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Interaction Mean Free Path in the Emulsion and Interaction Radius of the Nucleus

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Abstract:

The interaction mean free path of the high energy nucleus in the emulsion is studied with the Glauber Model and Hartree-Fock type variational calculation for the nuclear structure. It is found that the experimentally observed interaction mean free paths are well reproduceable. It is also found that the interaction radius of the projectile nucleus is determinable with the emulsion experiment.

The nuclear emulsion is one of the useful and powerful nuclear detector, and it played very important roles in finding various elementary particles historically. However, even though the electro-magnetic behaviour of a energetic charged particle in the emulsion is well known theoretically and experimentally[1], the nuclear interaction mean free path (IMFP) of a projectile nucleus in the emulsion is not well known. Thus far no reliable quantitative study on the IMFP exists, and only the empirical formula ($\lambda=\Lambda Z^{-b}$) is known[2]. This peculiar fact stems mainly from the difficulty of calculating the interaction cross sections between the projectile nucleus and the target nucleus (nuclear components of the emulsion).

Recently we have studied the interaction cross sections of high energy nucleus-nucleus scatterings[3] based on nuclear density distributions generated by a density dependent Hartree Fock (DDHF) type variational calculation[4] and the center of mass corrected Glauber model[5], which includes the terms up to second order in the nucleon-nucleon (NN) profile function evaluated with the Slater determinant. We have found that the experimental interaction cross sections of the stable and unstable light nuclei-stable nucleus scatterings mearsured by INS-LBL collaboration[6,7] are nicely reproduced. Furthermore we find that the interaction cross sections nicely satisfy the additivity relationship. The additivity relation, which have been suggested by Tanihata et al[6], is expressed as

$$\sigma_{int}(p,t) = \pi (R_p + R_t)^2. \quad (1)$$

Here R_p and R_t are respectively the interaction radii of the projectile and target nuclei, which are defined by the interaction cross sections of identical nuclei, in such a way that

$$R_p = \sqrt{\sigma_{int}(p,p)/4\pi} \text{ and } R_t = \sqrt{\sigma_{int}(t,t)/4\pi}. \quad (2)$$

In this letter, employing the same calculational method, we study the relationship between the interaction cross sections and the IMFP of the projectile nucleus in the emulsion. And then we show that the IMFPs experimentally observed in the emulsion[8] are well reproduceable, and also show that the emulsion experiment can provide a powerful method to determine the interaction radius of the projectile nucleus. Throughout this letter we concentrate our discussion on the case of the scattering at incident energy 1.88 GeV/N, and we employ the Skyrme V interaction[9] as for the density dependent effective interaction and the NN scattering amplitude of the usual high energy parametrization, that is

$$f(k_N;q) = \frac{k_N \sigma (i+\rho)}{4} e^{-aq^2/2}, \quad (3)$$

where parameters are taken to be[10]

$$\sigma_{pp} = \sigma_{nn} = 45.3 \text{ mb}, \sigma_{pn} = 40.8 \text{ mb}, \rho_{pp} = \rho_{nn} = -0.27,$$
$$\rho_{pn} = -0.50 \text{ and } a = 6.2 \text{ (GeV/c)}^{-2} \text{ at } E = 1.88 \text{ GeV/N}.$$

The root mean square (rms) matter radius r_{rms} and the interaction radius R_p are calculated for several nuclei and tabulated in columns 2 and 3 of Table I. The interaction cross sections are obtainable with the R_p shown in Table I, because those satisfy nicely the additivity relationship (eq.(1)). The proton interaction radius is found to be given by 0.37fm for p-^{4}He, 0.20fm for p-1p shell nucleus, 0.15fm for p-2s1d shell nucleus, 0.10fm for p-nucleus $A = 50 \sim 150$ and 0.05fm for p-heavier nucleus, respectively for each proton-nucleus scattering.

The IMFP λ_p of the projectile nucleus in the emulsion is given by

$$1/\lambda_p = \sum n_i \sigma_{int}(p,i), \quad (4)$$

where n_i is the composition of the nuclear component i in the emulsion and $\sigma_{int}(p,i)$ is the interaction cross section between the projectile nucleus and the target nucleus i. With the employment of eq.(1), eq.(4) can be expressed by

$$1/\lambda_p = AR_p^2 + BR_p + C, \quad (5)$$

with

$$A = \pi \sum n_i, \; B = 2\pi \sum n_i R_i, \text{ and } C = \pi \sum n_i R_i^2. \quad (6)$$

The coefficients A, B and C at 1.88 GeV/N are calculated for typical emulsions of the Ilford G5 and Fuji ET7B[11] and tabulated in Table II. To examine the energy dependence of the A, B and C, we calculate those coefficients at several incident energies (0.79 $\sim$ 2.1 GeV/N) and find that the energy dependence is very small (1% less for B and 2% less for C at 0.87 GeV/N). The IMFPs calculated for each nucleus are tabulated in columns 4 and 5 of Table I. We also obtain the proton IMFP λ_p = 32.7 cm and λ_p = 32.6 cm, respectively for the Ilford G5 and Fuji ET7B. In Fig.1 we compare the calculated IMFPs in Ilford G5 for 1.8 GeV/N projectiles with the experimental IMFPs obtained with ^{40}Ar beam[8]. We also plot the experimental IMFPs obtained with 2.1 GeV/N nuclear beams[12] in Fig.1. We can find nice agreement with the experimental IMFPs by ^{40}Ar beam. While we observe almost exactly 10 % underestimation of the calculated IMFP in the case of 2.1 GeV/N nuclear beams, this 10 % underestimation is hard to be understood within our treatment, because the energy dependence of NN scattering amplitude at around 2 GeV is very small[10], and also because we find nice agreement with experimental data[13] obtained by counter detection[14]. On the other hand nice agreement between calculated and experimental IMFPs suggests the possibility of the determination of the interaction radius from the emulsion experiment. Employing A, B and C values shown in Table II we calculate the interaction radii (R_p^*) from the experimental IMFPs and tabulate those with IMFPs in

Table III. While the ambiguity due to the experimental error is large, we obtain reasonable agreement between calculated R_p and derived R_p^*.

Here we stress the important implication of the interaction radius R_p. Thus far the interaction cross section has been studied with the semiempirical formula

$$\sigma(p,t) = \pi r_o^2 (A_p^{1/3} + A_t^{1/3} - \delta)^2, \qquad (7)$$

where the "overlap parameter" δ is meant to represent the diffuseness and partial transparency of the nuclear surfaces[15]. However, because the r_o and δ are coupled in eq.(7), these values are not uniquely determined. On the other hand the additivity relationship eq.(1) indicates that the parameters r_o and δ should be defined at each nucleus A_p (and A_t). Therefore the values of r_o and δ (or R_p) are considered to be characteristic quantities of the nucleus. Furthermore, since the interaction cross sections of nuclei are essentially independent of energy from 0.1 to 30A GeV[15], the interaction radius R_p is considered to be an energy independent characteristic nuclear radius in nucleus-nucleus scatterings (like the charge radius determined from electron scattering). Another important implication of the R_p is its isotope-dependence. Since the IMFP is given by a simple function of the R_p, the isotope-dependence of the IMFP may be observable in the emulsion, especially for the light nucleus. It seems to us that the experimental analysis of the IMFP in terms of the Z=1 converted phenomena with the formula $\Lambda = \lambda Z^b$ is quite inadequate and sometimes may lead to misunderstanding.

In summary, the IMFP of the projectile nucleus in the emulsion are generally well understandable in the framework of a realistic Glauber model calculation based on realistic nuclear wave functions. This nice agreement between the experimental and theoretical IMFPs can provide a simple but quite powerful method to determine the interaction radii of the stable and unstable nuclei. It may thus provide a means to investigate the consistency between normal nuclear physics and nuclear physics for nuclei far from stability. Furthermore this kind of analysis may provide us a significant reference in the study of the anomously short IMFP phenomena[2,8].

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Figure Captions.

Fig.1. The IMFPs in Ilford G5 at 1.8 GeV/N calculated with SKV interaction (solid circle) and experimental IMFPs obtained with ^{40}Ar beam[8] (cross) and obtained with 2.1 GeV/N nuclear beams[12] (open circle).

Table 1. The rms matter (r_{rms}) and interaction (R_p) radii and IMFPs (λ_p) of projectile nuclei in the emulsion at 1.88 GeV/N calculated with SKV interaction.

Proj.	r_{rms}	R_p	$\lambda_p^{a)}$	$\lambda_p^{b)}$	Proj.	r_{rms}	R_p	$\lambda_p^{a)}$	$\lambda_p^{b)}$
^{4}He	1.76	1.52	18.8	18.4	^{31}P	3.14	3.93	8.7	8.4
^{6}He	2.47	2.07	15.5	15.2	^{32}S	3.18	4.00	8.6	8.2
^{8}He	2.43	2.38	14.0	13.6	^{34}S	3.23	4.08	8.4	8.0
^{6}Li	2.48	2.07	15.6	15.2	^{35}Cl	3.26	4.12	8.3	8.0
^{7}Li	2.45	2.23	14.7	14.3	^{37}Cl	3.29	4.18	8.2	7.8
^{8}Li	2.44	2.35	14.1	13.7	^{36}Ar	3.28	4.16	8.2	7.9
^{9}Be	2.44	2.45	13.6	13.3	^{38}Ar	3.31	4.21	8.1	7.8
^{10}Be	2.43	2.54	13.2	12.9	^{40}Ar	3.37	4.30	7.9	7.6
^{10}B	2.44	2.54	13.3	12.9	^{39}K	3.33	4.24	8.0	7.7
^{11}B	2.44	2.61	13.0	12.6	^{41}K	3.38	4.32	7.9	7.5
^{12}C	2.44	2.67	12.7	12.3	^{40}Ca	3.34	4.26	8.0	7.7
^{13}C	2.49	2.77	12.3	11.9	^{44}Ca	3.44	4.41	7.7	7.4
^{14}N	2.54	2.85	12.0	11.6	^{48}Ca	3.51	4.53	7.5	7.1
^{15}N	2.56	2.92	11.7	11.4	^{56}Fe	3.69	4.82	6.9	6.6
^{16}O	2.58	2.98	11.5	11.1	^{58}Ni	3.72	4.86	6.9	6.6
^{18}O	2.72	3.17	10.9	10.5	^{63}Cu	3.84	5.08	6.5	6.2
^{19}F	2.78	3.25	10.6	10.2	^{65}Cu	3.88	5.12	6.4	6.2
^{20}Ne	2.83	3.33	10.4	10.0	^{79}Br	4.11	5.48	5.9	5.6
^{22}Ne	2.89	3.44	10.0	9.7	^{81}Br	4.14	5.52	5.9	5.6
^{23}Na	2.92	3.50	9.9	9.5	^{107}Ag	4.51	6.04	5.2	5.0
^{24}Mg	2.94	3.55	9.7	9.4	^{109}Ag	4.54	6.10	5.1	4.9
^{25}Mg	2.96	3.60	9.6	9.2	^{120}Sn	4.67	6.29	4.9	4.7
^{26}Mg	2.98	3.64	9.5	9.1	^{127}I	4.77	6.40	4.8	4.6
^{27}Al	3.00	3.68	9.4	9.0	^{181}Ta	5.36	7.27	4.1	3.9
^{28}Si	3.02	3.72	9.3	8.9	^{184}W	5.39	7.30	4.0	3.8
^{29}Si	3.06	3.79	9.1	8.7	^{208}Pb	5.56	7.66	3.8	3.6
^{30}Si	3.09	3.86	8.9	8.6	^{238}U	5.87	8.03	3.5	3.3

Units: r_{rms} in fm, R_p in fm and λ_p in cm.
Emulsions: a) Ilford G5 and b) Fuji ET7B.

Table 2. The coefficients A, B and C of eq.(5) for the IMFP in the emulsions at 1.88 GeV/N calculated with the SKV interaction.

Emulsion	A	B					C		
		(a)	(b)	(c)	(d)	(e)	(a)	(b,c,d,e)	
Ilford G5	2.47	1.28	1.24	1.23	1.22	1.21	2.81	2.80	
		(a)	(b)	(c)	(d)	(e)	(a)	(b,c)	(d,e)
Fuji ET7B	2.65	1.33	1.29	1.28	1.27	1.26	2.80	2.79	2.78

Units: A in 10^{-3}/cmfm^2, B in 10^{-2}/cmfm and C in 10^{-2}/cm for the IMFP in cm and the R_p in fm.
Projectiles: (a) ^{4}He, (b) 1p shell nucleus, (c) 2s1d shell nucleus, (d) A = 50∼150 nucleus and (e) heavier nucleus.

Table 3. The experimental IMFPs in Ilford G5 with 1.8 GeV/N ^{40}Ar beam[8] and the interaction radii derived.

Projectile.	λ_p	R_p^*
He	19.52 ± 0.65	1.42 ± 0.09
Li	14.67 ± 1.39	2.24 ± 0.28
Be	13.15 ± 1.46	2.56 ± 0.34
B	14.79 ± 1.71	2.21 ± 0.34
C	11.73 ± 1.20	2.92 ± 0.33
N	10.29 ± 1.21	3.34 ± 0.40
O	13.43 ± 1.65	2.50 ± 0.37
F	11.31 ± 1.33	3.04 ± 0.38
Ne	13.06 ± 1.71	2.59 ± 0.40
Na	11.68 ± 1.44	2.94 ± 0.40
Mg	11.19 ± 1.46	3.08 ± 0.43
Al	8.36 ± 1.04	4.09 ± 0.46
Si	8.93 ± 1.12	3.85 ± 0.45
P	8.99 ± 1.02	3.82 ± 0.41
S	9.72 ± 1.07	3.55 ± 0.38
Cl	8.07 ± 0.99	4.22 ± 0.46
Ar	10.50 ± 0.87	3.29 ± 0.28
^{40}Ar a)	8.97 ± 0.16	3.83 ± 0.06

Units: the IMFP λ_p in cm and the R_p^* in fm.
a). The primary beam.

Fig. 1