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Table 1. Ranges and Emission Angles of the Tracks [2].

	Track	Range(µm)	θ(degree)	φ(degree)
Point A	#1	19.1±0.4	113±7	262±7
	#2	5.2±0.5	66±7	97±8
	#3	23.0±0.4	66±3	78±2
Point B	#4	12517	87.14±1.2	48.19±1.2
	#5	286±4	150±1.0	153.1±1.2
	#6	7.7±0.6	40±4	265±4
point C	#7	≥14884	88±1.5	257.1±0.7
	#8	8.8±0.4	77±5	81±3

2. Formulation of Range and Energy Relation

We consider collision between charged particles of mass M_1, charge ze, and the velocity v_1 approach a stationary particle of mass M_2 and charge Ze. If the force between particles at distance r is given by the law of inverse square.

$$F=\frac{zZe^2}{4\pi\varepsilon_0 r^2} \qquad (1)$$

The impulse due to the Coulomb force is

$$\int_0^{\infty}\frac{zZe^2}{4\pi\varepsilon_0 r^2}\cos\psi\, dt=\int_{-\infty}^{\infty}\frac{zZe^2}{4\pi\varepsilon_0 r^2}\cos\psi\,\frac{ds}{v}. \qquad (2)$$

By substituting equation (1) in equation (2) and we obtain,

$$\Delta q=\frac{zZe^2}{4\pi\varepsilon_0}\int_{-\left(\frac{\pi}{2}-\frac{\theta}{2}\right)}^{\frac{\pi}{2}-\frac{\theta}{2}}\frac{\cos\psi\, d\psi}{pv_1} \qquad (4)$$

$$\Delta q=\frac{zZe^2}{2\pi\varepsilon_0 pv_1}\cos\frac{\theta}{2} \qquad (5)$$

According to equation (5),

$$2M_1v_1\sin\frac{\theta}{2}=\frac{zZe^2}{2\pi\varepsilon_0 pv_1}\cos\frac{\theta}{2} \qquad (6)$$

and then, obtained the impact parameter as

$$p=\frac{zZe^2}{4\pi\varepsilon_0 M_1v_1^2}\,\frac{\cos\frac{\theta}{2}}{\sin\frac{\theta}{2}} \qquad (7)$$

$$p=\frac{b}{2}\cot\frac{\theta}{2} \qquad (8)$$

where, $b=\frac{zZe^2}{2\pi\varepsilon_0 M_1v_1^2}$, b is the collision diameter.

The corresponding energy loss of the incident heavy particle is

$$Q=\frac{1}{2}\frac{(\Delta q)^2}{m}=\frac{z^2e^4}{8\pi^2\varepsilon_0^2 mp^2v^2}. \qquad (9)$$

As the heavy particle passes through a thickness of absorber in which there are N atoms of atomic number Z per m^3 the number of collisions transferring energy between Q and Q+dQ is the number of electrons within the annulus of area [illegible] transferred, for all impact parameters [illegible]

$$dT=2\pi\, NZ\, dx\int_{p_{min}}^{p_{max}} Q\, p\,dp$$

$$\frac{dT}{dx}=\frac{NZ}{4\pi\varepsilon_0^2}\,\frac{z^2e^4}{mv^2}\log\frac{P_{max}}{P_{min}}$$

For $P_{min}=0$, the energy loss becomes infinite.

Where m is the electron mass and Q_0 is the maximum energy transferred which can be seen

$$Q_0=2mv^2=\frac{4m}{M}T$$

with $T=1/2\, Mv^2$ the initial kinetic energy of the [illegible] particle.

$$dT=\pi NZ\, dx\, Q_0\,\frac{b^2}{4}\log\frac{P_{max}^2+\frac{b^2}{4}}{P_{min}^2+\frac{b^2}{4}}$$

Here, $Q_0=2mv^2$ and $b=\frac{ze^2}{2\pi\varepsilon_0 mv^2}$

The stopping power of charged particle by matter is as follow. The stopping power is defined as the energy lost by the particle per unit path in the substance. The theory of the stopping power depends on knowledge of the behavior of electrons in atoms. If the range is known as the function of energy, the stopping power can be written as,

$$\frac{dT}{dx}=NZ\frac{z^2e^4}{8\pi\varepsilon_0^2 mv^2}\log\frac{P_{max}^2+\frac{b^2}{4}}{P_{min}^2+\frac{b^2}{4}}$$

In this P_{min} may be set equal to 0, corresponding with the energy transfer Q_0. We thus put P_{max} [illegible]

Assuming that $P_{max}>>b/2$, the stopping power formula becomes

$$\frac{dT}{dx}=\frac{NZ}{8\pi\varepsilon_0^2}\,\frac{z^2e^4}{mv^2}\log\frac{4P_{max}^2}{b^2}$$

To a good approximation,

$$\frac{dT}{dx}=\frac{z^2e^4}{4\pi\varepsilon_0^2 mv^2}NZ\log\frac{2mv^2}{I}$$

where, $I=\frac{\omega ze^2}{2\pi\varepsilon_0 v}$

Finally, we obtained the stopping power as above equation (16).

The range of a heavy charged particle is equal to the path length in matter because the scattering is negligible. The stopping power varies with the energy of particle, and the range of the particle is given by

$$R=\int_0^T\frac{dT}{dT/dx}$$

Investigation of Range-Energy Relation In Nuclear Emulsions

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Abstract

We calculated the kinetic energies of various particles for different tracks in nuclear emulsion from range-energy relation derived from a simplified model. In our research work, firstly we studied collision between charged particles, energy loss by collision, stopping power and range-energy relation. This relation consists of the number of atoms, the average atomic number and the density of emulsion plate. We solved numerically the range-energy formulation to obtain the kinetic energy of particles for various tracks in emulsion plates. The kinetic energies of particles which decay in emulsion from Fuji ET 7D emulsion plates used in E373 experiment for five tracks were determined from range-energy relation. Our result values for various particles, namely, p, d, t, ^3He, ^4He, $^3_\Lambda H$, $^4_\Lambda H$, $^4_\Lambda He$, $^5_\Lambda He$ and $^6_\Lambda He$ are compared with these experimental data of Lambda hypernuclei in nuclear emulsion. It is found that there are some discrepancies between the results which is mainly due to simplification imposed in our formalism.

Keywords: range, energy, nuclear emulsion, hyper nuclei

1. Introduction

An emulsion stack consisted of eleven or twelve plates with $24.5 \times 25.0 - cm^2$ area. Since the most upstream plate was used to connect Ξ- hyperon tracks from the SciFi-Bundle detector, it was necessary to minimize the distortion of the emulsion gel of the plate. For this reason, a thin emulsion plate was located upstream followed by ten or eleven thick emulsion plates [1]. The thin plate had 70-µm-thick or 100-µm-thick emulsion gel on both sides of a 200-µm-thick plastic base film, and each thick plate had 500-µm-thick emulsion gel on both sides of a 40-µm-thick or 50-µm-thick plastic film.

All emulsion plates were prepared in Gifu University with the following procedure. First emulsion gel was poured to one side of the plastic film. They were dried in a drying cabinet which moved emulsion plates automatically so that they were dried uniformly. After drying the emulsion gel, gel was poured to the other side of the plates and dried in the same manner. Then, the emulsion plates were dried again with lower humidity. Each of the emulsion plates was divided to four plates with the size of 24.5 x 25.0cm^2.

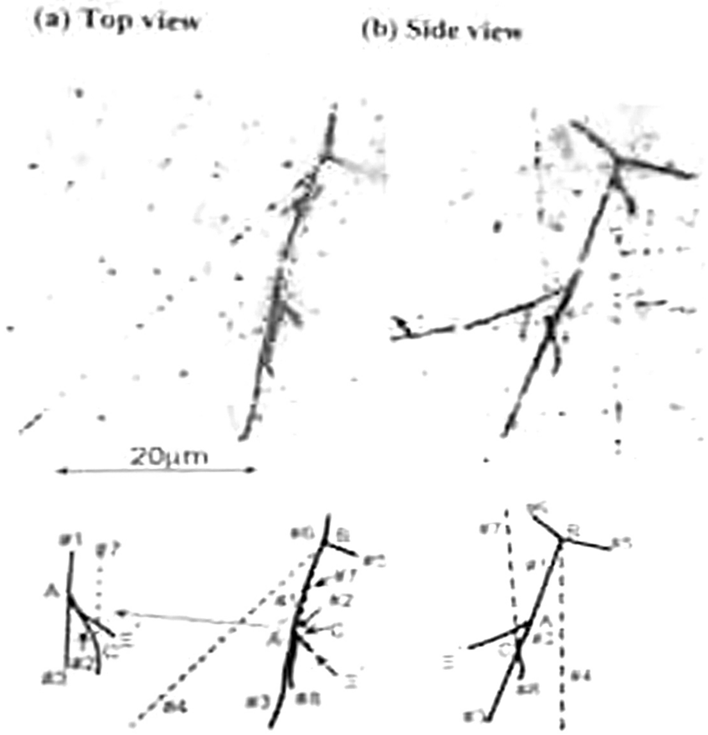

Figure 1. Picture and Schematic Drawing of the Event Viewed from the Vertical (a) and the Horizontal (b) Direction [2].

Figure 1. shows a picture and a schematic drawing of the event from E373 experiment [2]. The purpose of this experiment is to study double-strangeness nuclei via Ξ^- hyperon capture at rest. The Ξ^- was produced captured by a nucleus at point A. Three charged particles (track #1, #2, #3) were emitted from point A. Track #1 shows the topology of a decay into three charged particles at point B. Track #2 also shows a topology of decay into two charged particles at point C.

Table (1) summarizes the ranges and the emission angle of these tracks. The ranges were measured prior to swelling the emulsion. A package "SRIM 2000"[3,4,5] was used to calculate a kinetic energy from a range. The density of the emulsion of this plate was determined as $3.5 \pm 0.07 g/cm^3$ deduced from the measurement of the weight and volume of the emulsion plates. The two ranges at two different energies well with the range-energy relation calculated with SRIM2000.

The range may formally be obtained by integration of the expression for energy loss and the log term is neglected.

$$R = \int \frac{8\pi\varepsilon_0^2 m}{z^2 e^4 NZM}\, T\, dT \qquad (18)$$

We obtained range and energy relation as the following equation.

$$R = \frac{4\pi\varepsilon_0^2 m}{z^2 e^4 NZM} T^2 \qquad (19)$$

We also calculated range-energy relation by including log term as follow.

$$R = \int_0^T \frac{4\pi\varepsilon_0^2 m v^2}{z^2 e^4 NZ} \frac{1}{\log\left(2mv^2/I\right)}\, dT \qquad (20)$$

$$R = \frac{8\pi\varepsilon_0^2 m}{z^2 e^4 NZM} \int_0^T \frac{T}{\log\left(\frac{4mT}{MI}\right)}\, dT \qquad (21)$$

This formulation consists of the number of atoms, the average atomic number and the density of emulsion plate. The density of Fuji ET 7D emulsion is $3.55\times10^{-39}\,g/fm^3$. This formulation consists of the number of atoms, the average atomic number and the density of emulsion plate. The density of Fuji ET 7D emulsion is $3.55\times10^{-39}\,g/fm^3$. Table (2) shows the composition of the Fuji ET-7C and ET-7D emulsion [6]. We calculated the total atoms and average mass number of Fuji ET 7D emulsion. The average atomic number of emulsion is obtained 34.553 by summing the atomic number of each element by considering the weight ratio in emulsion plate. The total atoms of emulsion plate is obtained from Avogadro's law.

The lengths of tracks (Ranges) are used in E-373 experiment [2]. We solved numerically equation (19) and (21) by using FORTRAN code to obtain the kinetic energies of various particles for various ranges in emulsion plate.

Table 2. The Composition of the Fuji ET-7C and ET-7D Emulsion [6].

material	weight ratio(%)	mol ratio(%)
I	0.3	0.06
Ag	45.4	11.2
Br	33.4	11.1
S	0.2	0.2
O	6.8	11.3
N	3.1	5.9
C	9.3	20.6
H	1.5	40.0

3. Results and Discussion

We calculated the average atomic number (Z) and the total number of atoms of emulsion plate by considering the weight ratio of each element in the emulsion. The density of Fuji ET 7D emulsion is $3.55\times10^{-39}\,g/fm^3$. The lengths of tracks which we used in emulsion plate from E-373 experiment [2]. We solved numerically equation (19) and (21) to obtain the kinetic energies of various particles by using the simplified model. The results are shown in tables (3), (4) and (5).

Ichikawa et, al calculated the kinetic energies of possible particles for various tracks from range-energy relation which contains emission angle of the tracks (θ and ϕ) by using a package 'SRIM 2000' [2]. Their acceptable particles are ^{4}He for track #6 and #3, proton for track #5 and $^5_\Lambda$He for track #1 and #2. They assumed that Ξ^- hyperon was absorbed by light nucleus ^{14}N in the emulsion. Their results are shown in the following tables.

We calculated the kinetic energies of possible particles (p, d, t, ^{3}He, ^{4}He) for three tracks(track #6, #3,#5). The results are shown in table (3) and (4). It is seen that our results which neglect log term, agree fairly with the results of Ichikawa et, al [2] for short range but do not agree for long range. Our results which contain log term agree fairly with the results of Ichikawa et, al [2] for long range but do not agree for short range. Our calculated kinetic energy of acceptable particle (^{4}He) for track #6 and #3 which neglect log term, agree with the results of Ichikawa et, al [2].

The kinetic energies of hyper-nuclei ($^3_\Lambda$H, $^4_\Lambda$H, $^4_\Lambda$He, $^5_\Lambda$He, $^6_\Lambda$He) for track #1 and #2 were calculated from equation (19) and (21). The results are shown in table (5). It is observed that our result is in better agreement with those of Ichikawa et, al [2] for the longer the tracks. Our result which contains log term for $^5_\Lambda$He is in agreement with those of Ichikawa et, al [2] for track #1 and #2. This particle is acceptable particle.

Table 3. Various Kinetic Energies of Possible Particles for Track #6 (7.7 μm), Track #3 (23 μm) with our Results A , B and Ref [2].

Particles	Kinetic energy (MeV)			Kinetic energy (MeV)		
	A	B	track #6 [2]	A	B	track #3 [2]
p	0.610	0.550	0.67	1.029	1.168	1.39
d	0.801	0.670	0.76	1.455	1.272	1.74
t	0.981	2.468	0.84	1.781	2.080	1.98
^{3}He	2.122	1.585	2.2	3.563	1.959	4.82
^{4}He	2.350	1.645	2.3	4.104	4.230	3.33

Table 4. Various Kinetic Energies of Possible Particles for Track #5(286 μm) with our Results A, B and Ref [2].

Particles	Kinetic energy (MeV)		
	A	B	track #[2]
p	3.620	6.160	6.62
d	5.120	7.943	8.7
t	6.272	8.987	10.2
^{3}He	12.543	21.790	23.5
^{4}He	14.451	24.355	26.4

Table 5. Various Kinetic Energies of Possible Particles for Track #2 (5.2 μm) and by Track #1 (19.1 μm) with our Results A, B and Ref [2].

Particles	Kinetic energy (MeV)			Kinetic energy (MeV)		
	(A)	(B)	Track #2 [2]	(A)	(B)	track #1 [2]
$^3_\Lambda H$	0.824	0.590	0.58	1.678	0.641	1.75
$^4_\Lambda H$	0.943	0.425	0.56	1.882	1.615	1.88
$^4_\Lambda He$	1.887	2.130	1.6	3.843	4.500	4.73
$^5_\Lambda He$	2.096	1.625	1.6	4.270	4.900	4.98
$^6_\Lambda He$	2.290	1.888	1.6	4.666	4.680	5.18

4. Conclusion

We calculated the kinetic energies of various particles (p, d, t, ^{3}He, ^{4}He, $^3_\Lambda H$, $^4_\Lambda H$, $^4_\Lambda He$, $^5_\Lambda He$, $^6_\Lambda He$) for various tracks from range-energy relation by using a simplified model. Ichikawa et, al calculated the kinetic energies of various particles (p, d, t, ^{3}He, ^{4}He, $^3_\Lambda H$, $^4_\Lambda H$, $^4_\Lambda He$, $^5_\Lambda He$, $^6_\Lambda He$) whose tracks are found in Fuji ET 7D emulsion from E373 experiment [2]. They obtained the kinetic energy of various particles by using a package "SRIM 2000". They assumed that target as ^{12}N which absorbed Ξ^- at rest and they take the emission angles (θ, ϕ) which are shown in table (1.1).

We calculated the kinetic energies of various particles (p, d, t, ^{3}He, ^{4}He). It is observed that our calculated results which neglect log term, agree fairly with the results of Ichikawa et, al [2] for short range but do not agree for long range. Our calculated results which contain log term, agree fairly with the results of Ichikawa et, al [2] for long range but do not agree for short range.

We also calculated the [illegible] nuclei ($^3_\Lambda H$, $^4_\Lambda H$, $^4_\Lambda He$, [illegible]). Our result is in better agreement [illegible] Ichikawa et, al [2] for the longer the track [illegible] that there are some discrepancies between [illegible] which is mainly due to assumptions [illegible] formalism. The assumptions made in our model are as follows, (i) collision is a forward direction [illegible] 0) (ii) P_{max} >> b/2, where P_{max} = impact parameter, b=collision diameter (iii) I = kZ, where k [illegible] is deduced from experimental results) (iv) the atomic number and mass number of target is the average [?] atomic number and mass number emulsion plate.

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