сообщения
объединенного
института
ядерных
исследований
дубна

E2-85-586

K.K.Gudima*, G.Röpke**, H.Schulz***,
V.D.Toneev

EFFECTIVE RADII OF LIGHT COMPOSITES PRODUCED IN RELATIVISTIC HEAVY ION COLLISIONS

* The Moldavian Academy of Sciences,
Kishinev, USSR
** Wilhelm Pieck University, Rostock, GDR
*** Central Institute for Nuclear Research,
Rossendorf, 8051, Dresden, GDR

1985

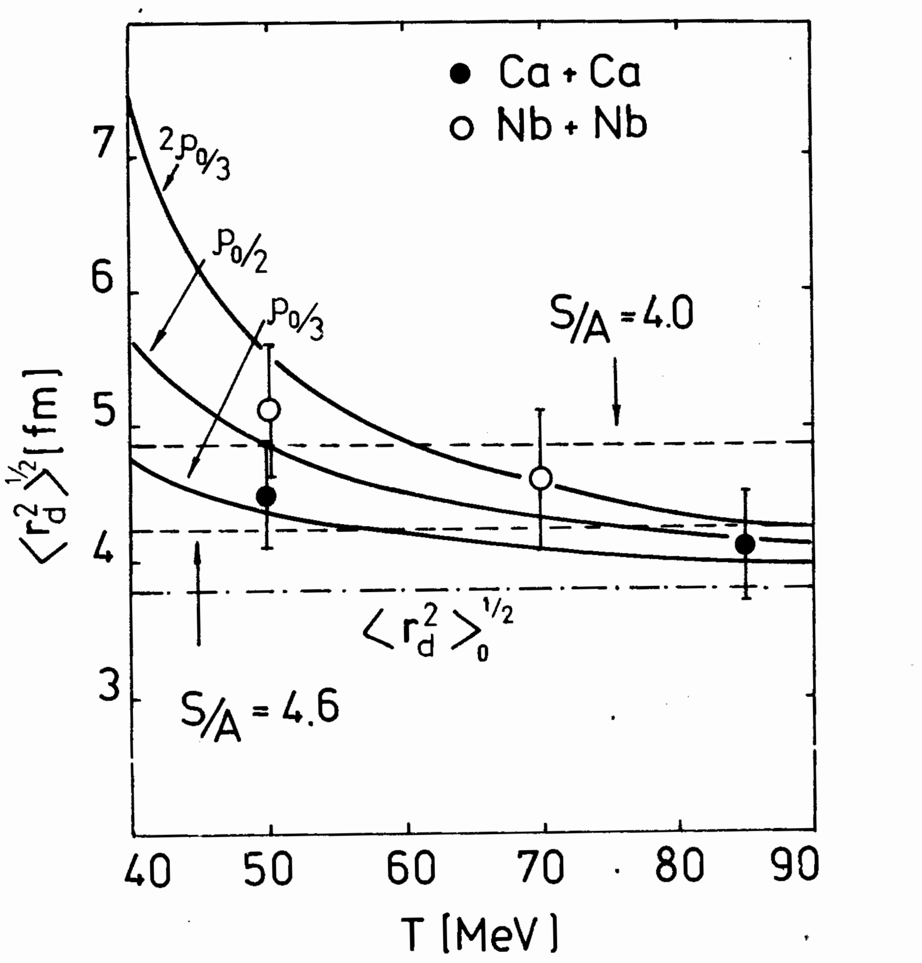
In recent papers Gutbrod et al.[1] and Doss et al.[2] reported on the first experimental data of cluster formation measured with a 4π detector (plastic ball) in high energy heavy ion collisions. The experimental data for the ratio of the deuteron-like pairs (d_{like}) to the proton-like particles (p_{like}) have shown that the cluster production increases with the multiplicity of charged particles and levels off at high multiplicity values. This particular behaviour indicates that the cluster formation process itself depends on the size of the emitting source. In view of these new data the limitations of the thermal model[3,4] assuming chemical equilibrium and of the original coalescence model[5] can clearly be seen because both the models predict a yield ratio independent of the size of the emitting source.

To reproduce the trend of the experimental data an improved version of the coalescence model of Sato and Yasaki[6] has been employed in which the cluster yield depends on both the size of the deuteron and the volume of the emitting source. The ratio of d_{like} to p_{like} is expressed throught (see refs.[1,2] for details)

$$d_{like}/p_{like} = 6(A-Z)/Z)(1+2(r_d/r_d)^2)^{-3/2} \times N_p(1+\frac{2}{3}mTr_d^2)^{-3/2} \quad . \tag{1}$$

where T is the temperature of the interacting region, r_d stands for the deuteron radius, N_p is the participant charge multiplicity and the factor $(A-Z)/Z$ account for the difference between neutron and proton number. The radius of the spherical source is parameterized by $r_p = r_0(\frac{A}{Z}N_p)^{1/3}$, where the factor A/Z converts the participant baryon charge multiplicity to participant baryon multiplicity. The radius r_0 is related to the density ρ of the source by $r_0 = (4\pi\rho/3)^{-1/3}$. Since the temperature could be determined independently from the proton spectra, the radii r_0 and r_d for the source and the deuteron, respectively, are free parameters. Applying formula (1) Doss et al.[2] (see also ref.[1]) obtained excellent fits to the experimental data of composite production in relativistic heavy ion collisions.

In the figure we show the fitted effective deuteron radii of ref.[2] as a function of the temperature. Since the error bars seem to be rather large, Doss et al.[2] concluded that a tendency to smaller composite radii at higher temperature cannot be seen. But this conclusion is not in disagreement with our previ-



The effective deuteron radius as a function of the temperature for given break-up density (solid lines) and the given entropy value (dashed lines). The dash-dotted line indicates the rms radius of a free deuteron. The experimental points are from Doss et al. /2/ The specific entropy values vary between 4.0 and 4.2 when taking their fitted break-up density values and calculating the entropy values with the free Fermi gas formula.

ous results /7/ where we have calculated coalescence radii as a function of the temperature at fixed break-up density and used them in cascade calculations. In this case the radii of the composities become smaller with increasing temperature and approach gradually the corresponding values for the free clus-

ters. In the figure this tendency cannot be seen because it is obscured by the fact that the fitted deuteron-like radii of Doss et al. /2/ correspond to different break-up densities ρ_b extracted via the parameter r_0 . In fact, their effective deuteron radii r_d have been inferred at such a break-up situations where the product $\rho_b \Lambda^3$ ($\Lambda = (2\pi\hbar^2/mT)^{1/2}$ is the thermal wave length) turns out to be almost constant, i.e., the mean phase space occupancy or the associated specific entropy of a free Fermi gas $S/A = 5/2 - \ln(\rho_b \Lambda^3/4) \simeq 4$ remain also nearly unchanged. Therefore, it is not surprising that the entropy values inferred in ref. /2/ via the cluster yields are also nearly independent of the bombarding energies and the target-projectile combinations. Finally let us mention that the entropy values of $S/A \simeq 4$ following from the simple phase space relation are very close to the findings of Doss et al. /2/ when employing Kapusta's method /8/ for extracting the specific entropy values (see also refs. /9,10/ for a discussion of the specific entropy calculated by means of the cascade model).

In the following we will not discuss the entropy problem and in what cases it is justified to use the free Fermi gas formula given above, but concentrate on the calculation of the effective radius of the deuteron embedded in a hot nuclear medium. We suppose that the composites are formed when the intermediate nuclear system reaches the break-up density. (For dynamical calculations see ref. /11/). At this moment, however, the composites cannot be treated as free particles, but they are still affected by the surrounding medium. This results in the known Mott mechanism discussed in ref. /12/. Qualitatively, this mechanism can be understood by considering the changing of phase space occupancy due to matter surrounding a composite. Since the cluster wave function in the momentum space overlaps with the Fermi-like distribution function of the medium, it becomes evident that the effective binding energy of a cluster does not only depend on the density, but also on the temperature and velocity of the clusters relative to the medium. Thus, clusters moving fastly relative to the medium are less degraded. Moreover, also for increasing temperatures the relevance of the Pauli blocking becomes gradually less essential because the Fermi distribution of all nucleons is spread out in momentum space. From this qualitative argumentation follows that at fixed break-up density the effective mean radii of embedded clusters become smaller with increasing temperature. However, if the adopted break-up situation is such that the quantity $\rho_b \Lambda^3$ is constant, then the quenching depends predominantly only on the velocity of the composites relative to the medium. A quantitative estimate of all these effects is given below where for the sake of simplicity we will consider the deuteron formation.

Accounting for the in-medium corrections one has to solve a Bethe-Goldstone type of equation for the deuteron embedded in a nuclear medium. As a consequence, the deuteron wave function becomes dependent on the density of the medium ρ, the temperature T and the velocity of the deuteron relative to the medium. Following the lines of refs. [7,12], we have calculated the effective deuteron radius $r_d = \langle \phi_d | r^2 | \phi_d \rangle^{1/2}$, where ϕ_d is the solution of the Bethe-Goldstone equation obtained in perturbation theory. The rms radius can be expressed throught the effective binding energy ϵ_d of the deuteron and take the following approximated form

$$\sqrt{\langle r_d^2 \rangle} = (3m/4\hbar^2 \epsilon_d)^{1/2} \qquad (2)$$

with

$$\epsilon_d \simeq \epsilon_d^\circ \left[1 - \frac{\rho_b \Lambda^3 a}{4\delta^{3/2}}\left(5 + \frac{3}{\delta} + \frac{P_d^2 \Lambda^2 \gamma}{8\pi \hbar^2 \delta^2}\right) e^{-\frac{P_d^2 \Lambda^2}{16\pi\hbar^2\delta^2}}\right] \qquad (3)$$

which is suitable for quick numerical estimates and reflects all the interesting features discussed above. Here $\epsilon_d^\circ = 2.226$ MeV is the deuteron binding energy, P_d denotes the deuteron momentum, $\gamma = \epsilon_d^\circ / T$ and $\delta = 1 + \gamma$. The quantity $a = 0.5$ has been introduced in order to simulate the quenching effect due to Pauli blocking when a more realistic deuteron wave function as following, e.g., from applying the Reid potential is used. The expression for the effective binding energy can further be simplified by replacing the prefactor $\rho_b \Lambda^3$ by the specific entropy and by considering a deuteron velocity equal to the thermal one. Since the remaining dependence on the temperature in (3) is then neglegible ($\gamma \simeq 0$, $\delta = 1$), one could use in place of (3) the condensed formula

$$\tilde{\epsilon}_d = \epsilon_d^\circ (1 - 4 e^{5/2 - S/A - 3/4}) \qquad (4)$$

indicating that the rms - radius should scale with the entropy only.

One should, however, be aware of identifying the specific entropy value introduced above for the sake of simplicity with the actual one. In fact the S/A values inferred from the break-up densities and the temperatures determined from the proton energy spectra agree well with the estimates made by employing Kapusta's method [8] (see ref. [2]) and are also at higher energies ($E_{beam} \gtrsim 1$ GeV/u) in reasonably good agreement with the cascade model predictions [9,10] but they are about two units off when employing the method of Stöcker et al. [13] (see ref. [2] for an extensive discussion of this point).

In the figure we show the results for r_d as a function of the temperature at given density or entropy values. In the latter case almost straight lines are obtained whereas in the other case the model predicts a decreasing effective radius for increasing temperatures as has been shown previously in ref. [7]. In the high temperature or low density limit $\langle r_d^2 \rangle$ approaches the value of the free cluster (dash-dotted line).

In summary at the disassembly stage of a hot nuclear system the effective radii of the formed clusters depend on the temperature and the density of the nuclear medium and on the velocity of the clusters relative to the emitting source. In a perturbation approach to the Bethe-Goldstone equation the rms deuteron radius could be expressed via the effective binding energy of a cluster embedded in a hot nuclear medium. The relatively weak dependence of the deuteron-like composites on the temperature of the nuclear medium inferred by Doss et al. [2] is due to the fact that the experimentally extracted dependences on temperature and break-up density compensate each other in such a way that $\rho_b \Lambda^3$ is nearly constant, which implies that both the cluster radii and the specific entropy remain also constant in a wide range of the temperature. It might well be that the constancy of $\rho_b \Lambda^3$ is not accidental but rather indicates that the disorder of the system has already reached such a degree that the disassembly process becomes almost independent of the beam energy and the projectile-target combinations. Comparing with the results of Doss et al. [2] one has, however, to note that our r_d values characterize the deuteron cluster whereas they parametrize the deuteron-like correlations.

The theoretical results represented have been obtained by disregarding any dynamical effects during the formation of the composites and can, therefore, give only a rough orientation on the connection between the effective cluster radii and the thermodynamical quantities characterizing the break-up stage.

The authors are indebted to H.Gutbrod for making the experimental data available before publication. Two of us (H.S. and G.R.) are grateful to the Nuclear Physics Division of the JINR for the kind hospitality extended to them.

REFERENCES

1. Gutbrod H.H. et al. Phys.Lett., 1983, 127 B, p.317.
2. Doss K.G.R. et al. GSI-Preprint 85-4, 1985 and Phys.Rev.C. in press.

3. Mekjian A.Z. Phys.Rev., 1978, C17, p.1051.
4. Kapusta J. Phys.Rev., 1980, C21, p.1301.
5. Gutbrod H.H., et al. Phys.Rev.Lett., 1976, 37, p.667.
6. Sato H., Yasaki K. Phys.Lett., 1981, 98B, p.153.
7. Schulz H., et al. Phys.Lett., 1983, 124B, p.458.
8. Kapusta J. Phys.Rev., 1984, p.1735.
9. Gudima K.K. et al. Preprint of Niels Bohr Institute NBI-85-11, 1985; JINR, E2-85592, Dubna, 1985.
10. Cugnon J., L'Hote D. In: Proc. 7th High Energy Heavy Ion Study, GSI-Report 85-10, 1985, p.253.
11. Barz H.W. et al. Z.Phys., 1982, A308, p.187.
12. Röpke G., Münchow L., Schulz H. Nucl.Phys., 1982, A379, p.536; Phys.Lett., 1982, 110B, p.21;
Röpke G. et al. Nucl.Phys., 1983, A399, p.587.
13. Stöcker H. et al. Nucl.Phys., 1983, A400, p.63c;
Jacak B.V. et al. Phys.Rev., 1984, C29, p.1744.

Received by Publishing Department
on July 31, 1985.

COMMUNICATIONS, JINR RAPID COMMUNICATIONS, PREPRINTS, AND PROCEEDINGS OF THE CONFERENCES PUBLISHED BY THE JOINT INSTITUTE FOR NUCLEAR RESEARCH HAVE THE STATUS OF OFFICIAL PUBLICATIONS.

JINR Communication and Preprint references should contain:

- names and initials of authors,
- abbreviated name of the Institute (JINR) and publication index,
- location of publisher (Dubna),
- year of publication
- page number (if necessary).

For example:

1. Pervushin V.N. et al. JINR, P2-84-649, Dubna, 1984.

References to concrete articles, included into the Proceedings, should contain

- names and initials of authors,
- title of Proceedings, introduced by word "In:"
- abbreviated name of the Institute (JINR) and publication index,
- location of publisher (Dubna),
- year of publication,
- page number.

For example:

Kolpakov I.F. In: XI Intern. Symposium on Nuclear Electronics, JINR, D13-84-53, Dubna, 1984, p.26.

Savin I.A., Smirnov G.I. In: JINR Rapid Communications, N2-84, Dubna, 1984, p.3.

SUBJECT CATEGORIES OF THE JINR PUBLICATIONS

Index	Subject
1.	High energy experimental physics
2.	High energy theoretical physics
3.	Low energy experimental physics
4.	Low energy theoretical physics
5.	Mathematics
6.	Nuclear spectroscopy and radiochemistry
7.	Heavy ion physics
8.	Cryogenics
9.	Accelerators
10.	Automatization of data processing
11.	Computing mathematics and technique
12.	Chemistry
13.	Experimental techniques and methods
14.	Solid state physics. Liquids
15.	Experimental physics of nuclear reactions at low energies
16.	Health physics. Shieldings
17.	Theory of condenced matter
18.	Applied researches
19.	Biophysics

Гудима К.К. и др. E2-85-586
Эффективные радиусы легких составных частиц, образованных в столкновении релятивистских тяжелых ионов

Экспериментальные тенденции поведения эффективных радиусов составных частиц, испущенных из горячего источника, образованного в столкновении релятивистских тяжелых ионов при различных энергиях, качественно воспроизводятся пертурбативным решением уравнения типа Бете-Голдстоуна для дейтрона, погруженного в горячую ядерную материю.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1985

Gudima K.K. et al. E2-85-586
Effective Radii of Light Composites Produced in Relativistic Heavy Ion Collisions

The experimental trend of the effective radii of composite particles emitted from a hot source in relativistic heavy ion collisions at different beam energies is qualitatively reproduced by solving a Bethe-Goldstone-type equation in a perturbative way for a deuteron embedded in a hot nuclear medium.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1985