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Composite Particle Emission in Relativistic
Heavy Ion Collisions

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ABSTRACT

Inclusive spectra of d, t, and ^3He have been measured over a wide range of fragment angles and energies. The observed spectra are well reproduced by the "coalescence model" with a coalescence radius p_0 which is independent of beam energies and which decreases as the sizes of the target-projectile combinations increase. The sizes of the interaction regions have been derived from these p_0 values. The experimental cross sections generally deviate from the predictions of the firestreak model.

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Energy spectra of composite particles emitted in relativistic heavy ion collisions have previously been shown to be consistent with two simple models: the coalescence model^{1,2} and the firestreak model.^{3,4} The coalescence model⁵ implies that nucleons which have relative momenta less than p_0 will coalesce to produce a composite particle. It predicts that the cross sections for the emission of light nuclei of mass A are simply related to the A^{th} power of the cross section for the emission of nucleons at the same momentum per nucleon. This model does not make any assumption about the mechanism which produced the distribution of nucleons in momentum space. In the firestreak model the interaction is assumed to be localized in the overlapping volume of the target and projectile nuclei, which is divided into streaks. In each of these streaks, the nuclear matter is treated as a thermodynamic system in a chemical equilibrium so that relative yields and momentum distributions for pions, nucleons, and light nuclei production can be calculated.^{3,4} The relationship between the nucleon and composite particle momentum spectra predicted by the coalescence model does not hold for the firestreak model because each streak contributes to the cross section with a different temperature. Therefore, it is of particular interest to test these models over a much wider kinematic range than in Refs. 1 and 2.

In the framework of a thermal model, Mekjian⁶ has related the p_0 values of the coalescence model to the volume of the fireball. The size of the source emitting nucleons can be deduced directly from the inclusive spectra of composite particles without having to measure the Hanbury-Brown Twiss effect⁷ in two-particle correlations. In the analysis of the 400 MeV/nucleon Ne + U data of Refs. 1 and 2, Mekjian⁶ found that the radius of the fireball varies from about 5 to 7 fm, depending on the emitted composite particle. These

large values of the source sizes were consistent with the picture of an expanding fireball and its dissociation at the freeze-out density. However, absolute cross sections of the data of Refs. 1 and 2 are in process of revision,⁸ so the published p_0 values are no longer valid. Therefore, it is worthwhile to derive the values of p_0 from independent experimental data and to determine the size of the emitting source to which they correspond.

The present letter deals with the study of light fragments (d, t, ^3He) produced in the collisions of symmetric (or almost symmetric) systems $^{12}\text{C} + ^{12}\text{C}$, $^{20}\text{Ne} + \text{NaF}$, $^{40}\text{Ar} + \text{KCl}$ as well as for asymmetric systems $^{12}\text{C} + \text{Pb}$, $^{20}\text{Ne} + \text{Pb}$, and $^{40}\text{Ar} + \text{Pb}$. The experiments were performed with 800 MeV/nucleon ^{12}C , ^{20}Ne , ^{40}Ar , 400 MeV/A Ne, and 2100 MeV/A Ne beams accelerated by the Berkeley Bevalac. Proton inclusive spectra were also measured in the same experiment. Momentum, charge, and mass of fragments were determined from measurements of bending angle, energy loss, and time of flight, as described in Refs. 9 and 10. With this system, detection and identification have been achieved for fragments having kinetic energies up to 1.3 GeV/A. This is in contrast to the data of Refs. 1 and 2, where the fragments have been detected for kinetic energies only up to 150 MeV/nucleon.

Examples of inclusive spectra are displayed on Figs. 1 and 2 respectively for d, t and ^3He produced at 800 MeV/A. The shapes of the composite particle momentum spectra are well reproduced by the A^{th} power of the observed proton spectra. The word "observed" is emphasized here because baryon conservation causes a depletion in the number of nucleons available for observation whenever a composite fragment is formed. In some kinematical regions the yield of composites actually exceeds the number of protons observed. The striking agreement between the calculations and the data is not obtained when the observed

proton spectra are modified to take into account such depletion effects. Similar observations have been made by Gosset et al.² who noticed that their data, too, did not fit as well when non-depleted proton spectra were used in the calculation, even though their formulation of the coalescence model is based on the original distribution of nucleons in momentum space.

Because of the excellent fits to our data we calculated a "coalescence radius" using the observed proton spectra. We assume the neutron and proton momentum spectra have the same shapes. Let us define the ratio C as

$$C = E_A d^3\sigma_A(P_A)/d^3P_A / (E_p d^3\sigma_p/d^3p_p)^A \quad (1)$$

where $A = x + y$, x and y being, respectively, the proton and neutron numbers in the composite particle, and $P_A = A \cdot p_p$. Then the coalescence radius p_0 is given by²

$$p_0^3 = \frac{3m\sigma_0}{4\pi} x!y! \left(\frac{Z_p + Z_T}{N_p + N_T} \right)^y (x + y)^{2C} \frac{1}{x+y-1} \quad (2)$$

where σ_0 is the nucleus-nucleus total reaction cross section, Z_p and N_p are respectively the proton and neutron numbers in the projectile, Z_T and N_T are the proton and neutron numbers in the target, and m is the nucleon mass. The values of σ_0 were taken as follows: For the $^{12}\text{C} + ^{12}\text{C}$ system we used the σ_0 measured by Jaros et al.¹² at .87 GeV/A incident energy. For the other systems we used the semi-empirical hard sphere expression¹³ with the parameters of Ref. 14.

The value of the parameter $\tilde{p}_0$ is obtained by explicitly removing spin alignment and phase factors from p_0 ;⁶ i.e.,

$$(p_0^3)^{A-1} = A^3 \frac{(2s+1)}{2^A} (\tilde{p}_0^3)^{A-1} . \quad (3)$$

The coefficients C , p_0 , and $\tilde{p}_0$ derived from the present experimental data are listed in Table I. The values of p_0 (or $\tilde{p}_0$) are determined with an accuracy of $\pm 10\%$ due to experimental errors in absolute cross sections. Within this precision the p_0 (or $\tilde{p}_0$) values appear to be independent of incident energy; they decrease as the sizes of target projectile combinations increase. The quantity $\tilde{p}_0$ is systematically smaller for deuterons than for tritons and ^3He .

Our results indicate that equation (1) reproduces the experimental data very well. What physical models lead to such behavior? One that does is the thermal model of Mekjian.⁶ It assumes that a chemical equilibrium is reached during the expansion of the fireball, and the particles are emitted at the freeze-out density where the interactions stop. A nice feature of this model is that it is possible to relate the size of the fireball at the freeze-out density V to the coefficient $\tilde{p}_0$ of Eq. 3:

$$V = \left(\frac{E_0}{x!y!e^{kT}} \right)^{\frac{1}{A-1}} (3h^3/4\pi\tilde{p}_0^3) \quad (4)$$

where E_0 is the binding energy of the ground-state composite particle and kT the temperature of the fireball. Numerically, the term $\left(e^{E_0/kT} \right)^{1/(A-1)}$ has been replaced by 1 as $E_0 \ll kT$. This approximation affects the volume by, at most, 4% for deuteron and, at most, 8-9% for ^3He or triton, both of which are negligible compared to the uncertainty on $\tilde{p}_0^3$. For the Ne + Pb system these volumes have been found to be a factor 4 smaller than those reported in Ref. 6. The radii R of the equivalent sphere ($V = \frac{4}{3}\pi R^3$) derived from the present measurements are listed in Table I. Empirically R can be expressed by

$$R = a(A_p^{1/3} + A_T^{1/3}) + b \quad (5)$$

with $a = 0.24 \pm 0.08$ fm and $b = 1.9 \pm 0.5$ fm for deuterons and $b = 1.5 \pm 0.5$ fm for tritons and ^3He . For the Ar + Pb system, our analysis leads to values of R ranging between $3.4 \pm .3$ and $4.3 \pm .3$ fm, depending on the emitted fragment. For this same system a pion interferometry experiment¹⁵ performed at 1.8 GeV/A incident energy gives a value of $3.1 \pm .93$ fm in an inelastic trigger mode and $3.98 \pm .78$ fm for the central collision trigger mode.

It is interesting to note that such different experiments lead to similar dimensions for the size of the interaction region. It has also to be noticed that when $\left[e^{E_0/kT} \right]^{1/(A-1)} \approx 1$, as it is in our case, the relationship between V and $\tilde{p}_0$ corresponds simply to what is expected from phase space. Therefore, the determination of the size of the interaction region does not necessarily require that the system is in thermal equilibrium.

In thermal models the freeze-out density is the ratio of the number of interacting particles (participants) to the interaction volume. In our case these values range from 0.4 to 1.5 of normal nuclear density (with $\pm 30\%$ errors). The upper values are larger than one would expect for an expanding fireball. It should be kept in mind, however, that the underlying assumption that complete thermal equilibrium is reached undoubtedly oversimplifies the real situation. After all, it is not only possible, but even likely that some of the participants undergo direct processes which cause them to scatter out of the region of interaction before the system has a chance to equilibrate.

The present data are also compared with the predictions of the firestreak model in Figs. 1 and 2. It shows that firestreak calculations¹⁷ generally do not reproduce either the shape of the spectra in the overall momentum range or the

relative yields observed at the different laboratory angles. In general the firestreak calculations are more strongly forward and backward peaked than the experimental data. The discrepancies between the model predictions and the experimental data are larger for the light targets than for the heavy targets. It will be interesting to investigate the effect of transparency, as one expects that the hypothesis of thermodynamical equilibrium breaks down when the number of nucleons in the tubes is too small. More extensive comparison as well as detailed discussion of the firestreak calculations will be discussed in a forthcoming paper.

In conclusion, the spectra of composite fragments of mass A are well described as the A^{th} power of the proton spectra over a wide area of momenta and angles. On the basis of the thermal or statistical models, we obtain a reaction radius of 3-4 fm. Firestreak calculations are generally not able to reproduce the data over the wide ranges of momentum and angle of this experiment, especially for light targets.

It is interesting to extend the present studies to events biased by high multiplicities, as these data should correspond more specifically to central collisions. The freeze-out densities are directly related to the ratios of production of the different fragments. This is the subject of a subsequent paper.

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REFERENCES

1. H. H. Gutbrod, A. Sandoval, P. J. Johansen, A. M. Poskanzer, J. Gosset, W. G. Meyer, G. D. Westfall and R. Stock, Phys. Rev. Lett. 37, 667 (1976).
2. J. Gosset, H. H. Gutbrod, W. G. Meyer, A. M. Poskanzer, A. Sandoval, R. Stock, and G. D. Westfall, Phys. Rev. C16, 629 (1977).
3. W. D. Myers, Nucl. Phys. A296, 177 (1978).
4. J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C18, 844 (1978).
5. A. Schwarzschild and Č. Zupančič, Phys. Rev. 129, 854 (1963).
S. F. Butler and C. A. Pearson, Phys. Rev. 129, 836 (1963)
6. A. Mekjian, Phys. Rev. Lett. 38, 640 (1977); A. Mekjian, Phys. Rev. C17, 1051 (1978).
7. R. Hanbury-Brown and R. Q. Twiss, Nature (London) 178, 1046 (1956).
8. A. M. Poskanzer, invited paper for the International Conference on the Dynamical Properties of Heavy Ion Reactions, Johannesburg, South Africa, August 1978, and private communication.
9. S. Nagamiya, L. Anderson, W. Brückner, O. Chamberlain, M.-C. Lemaire, S. Schnetzer, G. Shapiro, H. Steiner, and I. Tanihata, Phys. Lett. (in press).
10. S. Nagamiya, talk delivered at the 4th Summer Study on High Energy Nuclear Collisions, July 1978.
11. W. Schimmerling, private communication, 1979.
12. J. Jaros, A. Wagner, L. Anderson, O. Chamberlain, R. Z. Fuzesy, J. Gallup, W. Gorn, L. Schroeder, S. Shannon, G. Shapiro, and H. Steiner, Phys. Rev. C18, 2273 (1978).
13. A. S. Goldhaber and H. H. Heckman, LBL 6570, Annual Review of Nuclear Science 28, 161 (1978).

14. P. J. Lindstrom, D. E. Greiner, H. H. Heckman, B. Cork, and F. S. Bieser, Proc. 14th Int. Conf. on Cosmic Rays (München, 1974), p. 2315.
15. S. Y. Fung, W. Gorn, G. P. Kiernan, J. J. Lu, Y. T. Oh, and R. T. Poe, Phys. Rev. Lett. 41, 1592 (1978).
16. R. Bond, P. J. Johansen, S. E. Koonin, and S. Garpman, Phys. Lett. 71B, 43 (1977).
17. The authors thank J. Gosset and G. Westfall for the firestreak calculations.

system	energy MeV/A	σ_0 mb	fragment	C	p_0 MeV/c	$\tilde{p}_0$ MeV/c	R fm
C + C	800	939	d	3.33×10^{-5}	304	167	2.9
			t, ^3He	6×10^{-10}	280	204	2.6
C + Pb	800	2964	d	6×10^{-6}	221	122	3.9
			t	3×10^{-11}	219	159	3.4
			^3He	2.5×10^{-11}	226	164	3.3
Ne + NaF	400	1301	d	1.5×10^{-5}	259	142	3.4
			t, ^3He	8×10^{-11}	223	162	3.3
	800		d	1.5×10^{-5}	259	142	3.4
			t, ^3He	2×10^{-10}	260	189	2.8
	2100		d	1.5×10^{-5}	259	142	3.4
			t, ^3He	6×10^{-11}	212	154	3.5
Ne + Pb	400	3497	d	4×10^{-6}	205	113	4.2
			t	1.5×10^{-11}	207	150	3.6
			^3He	8×10^{-12}	198	144	3.7
	800		d	4×10^{-6}	205	113	4.2
			t	1.25×10^{-11}	199	145	3.7
			^3He	6×10^{-12}	189	137	3.9
	2100		d	4×10^{-6a}	205	113	4.2
			t	2.4×10^{-6b}	173	95	5.0
				9×10^{-12}	190	138	3.9
			^3He	8×10^{-12}	198	144	3.7
Ar + KCl	800	2445		8×10^{-6a}	260	143	3.3
			d	6×10^{-6b}	236	130	3.7
				5×10^{-11a}	254	185	2.9
			t, ^3He	3.33×10^{-11b}	238	173	3.1
Ar + Pb	800	4545		4×10^{-6a}	223	123	3.9
			d	3×10^{-6b}	203	112	4.3
				10^{-11a}	211	153	3.5
			t	7×10^{-12b}	199	144	3.7
				8×10^{-12a}	216	157	3.4
			^3He	5×10^{-12b}	200	145	3.7

Table I. C, p_0 , $\tilde{p}_0$, and R derived from the present data. Typical experimental errors are $\pm 30\%$ for C and $\pm 10\%$ for p_0 , $\tilde{p}_0$, and R. Unit of C is $(\text{mb}/\text{sr}/(\text{GeV})^2)^{1-A}$.

a), b) Proton inclusive spectra measured in two sets of runs a) and b) differ by at most 30%, which is within the range of precision expected on the determination of absolute $\tilde{p}_0$ cross sections. Therefore it introduces errors on C, p_0 , $\tilde{p}_0$, and R which are still smaller than those quoted above.

FIGURE CAPTIONS

- Fig. 1. Comparison of the inclusive spectra of deuterons produced in the Ar + KCl collision at 800 MeV/A with the coalescence model and firestreak calculations.
- Fig. 2. Comparison of the inclusive spectra of tritons and helium-3 produced in the Ar + KCl collision at 800 MeV/A with the coalescence model and firestreak calculations.

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Fig. 1

Ar+KCl $\rightarrow$ t, $^3\text{He} + \text{X}$ 800 MeV/A

XBL 792-608 A

Fig. 2

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