Composite particle production in high-energy reactions and size of production source

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Production cross sections of composite particles at $\Theta_{\rm lab}=90°$ (the target-rapidity region) from 12-GeV proton reaction on nuclear targets have been measured. The particle spectra were analyzed with the coalescence model, and the radius of the production source was deduced to be $R_0^{\rm rms}=1.7\pm0.5$ fm. The radius is significantly smaller than the nuclear radii, and is independent on the target nuclear mass within uncertainties.

[NUCLEAR REACTIONS: Al, Cu, Ag, Ta $(p,x)p$, d, ^{3}He, ^{4}He, $E_p=12$ GeV; measured $\sigma(p/A,\Theta=90°)$; deduced size of emitting source.]

Some possibilities of determining the size of interaction volume in high-energy reactions have been proposed and tested. These are by observations of: (1) two-pion correlations,[1,2] (2) two-nucleon correlations,[3] and (3) composite particle production.[4,5] The first method has been applied to hadron-hadron reactions, and more than a dozen experiments have been reported. For nuclear reactions, however, although all three methods could be used, only a few examples have been reported, and results are somewhat confusing.

From a study of composite particle production, Lemaire *et al.*[6] deduced the size of the interaction volume in high-energy heavy-ion reactions to be 3 to 4 fm by use of the thermal model by Mekjian,[4] while Zarbakhsh *et al.*[7] reported a smaller size from a two-proton correlation experiment. One of purposes of this paper is to show that if we use a more general model by Sato and Yazaki[5] to analyze the composite particle production data, the results would become consistent; i.e., the radii would become smaller and close to those obtained using the two-proton correlation data.[8]

We have studied the production of composite particles (p, d, ^{3}He, and ^{4}He) at $\Theta_{\rm lab}=90°$ (the target-rapidity region) in reactions of 12-GeV protons on nuclear targets (Al, Cu, Ag, and Ta). The experiments were carried out at the KEK 12-GeV proton synchrotron. The particles were measured by use of a low-momentum $\pi\mu$ channel[9] as a spectrometer by putting a three-element telescope [100 μm SSD-500 μm SSD-13 mm NaI (T1)] on the focus point of the channel. The maximum channel momentum was 500 MeV/c, so that the observed momenta were limited to (charge)$\times$500 MeV/c or less. The solid angle subtended by the channel was calculated to an accuracy of 5% with a Monte Carlo calculation computer code, DECAY TURTLE.[10] The primary beam intensity was monitored with a secondary-electron emission chamber. We estimated overall uncertainties for absolute values of cross sections to be about 50% although relative values have much less ambiguity ($\lesssim$10%).

The experimental results were compared with the coalescence-model fits with the following relation between the cross sections for production of composite particles, $[d^3\sigma(Z,N;P=Ap)/dp^3]$, and protons, $[d^3\sigma(1,0;p)/dp^3]$:

$$A^3\left[\frac{d^3\sigma(Z,N;P=Ap)}{dp^3}\right]=\frac{2S_A+1}{2^A}\frac{1}{Z!N!}\left[\frac{1}{\sigma_0}\frac{4\pi p_0^3}{3}\right]^{A-1}\left[\frac{d^3\sigma(1,0;p)}{dp^3}\right]^Z\left[\frac{d^3\sigma(0,1;p)}{dp^3}\right]^N, \qquad (1)$$

where Z, N, $A=Z+N$, and S_A are the proton number, neutron number, mass number, and spin of the emitted composite particle, respectively. The σ_0 is the total reaction cross section. Ignoring the Coulomb effect, the neutron production cross section was assumed to be (N_T/Z_T) times that for proton production (the subscript T stands for target):

$$\left[\frac{d^3\sigma(0,1;p)}{dp^3}\right]=\left[\frac{d^3\sigma(1,0;p)}{dp^3}\right](N_T/Z_T)\ .$$

Instead of calculating the composite particle spectra from the proton spectrum, the fit was made to d, ^{3}He, and ^{4}He spectra to deduce the proton spectrum. Results of the fit are in good agreement, as shown in Fig. 1, except for the low-energy part. The excess component of the low-momentum protons may be due to protons emitted in a different time scale by a process such as evaporation. The Coulomb interaction could also be a cause for the deviation in this low-energy region. In the following, we shall discuss the size of source from the coalescence radius p_0 which gave the best fits to the spectra above 200 MeV/c per nucleon. For deduction of p_0 from the fitting parameter $(p_0{}^3/\sigma_0)$, we used the formula given by Lindström *et al.*[11] for σ_0: $\sigma_0=\pi[1.3(A_p{}^{1/3}+A_T{}^{1/3}-b)]^2$ $=(\pi[1.3A_T{}^{1/3}]^2$, for protons). The values for p_0 are listed in Table I,

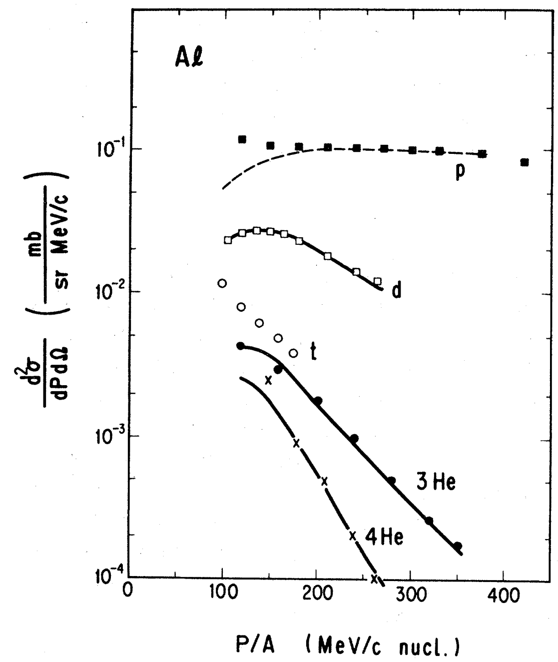

FIG. 1. An example of cross section data for production of composite particles at 90° from 12-GeV protons on nuclear target (Al target). The solid curves are the best fits by the coalescence model and the dashed curves are proton spectra from the fits.

TABLE I. (I) Coalescence radii p_0 (MeV/c) obtained from the fits to experimental data above 200 MeV/c per nucleon. For deduction of p_0, $\sigma_0=\pi[1.3A_T{}^{1/3}]^2$ was assumed. Uncertainties shown in brackets are for relative values. For absolute values, systematic uncertainties due to the beam intensity measurement had to be added. (II) Root-mean-square radii of sources deduced from p_0 (a) with the Mekjian model (Ref. 4), R_{MK}^{rms}, and (b) with the Sato-Yazaki model (Ref. 5), R_0^{rms} (fm). (III) Root-mean-square radii deduced from the ratio of p_0 for different particles with the Sato-Yazaki model, R_0^{rms} (fm).

	Target	Al	Cu	Ag	Ta	
	p_0 (d)	265 (±2%)	220 (±5%)	205 (±6%)	190 (±7%)	
(I)	p_0 (^{3}He)	320 (±2%)	270 (±4%)	255 (±6%)	240 (±7%)	(MeV/c)
	p_0 (^{4}He)	400 (±2%)	330 (±2%)	325 (±2%)	310 (±2%)	
	R_{MK}^{rms} (d)	2.8±0.4	3.4±0.5	3.6±0.5	3.8±0.7	
(IIa)	R_{MK}^{rms} (^{3}He)	2.2±0.3	2.6±0.4	2.8±0.4	3.0±0.5	(fm)
	R_{MK}^{rms} (^{4}He)	1.7±0.3	2.1±0.3	2.1±0.3	2.2±0.4	
	R_0^{rms} (d)	$0.7^{+1.2}_{-0.7}$	2.1±0.9	2.5±0.9	2.9±0.9	
	R_0^{rms} (^{3}He)	1.4±0.7	2.0±0.8	2.3±0.7	2.5±0.7	(fm)
(IIb)	R_0^{rms} (^{4}He)	$1.1^{+0.7}_{-0.6}$	1.7±0.5	1.8±0.5	2.0±0.5	
	R_0^{rms} (average)	1.1±0.4	1.9±0.4	2.2±0.4	2.5±0.4	(fm)
(III)	R_0^{rms}	1.6±0.2	1.5±0.3	1.3±0.4	1.2±0.5	(fm)

part I. The p_0 depends upon the observed particle while the dependence on the target is small.

Assuming thermal and chemical equilibrium of the system, Mekjian[4] gave the following relation between the radius of source R_{MK} and the p_0,

$$P_0 = \frac{k\hbar}{R_{MK}}; \quad (2)$$

($k = 4.84$, 4.70, 4.48 for d, ^{3}He, and ^{4}He, respectively). The root-mean-square radii $R_{MK}^{\rm rms} = \sqrt{3/5}R_{MK}$ obtained are listed in Table I part (IIa). The values range from 2 to 4 fm and depend upon the observed particle. The result is very similar to the case of heavy-ion reactions reported in Ref. 6.

Recently, Sato and Yazaki[5] developed a more general model applicable both to the two-nucleon correlation and to the composite particle production data. The model requires no assumption about the equilibrium. According to the model, the radius of source R_0 is related to p_0 as

$$p_0 = \frac{\kappa\hbar}{\sqrt{R_0^2 + R_C^2}};$$

$$(\kappa = 3.11,\ 3.25,\ 3.23,$$

$$R_C = 2.24,\ 1.67,\ 1.31\ \text{fm}$$

$$\text{for } d,\ ^3\text{He, and } ^4\text{He, respectively}), \quad (3)$$

where R_C is the radius of emitted particle. The values of $R_0^{\rm rms} = \sqrt{3/2}R_0$ calculated from p_0 are listed in Table I part (IIb).

Comparing relations (2) and (3), we can ascribe the particle dependence of R_{MK} for the spread of the wave function of the emitted particle. Indeed, in the present analysis we observed that the dependence of R_0 and R_C is smaller than that of R_{MK}. We could recalculate R_0 for the heavy ion reactions from R_{MK} in Ref. 6. Then, the values R_0 would become smaller and close to those reported in the two-proton correlation experiment.[7]

Because the above discussion, based on p_0, has drawbacks due to two factors, (1) the large experimental uncertainties in the absolute values of cross sections and (2) the ambiguity in the assumption on σ_0, we made a different analysis based on ratios of p_0; $p_0(^3\text{He})/p_0(d)$ and $p_0(^4\text{He})/p_0(d)$. By taking the ratios we can cancel both ambiguities mentioned above. The values $R_0^{\rm rms}$ to give the best fit to the p_0 ratios were thus obtained with better accuracies as shown in Table I part (III). The results on $R_0^{\rm rms}$ are summarized in Fig. 2. The radii are significantly smaller than the nuclear radii and seem to be independent of the size of the target nucleus.

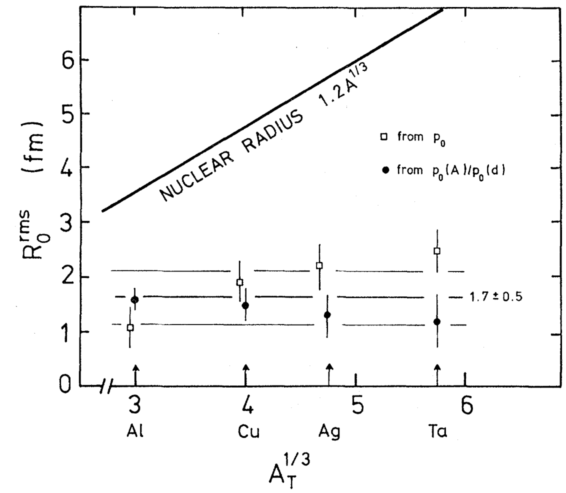

FIG. 2. The root-mean-square radius of the source $R_0^{\rm rms}$ versus the target mass. Open squares are values deduced from p_0 [$R_0^{\rm rms}$ (average) in Table I, part (IIb)], and closed circles are from the ratios of p_0 [Table I, part (III)]. The two sets of $R_0^{\rm rms}$ are not independent of one another, being deduced from the same experimental data.

In summary, we conclude that: (1) The radius of particle production source deduced with the Sato-Yazaki model is $R_0^{\rm rms} = 1.7 \pm 0.5$ fm,[12] which is significantly smaller than the target nuclear size; (2) the dependence of R_0 on the emitted particle is small. The major source of the dependence of p_0 (and, therefore, of R_{MK}) on the emitted particle is the size of the particle; (3) while the coalescence model works well for high-momentum particles (with $p/A \gtrsim 200$ MeV/c per nucleon), significant deviations were observed in the low-momentum part, probably due to protons in a different time scale through a process such as evaporation.

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[8]In order to avoid confusion due to the definition of the radius parameter, we use the root-mean square radius $R^{\rm rms}$; $R^{\rm rms}=\sqrt{3/2}R^{\rm Gaussian}=\sqrt{3/5}R^{\rm square}$.

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[12]A simple average of the eight values for $R_0^{\rm rms}$ in Fig. 2 is 1.66 ± 0.27 fm. However, since those are not independent we concluded the value for $R_0^{\rm rms}$ to be 1.7 ± 0.5 fm with the conservative error.