ELSEVIER

27 October 1994

PHYSICS LETTERS B

Physics Letters B 338 (1994) 397–402

Helium production in 10.7 *A* GeV Au induced nucleus–nucleus collisions

EMU01 Collaboration

M.I. Adamovich [a], M.M. Aggarwal [b], Y.A. Alexandrov [a], R. Amirikas [c], N.P. Andreeva [d], Z.V. Anzon [d], R. Arora [b], F.A. Avetyan [e], S.K. Badyal [f], A.M. Bakich [c], E.S. Basova [g], I.K. Bazarov [g], K.B. Bhalla [h], A. Bhasin [f], V.S. Bhatia [b], V.G. Bogdanov [i], V. Bradnova [j], V.I. Bubnov [d], T.H. Burnett [k], X. Cai [l], D.A. Carshiev [g], I.Y. Chasnikov [d], L.P. Chernova [m], M.M. Chernyavski [a], S. Dhamija [b], G.Z. Eligbaeva [d], L.E. Eremenko [d], A.S. Gaitinov [d], E.R. Ganssauge [n], S. Garpman [o], S.G. Gerassimov [a], C. Graf [n], J. Grote [k], K.G. Gulamov [m], S.K. Gupta [h], V.K. Gupta [f], B. Jakobsson [o], L. Just [p], S. Kachroo [f], G.S. Kalyachkina [d], E.K. Kanygina [a], M. Karabova [j,p], S. Kitroo [f], S.P. Kharlamov [a], A.D. Kovalenko [j], S.A. Krasnov [j], V. Kumar [h], V.G. Larionova [a], Y.D. Li [l], L.S. Liu [l], S. Lokanatan [h], J.J. Lord [k], N.S. Lukicheva [m], S.B. Luo [q], L.K. Mangotra [f], N.A. Marutyan [e], A.Y. Mashkov [m], N.V. Maslennikova [a], I.S. Mittra [b], S. Mokerjee [h], S.Z. Nasyrov [g], V.S. Navotny [m], J. Nystrand [o], M. Ochs [n], G.I. Orlova [a], I. Otterlund [o], L.S. Peak [c], N.G. Peresadko [a], N.V. Petrov [g], V.A. Plyushchev [i], V.V. Rusakova [j], W.Y. Qian [l], Y.M. Qin [q], R. Raniwala [h], S. Raniwala [h], N.K. Rao [f], M. Roeper [n], N. Saidkhanov [m], N.A. Salmanova [a], L.G. Sarkisova [e], V.R. Sarkisyan [e], G.S. Shabratova [j], A.M. Seitimbetov [d], C.I. Shakhova [d], S.N. Shpilev [m], D. Skelding [k], K. Söderström [o], Z.I. Solovjeva [i], E. Stenlund [o], L.N. Svechnikova [m], M. Tothova [p], M.I. Tretyakova [a], T.P. Trofimova [q], U.I. Tuleeva [g], B.P. Tursunov [g], S. Vokal [p], J. Vrlakova [p], H.Q. Wang [o,l], Z.Q. Weng [r], R.J. Wilkes [k], Y.L. Xia [r], C.B. Yang [l], D.H. Zhang [q], P.Y. Zheng [s], S.I. Zhokhova [m], D.C. Zhou [l]

[a] *P.N. Lebedev Institute of Physics, Moscow, Russia*
[b] *Department of Physics, Panjab University, Chandigarh, India*
[c] *School of Physics, University of Sydney, Sydney, Australia*
[d] *High Energy Physics Institute, Almaty, Kazakhstan*
[e] *Yerevan Physics Institute, Yerevan, Armenia*
[f] *Department of Physics, University of Jammu, Jammu, India*
[g] *Laboratory of Relativistic Nuclear Physics, Institute of Nuclear Physics, Tashkent, Uzbekistan*
[h] *Department of Physics, University of Rajasthan, Jaipur, India*
[i] *V.G. Khlopin Radium Institute, St. Petersburg, Russia*
[j] *Laboratory of High Energies, Joint Institute for Nuclear Research (JINR), Dubna, Russia*

SSDI 0370-2693(94)01094-3

[k] *Department of Physics, University of Washington, Seattle, WA, USA*
[l] *Institute of Particle Physics, Hua-Zhong Normal University, Wuhan, Hubei, China*
[m] *Laboratory of High Energies, Physical-Technical Institute, Tashkent, Uzbekistan*
[n] *F.B. Physik, Philipps University, Marburg, Germany*
[o] *Department of Physics, University of Lund, Lund, Sweden*
[p] *Department of Nuclear Physics and Biophysics, Safarik University, Kosice, Slovak Republic*
[q] *Department of Physics, Shanxi Normal University, Linfen, Shanxi, China*
[r] *Department of Physics, Hunan Education Institute, Changsha, Hunan, China*
[s] *Institute of High Energy Physics, Academica Sinica, Beijing, China*

Received 17 June 1994; revised manuscript received 12 August 1994
Editor: L. Montanet

Abstract

Angular distributions of projectile-associated He fragments from Au induced reactions in nuclear emulsions at 10.7 *A* GeV have been measured with a precision of ± 0.1 mrad. Two emission components are indubitably appearing, one representing fragmentation of a fermionic system while the other one exhibits large transverse momentum transfer. Possible explanations for the latter component are discussed.

Possessing a complete 4π detector with very good spatial resolution (about 1 μm), electron sensitive emulsions are well suited both for investigations of event topology and for measurements of angular distributions of different kinds of particles from nuclear reactions. In high energy heavy-ion collisions it is e.g. easy to single out projectile associated helium nuclei and measure their angles with very high precision.

The most gentle kinds of Au induced collisions at 10.7 *A* GeV are electromagnetic dissociation and pure elastic scattering which we exclude in this investigation. For somewhat smaller impact parameters one expects fragmentation which is normally described as a sudden liberation of a part of a fermionic system [1,4]. In this paper we will investigate if the emission of projectile associated He-fragments is limited to the fragmentation region in phase space. However, if communication between participant and spectator matter takes place, He-fragments are expected to be emitted also outside this region. If so, it is important to understand the mechanisms behind this transfer of energy and momentum. Some experiments [5–7] at lower energies have shown an extended momentum tail of the projectile associated fragments.

Ten stacks containing 30 pellicles of $10 \times 10 \times 0.06$ cm^3 NIKFI-BR2 emulsions, with a sensitivity of 30 grains/100 μm for a singly charged minimum ionizing particle, were exposed horizontally to the 10.7 *A* GeV Au beam of AGS, Brookhaven. 929 minimum bias inelastic events giving a mean free path of 4.99 ± 0.16 cm, have been used for this investigation. The KLMM Collaboration [8] found an interaction mean free path of 4.7 ± 0.2 cm, consistent with our value.

Helium fragments originating from the projectile have been selected by the following criteria: (a) an emission angle, $\Theta < 10°$, and (b) a gap density which remains constant within two standard deviations for at least 6 mm. Only the projected angle in the emulsion plane is included in the subsequent investigation since the error becomes larger than 0.1 mrad when the dip angle must be introduced.

In addition we measured He fragments from Au+Au interactions in emulsion chambers [9,10]. Here, a 250 μm thick gold foil is placed in front of a series of thin plastic sheets, each covered on both sides by nuclear emulsion (FUJI ET-7B) [10]. The emulsion chambers are exposed perpendicular to the target foil. Doubly charged projectile fragments are identified by their spot sizes. This may give a minor admixture of $Z = 3$ fragments. The emission angles are determined from coordinate measurements in the emulsion plane placed 4 mm from the Au target foil. In this case the error is the same (≈ 0.1 mrad) for the two components of the emission angle.

In the subsequent presentation we classify the events with respect to the number of He fragments (N_{He}) and

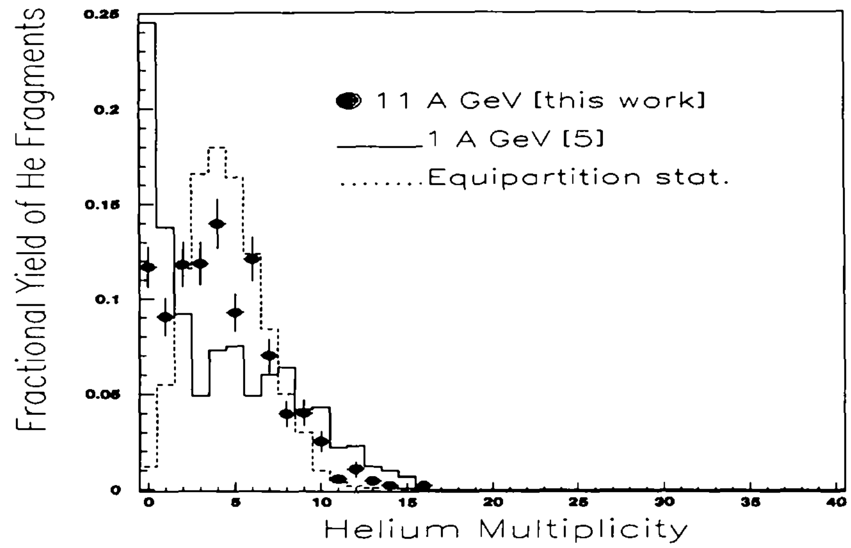

Fig. 1. Multiplicity distribution of He particles.

the number of shower (pions and protons) particles [n_s, $dE/dx < 1.4(dE/dx)_{\rm min}$].

In Fig. 1 we show the multiplicity distribution of projectile-associated He fragments. The tail of the distribution extends up to 16 such fragments which is about the same as observed in Au interactions with emulsion nuclei at 1 *A* GeV collisions [6] (the solid histogram in Fig. 1). The mean value is the same in the two studies (our data gives $N_{\rm He} = 4.2 \pm 0.1$ as compared to $N_{\rm He} = 4.1$ at the lower energy), but this is a coincidence since the shape of the distribution is quite different. The KLMM Collaboration [8] reports a value of $N_{\rm He} = 4.6 \pm 0.1$ at the BNL energy, quite consistent with our data. The dashed histogram in Fig. 1 represents a statistical equipartition decay of spectators with masses determined by the clean-cut geometry. This means that each set of fragments is given its combinatorial weight,

$$W_{Z_{\rm spec}}(N_1, N_2, N_3, \ldots, N_{Z_{\rm spec}}) = \frac{Z_{\rm spec}!}{\prod_{Z=1}^{Z_{\rm spec}} (Z!)^{N_Z} N_Z!}, \tag{1}$$

provided that

$$Z_{\rm spec} = \sum_{Z=1}^{Z_{\rm spec}} N_Z Z, \tag{2}$$

where $N_1, N_2, N_3, \ldots N_{Z_{\rm spec}}$ are the number of fragments with $Z=1, Z=2, Z=3, \ldots, Z=Z_{\rm spec}$, respectively, $Z_{\rm spec}$ being the charge of the spectator. The calculated $N_{\rm He}$ distribution averaged over al impact parameters exhibits fewer events with $N_{\rm He} = 0$, 1 but gives a proper description of the high multiplicity tail. The statistical equipartition decay of spectators is oversimplified. A proper description should incorporate complex decay modes [11,12] based on grand canonical statistics with all constraints for finite nuclei invoked but the simple approach used here reproduces multiplicities larger than 5 astonishingly well. However it will be shown below that the impact parameter dependence of the multiplicities deviates strongly from the equipartition prescription.

The measurement of projected angles allows us to calculate the dispersion of the projected momentum distribution under the assumption that the He emitting source moves with the velocity of the beam. In Fig. 2 we show the distribution of the projected angle in the horizontal plane (Θ_{xz}). This cannot be fitted by one single gaussian distribution but possibly by the sum of two. If one gaussian is fitted in the region $\Theta_{xz}^2 > 0.001$ rad^2 and then subtracted from the total distribution we obtain dispersions of 6.94 mrad and 19.8 mrad, respectively. This corresponds to (gaussian) momentum dispersions, σ, of 322 ± 3 MeV/c and 919 ± 75 MeV/c or average transverse momenta of $\langle p_t \rangle = \sqrt{\pi/2}\sigma = 404$ MeV/c and 1152 MeV/c, respectively. Note that these values are valid only under the assumption that the

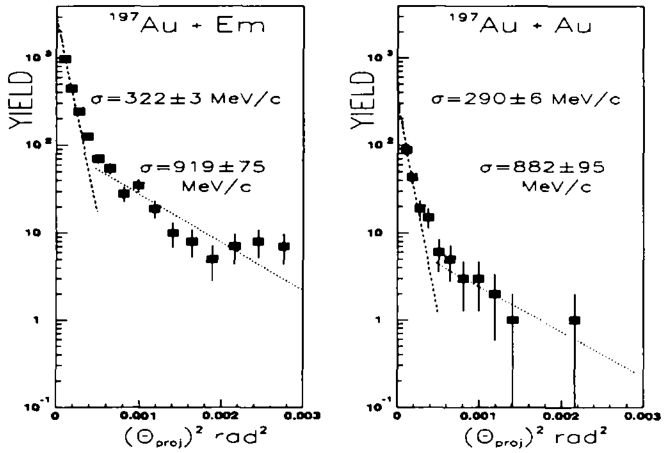

Fig. 2. Yield of He particles as a function of Θ^2_{proj} in rad^2.

emitting source is moving with the velocity of the beam.

In Fig. 2b we used both angular components, Θ_{xz} and Θ_{yz} projected on a plane perpendicular to the beam [13] direction z, (referred to as Θ_{proj} in Fig. 2), for the Au + Au chamber data since the two projected angles should be independent. The chamber data have some bias against low multiplicity events and therefore against peripheral collisions.

A fermionic breakup should lead to momentum spectra of a gaussian type with a width of [1]

$$\sigma(p_x) = \sigma(p_y) = \sqrt{F(A-F)/(A-1)}\ \sigma_0\,, \qquad (3)$$

where F is the mass number of the fragment, A the mass of the projectile and $\sigma_0 = p_F/\sqrt{5}$ is approximately 119 MeV/c for a fragmenting Au nucleus [14]. The experimental Au + Em value of σ corresponds to, $\sigma_0 = 162 \pm 2$ MeV/c for pure ^{4}He emission or to 164 MeV/c if we include the expected $\approx 10\%$ ^{3}He contribution. These values are significantly larger than the one expected from a zero temperature fermionic breakup. Data on helium emission in collisions with somewhat lighter projectiles [3,15] show the same tendency. If the larger width is due to any additional, collective source of momentum in random direction from the Au nucleus one expects an enhanced momentum dispersion of the type,

$$\sigma^2 = \sigma_0^2 F(A-F)/(A-1) + \sigma_1^2 (F/A)^2\,, \qquad (4)$$

and in any direction (x), $\sigma_1^2 = \langle p_x^2 \rangle$ which is the collective mean squared momentum transfer to the fragmenting nucleus.

The most obvious extra term in Eq. (4) is the one coming from Coulomb repulsion between projectile- and target nucleus prior to breakup. Assuming full Coulomb momentum transfer with a distance of closest approach equal to the sum of the radii, we obtain however a second term in Eq. (4) of only ~90 MeV/c giving a total σ of 254 MeV/c in Eq. (4) if $\sigma_0 = 119$ MeV/c is used. This is still too small to account for the experimental width. If in addition a secondary breakup of the spectator takes place one obtains a larger additional Coulomb component. A pure two-body decay of the projectile spectator gives $\sqrt{\langle p^2 \rangle} \approx 400$ MeV/c for the average spectator and therefore $\sqrt{\langle p_x^2 \rangle} \sim 230$ MeV/c. This gives $\sigma \approx 330$ MeV/c, which is very close to the experimentally observed value. A strong communication between spectator and participant matter may of course also lead to an enhanced dispersion. In fact, p_t data on forward emission of both protons and neutrons (no secondary Coulomb term) from similar reactions [16] stress the difficulty to separate the true spectator component from strongly interacting nucleons. A collective hydrodynamical "bounce-off" effect [17] could possibly be an alternative explanation for the enhanced width of the soft component.

We now turn to the second, hard component in Fig. 2 and first note that neither the bounce-off process nor any binary Coulomb decay can possibly explain it. Instead one may look for the explanation among strong interaction processes. Data on elastic and inelastic

($pp \rightarrow NN + m\pi$) nucleon–nucleon scattering are rather complete and here we use those from Ref. [18] at ≈6 GeV/c where the $p_\perp^2$ distribution are parametrized by two exponentials. If the coalescence hypothesis is valid [19,20], i.e. that nucleons with positions inside a phase-space sphere of radius p_0 are forming bound clusters, the momentum vector distribution of fragments is found from the corresponding nucleon momentum distribution raised to the power of the fragment mass. Performing this calculation with the parametrized pp scattering data gives $\sigma_x = 2(\sqrt{2|d(\ln f)/dp_\perp^2|})^{-1} \approx 478 \pm 14$ MeV/c and 659 ±9 MeV/c for the inelastic $p_\perp^2$ exponentials. This is not in agreement with our data but when introducing the elastic ($pp \rightarrow pp$) hard component one obtains $\sigma_x = 880$ MeV/c which agrees both with Au + Em and Au + Au data.

This approach offers no direct explanation for the He fragment emission unless we assume that nucleons coalesce within a system in statistical equilibrium. Thus it would more point to a thermal process than to some kind of direct scattering process. If we instead believe that He-fragments are emitted in direct scattering processes we should look into data for Nα and $\alpha\alpha$ scattering. Data on free αp scattering at 8.6 GeV/c [21] and $\alpha\alpha$ scattering at 7.2 GeV/c [22] shows that the square of the four-momentum transfer (t) to the alpha particle can be parametrised in terms of one single exponential. For $p_\perp \ll \sqrt{s}$ the approximation $t \approx -p_\perp^2$ is valid (s is the squared of the CM energy). For αp scattering $\langle p_\perp \rangle \approx 170$ MeV/c and $\alpha\alpha$ scattering gives $\langle p_\perp \rangle \approx 541$ MeV/c. This means that αp scattering can be ruled out as the explanation of the hard component in Fig. 2. Also $\alpha\alpha$ scattering ($\sigma \approx 430$ MeV/c) has a too small dispersion but what then remains to introduce is the internal momenta of the He cluster in both nuclei. It is beyond the scope of this paper to include many-body wavefunctions properly but it is clear that this would increase the dispersion of the He fragment momenta.

Finally we investigate possible differences in the transverse momentum distribution in events with different topology. The parameter $n_s/\langle n_s \rangle$ is an energy independent measure of the impact parameter i.e. the number of participants. Fig. 3a shows that the n_s–N_{He} correlation. $\langle N_{He} \rangle$ rises with n_s up to ~6.5 for $n_s/\langle n_s \rangle \approx 2$ and then significantly drops for larger n_s indicating that the breakup of the spectator into $Z = 1$ fragments becomes dominant. If the equipartition prescription is introduced we obtain the dashed curve which shows a completely different behaviour. The translation is obtained using the geometrical part of the Fritiof model [23]. The discrepancy between this estimation and the data indicates a more complex relation between N_{He} and centrality than this approach accounts for but also that the data may be sensitive to the specific mechanism.

In Fig. 3b it is shown that the $\langle p_\perp \rangle$ value, estimated under the assumption that the source of emission moves

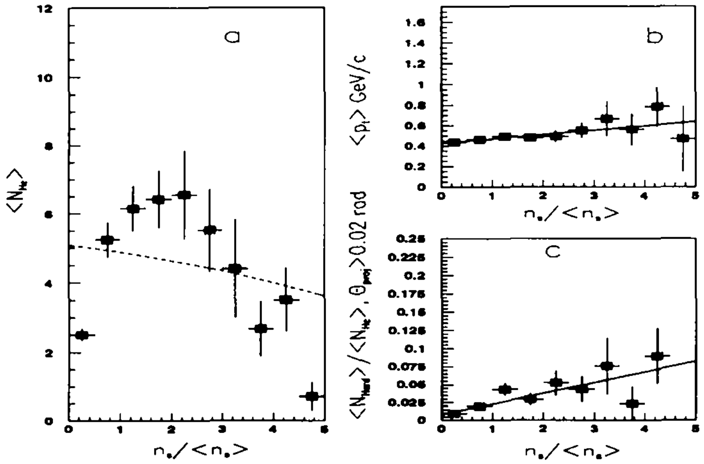

Fig. 3. Distribution of $\langle N_{He} \rangle$ (a), $\langle p_\perp \rangle$ (b), and $\langle N_{Hard}(\Theta_{proj} > 0.02\ \text{rad}) \rangle / \langle N_{He} \rangle$ (c) as a function of centrality ($n_s/\langle n_s \rangle$). The solid lines in (b) and (c) are only to guide the eye.

with the beam velocity, increases monotonically but only weakly with n_s. If we instead assume that $\langle p_\perp \rangle$ is constant the source must slow down considerably in order to account for the experimental behaviour. As a consequence of the results in Fig. 3b the relative number of He fragments in the hard component (taken to be those with $\Theta_{zz} > 0.02$ rad, c.f. Fig. 3c) increases with n_s.

We have measured multiplicity and angular distributions of He-fragments emitted in Au+Em and Au + Au interactions at 10.7 *A* GeV/*c*. We observe two components in the angular distribution, one soft component and one hard. The soft component can be understood by fermionic breakup if additional Coulomb repulsion is introduced and if one assumes that the process occurs in two steps; the excited fragment is formed and decays afterwards. The understanding of the hard component is not complete. We have discussed αα and αp quasi elastic scattering as possible candidates. Also other kinds of processes where the communication between spectator and participant matter is strong are potential candidates for explaining the hard He component. The dependence of the momentum distribution on centrality is quite weak.

Financial support from the Swedisch Natural Science Research Council, the International Science Foundation within the Russian Foundation of Fundamental Research, the German Federal Minister of the Research and Technology, the Department of Science and Technology of the Government of India, the National Science Foundation of China, the Distinguished Teacher Foundation of the State Education Commission of China, the Fok Ying Tung Education, and the US Department of Energy and the National Science Foundation are cordially and gratefully acknowledged.

References

[1] A.S. Goldhaber, Phys. Lett. B 53 (1974) 306.
[2] D.E. Greiner et al., Phys. Rev. Lett. 35 (1975) 152.
[3] L. Anderson et al., Phys. Rev. C 28 (1983) 1224.
[4] Y.P. Viyogi et al., Phys. Rev. Lett. 42 (1979) 33.
[5] B. Jakobsson, R. Kullberg and I. Otterlund, Lett. Nuovo Cimento 15 (1976) 444.
[6] C.J. Waddington et al., Phys. Rev. C 31 (1985) 388.
[7] N.P. Andreeva et al., Sov. Phys. JETP Lett. 47 (1988) 23.
[8] M.L. Cherry et al., Krakow Report 1671/PH 1 (1994).
[9] S. Garpman et al., Nucl. Instrum. Methods A 269 (1988) 134.
[10] S. Persson, Comput. Phys. Commun. 55 (1989) 103.
[11] D.H.E. Gross, Rep. Prog. Phys. 53 (1990) 605, and references therein.
[12] J.P. Bondorf, Nucl. Phys. A 443 (1985) 321; A 444 (1985) 460.
[13] M.I. Adamovich et al., Phys. Rev. C 40 (1989) 66.
[14] E.J. Moniz et al., Phys. Rev. Lett. 26 (1971) 445.
[15] F.P. Brady et al., Phys. Rev. Lett. 60 (1988) 1699.
[16] J. Barrette et al., Phys. Rev. C 45 (1992) 819.
[17] H.R. Jaqaman and A.A. Mekjian, Phys. Rev. C 31 (1985) 146.
[18] M.A. Abolins et al., Phys. Rev. Lett. 25 (1970) 126.
[19] H.H. Gutbrod et al., Phys. Rev. Lett. 37 (1976) 667.
[20] V.M. Kolybasov and Yu.M. Sokolskikh, Sov. Phys. JETP Lett. 47 (1988) 28.
[21] V.V. Glagolev et al., Phys. Rev. C 18 (1978) 1382.
[22] L. Satta et al., Phys. Lett. B 139 (1984) 263.
[23] B. Nilsson-Almqvist and E. Stenlund, Comput. Phys. Commun. 43 (1987) 387.