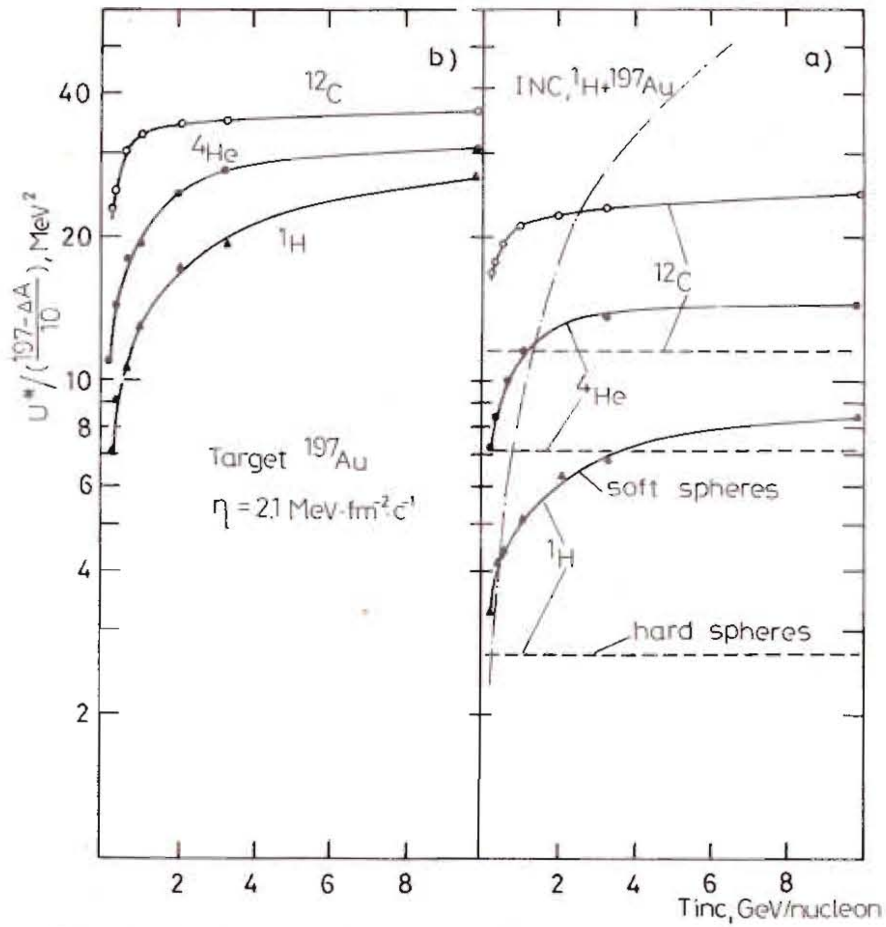

Fig. 3. Excitation energy of residual nuclei as a function of the kinetic energy/nucleon of the projectile. a) Without the friction energy. The solid lines refer to the collision of soft spheres, the dashed lines - hard spheres. The INC calculation is presented for $^1H + Au$ *interaction. b) Friction energy is included in the collisions of soft spheres. The excitation energy is given in units of* $\bar{U}^*/[(197 - \Delta A)/10]$, *where* $\bar{U}^*$ *is taken at the impact parameter with the maximum weight.*

equilibrium temperature T. Here ΔA is the number of nucleons swept away from the target in the interaction. The main difference in the behaviour of $\bar{U}^* = f(T_{kin.}\ proj.)$ for the collision of soft and hard spheres comes from the difference in $\Delta A = f(T_{kin.}\ proj.)$ and $\Delta A = const(T_{kin.}\ proj.)$.

Later on we postulate, as in the hydrodynamical approach[25], that nuclear fluid is viscous. Then friction arises over the region of contact of two colliding nuclei. Work done against this friction force is the thermal energy localized in the separation surface. The depth of this surface is approximately equal to the internucleon distance. We take it equal to 1.2 fm.

Let x -axis be oriented along the collision direction. Then there is a velocity gradient in the plane y–z

$$\mathrm{grad}\, v_x(y,z) = (\Delta v_x(y,z)/\Delta\nu)(\Delta\nu/\lambda). \qquad (1)$$

$v_x(y,z)$ is the velocity of the streak in the vicinity of the separation area in the rest frame of the spectator. For friction energy we have

$$U_{fr}(b) = 0.5 \int_{S(b)} \eta \cdot \frac{\Delta v_x(y,z)}{\lambda} \cdot \frac{\ell(y,z)}{2} \cdot dS(y,z). \qquad (2)$$

Here η is the coefficient of shear viscosity and dS is the element of the area S(b) of contact. The length component $\ell(y,z)$ of $dS(y,z)$ along the direction of collision is limited by the surface of both colliding nuclei. A value 0.5 comes from the shearing of friction energy equally between the participant and spectator parts. The gradient $\Delta v_x(y,z)/\lambda$ is taken in the direction of the centre of the projectile[x]. We take $\eta = 2.1$ MeV·fm^{-2}·c^{-1} from theoretical paper[16]. This value is well coincident with the one extracted from the fission data[17]. The next conclusions can be drawn from fig.3b irrespective of the value of η:

1. The excitation energy of the target nucleus tends to a limiting value at a projectile kinetic energy of $\gtrsim$ 5 GeV.

2. The excitation energy (or nuclear temperature) increases only slightly with increasing projectile mass.

3. The results of fig.3b are in large discrepancy with the INC calculation (see $^1H + Au$, INC, fig.3a).

4. If the target spectator velocity is $v_t \sim \bar{U}_{fr}$, then the conclusion follows: anisotropy of slow particles emitted by the excited nucleus is approximately equal in the case of ^1H- and ^4He-projectiles and lower for ^{12}C -projectile. This is due to the flat tail of the $\rho(r)$ function for heavy nucleus (projectile).

---

[x] The slight variation of λ in the limits of ±0.3 fm causes the variation of $\Delta v_x(y,z)$, so the value of grad $\overline{v_x}(y,z) \approx const(\lambda)$ and $U_{fr}(b) \approx const(\lambda)$.

What can we say about the temperature of the excited residue? There is a common method to extract T from the shape of the energy spectra of the emitted medium mass fragments. All spectra resemble an evaporation Maxwellian form. In the rest frame of the source

$$\sigma(E) \sim (E - V^c) \cdot \exp[-(E - V^c)/T], \qquad (3)$$

where E, V^c and T are the kinetic energy, Coulomb barrier of the emitted charged particle and temperature of the excited nucleus. A Maxwellian fit to the spectra indicates an apparent V^c which is much lower than the nominal Coulomb barrier, and apparent too high T of ~10÷15 MeV. So it was proposed [18] to regard V^c and T only as parameters (without any physical sense). Previously we have noted [19] that the ratio of the yields of fragments emitted from two isotopes as a target nuclei can give a real value of T independently of the choice of model for fragment emission. Starting from phase-space considerations [20], for the ratio of the yields of fragments emitted from two different isotopes one can obtain

$$R \simeq const \cdot \exp[(\Delta Q - \Delta V^c)/T], \qquad (4)$$

where $-\Delta Q$ and ΔV^c are the differences of binding energies and Coulomb barriers of fragments emitted by two target isotopes. In fig.4 we present R for various light fragments produced in reactions of ^1H (1.0 GeV) on ^{112}Sn, ^{124}Sn. Data are taken from Ref. [21]. The fit by Eq.(4) to the experimental data gives T = = 4.4±0.2 MeV. It seems that the high apparent T extracted from the fragment energy spectra, Eq.(3), may be due to the combination of a low-energy component of the spectra, evaporation from the excited nucleus with low T, and a high-energy component - from the decay of a fireball-like system [13,22]. The latter component makes a rather low contribution to the cross section, but it decisively defines apparent T extracted by Eq.(3). Nevertheless, this component can increase only slightly T extracted by Eq.(4). It seems that the ratio (4) may serve as some "nuclear thermometer" for measuring the temperature of residual nucleus.

Close arguments concerning the apparent nuclear temperature have been advanced by Aichelin et al. [23]. The authors criticized the identification of T extracted by Eq.(3) as a true nuclear temperature that can be used in experimental data analysis in an attempt to discover a signature of a liquid-gas phase transition in excited nuclei [24].

Using the method of calculation of $\bar{U}^*$ presented in this paper for the reaction ^1H (1.0 GeV) on ^{112}Sn, we have obtained T = 4.35 MeV with η = 2.1 MeV$\cdot$ fm$^{-2} \cdot c^{-1}$.

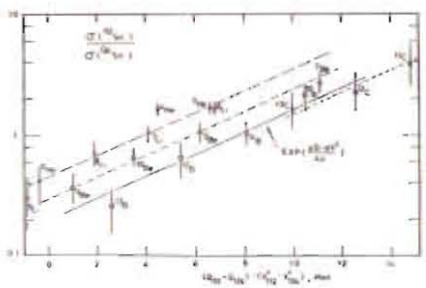

Fig.4. "Nuclear thermometer" is the ratio of the yields of fragments emitted (at lab angle 60°) in the reaction ^1H (1.0 GeV) on ^{112}Sn, ^{124}Sn. The solid lines are the fit to experimental data [21]. T = = 4.4±0.2 MeV.

Recently it has been suggested [26] that the spectator temperature may serve as a signal for quark-matter formation in high-energy interactions. The excitation energy imparted to the spectator by friction is equal to zero in this case because of confinement for quarks. Then for some high energy our thermometer will show a substantial "cooling" of the system from ~5.5 down to ~2.5 MeV. In the reaction ^1H (400 GeV) on ^{131}Xe Hirsh et al. [27] have obtained T = 3.28 MeV from fitting the fragment isotopic yield. Is this a signature of the quark-gluon phase?

REFERENCES

1. Metropolis N. et al. Phys.Rev., 1958, 110, p.185; Phys. Rev., 1958, 110, p.240.
2. Bertini H.W., Guthrie M.P. Nucl.Phys., 1971, A169, p.670.
3. Barashenkov V.S., Toneev V.D. Interactions of High-Energy Particles and Atomic Nuclei with Nuclei. Atomizdat, M., 1972.
4. Yariv Y., Fraenkel Z. Phys.Rev., 1979, C20, p.2227.
5. Morrissey D.J. et al. Phys.Rev., 1978, C18, p.1267.
6. Bowman J.D., Swiatecki W.J., Tsang C.-F. LBL-2908, 1973.
7. Westfall G.D. et al. Phys.Rev.Lett., 1976, 37, p.1202.
8. Gosset J. et al. Phys.Rev., 1977, C16, p.629.
9. Oliveira L.F., Donagelo R., Rasmussen J.O. LBL-8151, 1978.
10. Hüfner J., Schäfter K., Schürman B. Phys.Rev., 1975, C12, p.1988.
11. Barashenkov V.S. et al. Acta Phys.Pol., 1980, B11, p.39.
12. Myers W.D. Nucl.Phys., 1978, A296, p.177.
13. Gosset J., Kapusta J.I., Westfall G.D. Phys.Rev., 1978, C18, p.844.
14. Avdeichikov V.V., Mrowczynski St. Phys.Lett., 1984, 134B, p.293.
15. DeJager C.W., DeVries H., DeVries C. At.Data Nucl. Data Tables, 1974, 14, p.479.
16. Weström M. Phys.Lett., 1978, 76B, p.249.

17. Davies K.T.R., Sierk A.J., Nix J.R. Phys.Rev., 1976, C13, p.2385.
18. Poskanzer A.M. et al. Phys.Rev., 1971, C4, p.1759; Bowman J.D. et al. Phys.Rev., 1974, C9, p.836.
19. Avdeichikov V.V. Phys.Lett., 1980, 92B, p.74.
20. Weisscopf V.F. Phys.Rev., 1937, 52, p.295; Friedman W.A., Lynch W.G. Phys.Rev., 1983, C28, p.16; Gale C., Das Gupta S. Phys.Rev., 1984, C29, p.1339.
21. Volnin E.N. et al. Phys.Lett., 1975, 55B, p.409.
22. Abashidze L.I. et al. Nucl.Phys., 1985, A437, p.573.
23. Aichelin J., Hüfner J., Ibarra R. Phys.Rev., 1984, C30, p.107; Boal D.H. Phys.Rev., 1984, C30, p.119.
24. Panagioutou A.D. et al. Phys.Rev.Lett., 1984, 52, p.496; Panagioutou A.D., Curtin M.W., Scott D.K. Phys.Rev., 1984, C31, p.55.
25. Beckmann R. et al. Phys.Lett., 1981, 105B, p.411.
26. Raha S. et al. Phys.Rev.Lett., 1984, 53, p.138.
27. Hirsh A.S. et al. Phys.Rev., 1984, C29, p.508.

Received by Publishing Department
on October 21, 1985.

Авдейчиков В.В. E2-85-748
Возбуждение остаточных ядер в модели файрстрик

В рамках модели файрстрик предлагается метод расчета энергии возбуждения остаточных ядер, образующихся в ядро-ядерных столкновениях. Показано, что диффузность ядер и вязкость ядерной материи существенно определяют величины полной энергии возбуждения и ее зависимость от энергии первичного иона. Вводится понятие "ядерный термометр" как метод для измерения температуры возбужденного ядра.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1985

Avdeichikov V.V. E2-85-748
Excitation of Target Residues in the Firestreak Model

The nuclear firestreak model is used to calculate the excitation energy of residual nuclei in nucleus-nucleus collisions. The incorporation of diffuse surfaces of interacting nuclei has introduced the dependence of nucleus excitation on the energy of the projectile. Shear viscosity of nuclear matter is also taken into account. "Nuclear thermometer" is proposed to measure the temperature of target residues.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1985