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FURTHER STUDY ON GREY PARTICLES PRODUCTION IN ^{3}He AND ^{4}He INTERACTIONS WITH EMULSION AT 4.5A GeV/c

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Experimental results of two helium isotopes at the same incident momentum reveal several trends belonging to grey particles productions. Hence, the interactions of 4.5A GeV/c ^{3}He and ^{4}He with emulsion nuclei are presented and analyzed. The dependence of the grey particle production in the forward hemisphere (FHS) and backward hemisphere (BHS) (which is restricted beyond the kinematic limits) on projectile and target sizes is studied. The average grey particles multiplicity can be correlated with the target size A_T and the parameter Q which represents the interaction centrality. The experimental data are examined in the framework of the modified cascade model. The study can provide a possibility to explain production mechanism at high energy.

Keywords: *Helium Interactions with Emulsion, Grey Particle Production, Modified Cascade Model.*

INTRODUCTION

Recently, there have been intense experimental efforts [1–5] in investigating the features of the interactions accompanied by the production of particles from nuclei in the backward hemisphere (BHS). However, till now the theoretical description has not been realized to explain such production. In free nucleon–nucleon collisions the production of the fast protons in the BHS is strictly forbidden. Therefore, the study of such production can provide a tool of information about the internal nuclear momentum distribution. The observation of such protons may then be an evidence of exotic production mechanisms such as production from clusters [6, 7] where a cumulative production is occurred through the interaction between the incident nucleon and multi–nucleon clusters in the target. It is observed that, the spectra of the energetic proton are independent on projectile mass and energy. The authors of ref. [6, 7] support a role of pion production in the earlier stage of collision followed by absorption in the nuclear environment and ejection of high–energy backward protons [8], which can be explained by two possibilities:

i– A production of pion followed by absorption of it by two target nucleons resulting in two back–to–back nucleons.

ii– A production of the Δ^{++}(1232) and its subsequent absorption of a target nucleon via $\Delta + N \rightarrow N + N$ resulting in the emission of two protons which will tend to have a near 180^{o} correlation.

On the other hand, this work is an extension of previous investigations [9–12] in which the particle production from the interactions of ^{6}Li, ^{7}Li, ^{12}C, ^{22}Ne, ^{28}Si, and ^{32}S at momentum of 4.1 – 4.5A GeV/c was studied. The present study is devoted to investigate the grey particles in ^{3}He and ^{4}He interactions with light CNO, heavy AgBr and emulsion at 4.5A GeV/c. The data are analyzed in the framework of the modified cascade model MCM [13, 14]. A generation of 5000 interactions is simulated for each projectile–target combination using the code developed by Barashenkov et al., [15]. In this model, it is assumed that when one projectile nucleon interacts with one of the target nucleons the creation of a new particle takes place. The nucleon participating from target acquires momentum and begins to move in the nucleus. It can interact with other target or projectile nucleons to produce new particles or suffer elastic rescattering. The concept of formation time of secondary particles was introduced by Kawrakow et al., [16]. More details on the model are given in [13, 14].

EXPERIMENTAL DETAILS

The study employed two stacks of BR–2 nuclear emulsion pellicles which were exposed horizontally to 4.5A GeV/c ^{3}He and ^{4}He beams at Dubna synchrophasatron. These pellicles have dimensions of 10x20 cm^{2} and 600 μm thick with sensitivity of about 30 grains per 100 μm for the minimum ionizing particles. By along–the track double scanning technique (fast in the forward direction and slow in the backward one), the interactions of the beam particles were detected. The primary tracks were picked up at a distance of about 2 mm from the leading edge of each plate and were followed until they either interacted or left the emulsion plates. The events showing interactions within 20 μm from the top or bottom surface of the pellicle were rejected. A total of 1685 and 1092 inelastic interactions were picked up by following 332.6 m and 217.6 m of primary track length, leading to mean free paths of 19.47 ± 0.48 cm and 19.93 ± 0.60 cm for ^{3}He and ^{4}He beams, respectively.

Classification of Secondary Charges

Depending on the ionization, all the tracks emitted from the interaction vertices were classified according to the commonly accepted emulsion experiment terminology.

i– Shower particles; they are singly charged particles with velocity $\beta \geq 0.7$, and relative ionization (number of grains per unit length) $I / I_o \leq 1.4$ (where I_o is the plateau ionization of singly charged minimum ionizing particles). They are mostly pions having energy above 70 MeV and singly charged fragments with energy above 400 MeV. Their multiplicity is denoted by n_s.

ii– Grey particles; their ionization corresponds to protons with $1.4 < I / I_o \leq 10$, $0.3 \leq \beta < 0.7$. They consist mainly of protons (having energy less than 400 MeV) knocked out from the target nucleus during the collision with a few percent admixture of π–mesons with momentum $60 \leq P \leq 170$ MeV/c. Their multiplicity is denoted by N_g.

iii– Black particles; they are charged particles having a velocity $\beta < 0.3$ with residual range of R < 3 mm in emulsion. Generally, these tracks are due to protons of kinetic energy less than 30 MeV. Their multiplicity is denoted by N_b.

Grey and black tracks amount the group of heavily ionizing tracks $N_h=N_g+N_b$.

The projectile fragments PFs are those emitted within angle $\theta_{Lab.} \leq 3^{o}$. Here, they are singly and doubly charged particles. The total charge of the stripped fragments in the forward cone per event is calculated and denoted by Q.

Separation of Events According to Target Type

In the present work, we separate the observed events due to the interactions with light CNO and heavy AgBr target components as follows,

1) All events with $N_h \leq 8$ are due to collisions with light elements (CNO, A = 14) in addition to some peripheral collisions with heavy elements (AgBr, A = 94). To separate the events due to the heavy emulsion components from the group of events having $N_h \leq 8$, the method described, in ref. [17] was applied. The details of this separation are given in [9, 18].

2) All events with $N_h > 8$ belong to the heavy group (AgBr).

RESULTS AND DISCUSSION

Multiplicity Characteristics

Multiplicity characteristics of the emitted particles can be well carried out using the average particle multiplicities and their multiplicity distributions.

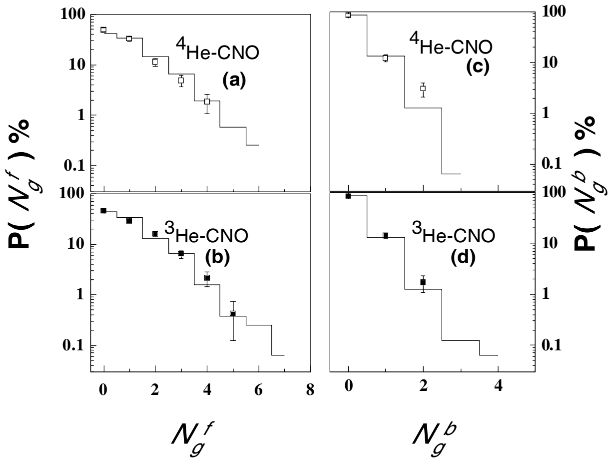

Figure 1. The experimental data of the forward (a, b) and backward (c, d) grey particle multiplicity distributions due to the interactions of ^{3}He and ^{4}He with the light target group of emulsion CNO, compared with the theoretical predictions of the modified cascade model (histograms).

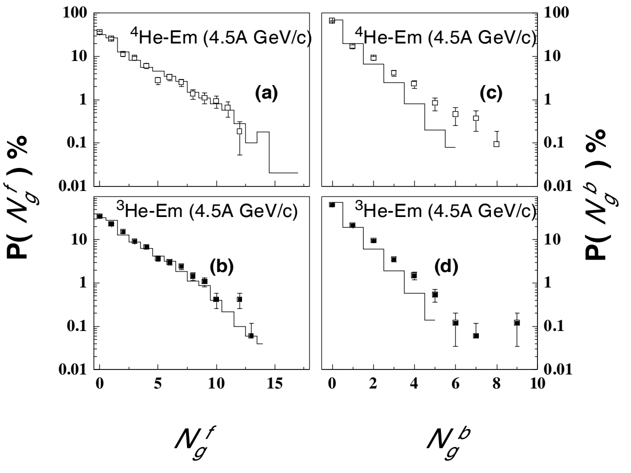

Figure 2. The experimental data of the forward (a, b) and backward (c, d) grey particle multiplicity distributions for ^{3}He and ^{4}He (4.5A GeV/c) with emulsion, compared with the theoretical predictions of the modified cascade model MCM (histograms).

Hence, the multiplicity distributions of grey particles produced in FHS and BHS due to the interactions of ^{3}He and ^{4}He at 4.5A GeV/c with different emulsion target nuclei are shown in Figure 1. through Figure 3. The experimental distributions of the forward grey particles P(N_g^f) and of backward ones P(N_g^b) are compared with the predictions of the modified cascade model MCM (histograms). All the distributions are normalized to the same number of events. The average values of the grey particles multiplicity for the two studied projectiles are listed in Tables 1. and 2.

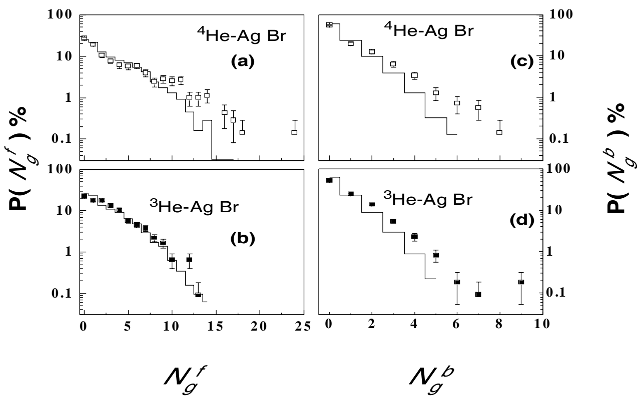

Figure 3. The experimental data of the forward (a, b) and backward (c, d) grey particle multiplicity distributions due to the interactions of ^{3}He and ^{4}He with the heavy target group of emulsion AgBr, compared with the theoretical predictions of the MCM (histograms).

Table 1. The average grey particle multiplicities in the forward and backward directions due to the interactions of ^{3}He and ^{4}He (4.5A GeV/c) with different emulsion targets [CNO, emulsion and AgBr]. The experimental data are compared with the theoretical predictions of the modified cascade model (parentheses).

Projectile	Target	$< N_g^f >$	$< N_g^b >$
^{3}He	CNO	0.91±0.02 (0.9 0)	0.18±0.01 (0.17)
	Em	1.92±0.06 (1.84)	0.61±0.03 (0.40)
	AgBr	2.63±0.08 (2.41)	0.85±0.03 (0.55)
^{4}He	CNO	0.77±0.04 (0.95)	0.18±0.01 (0.16)
	Em	1.91±0.07 (2.05)	0.67±0.04 (0.45)
	AgBr	3.36±0.13 (2.73)	0.93±0.04 (0.62)

From Figure 1. through Figure 3., one can see that, in the FHS and BHS, the probability decreases systematically along the multiplicity range regarding the excess in the multiplicity of the forward particles than the backward ones.

Table 2. The average grey particle multiplicities in the forward and backward directions in addition to (F / B) ratio due to the interactions of ^{3}He and ^{4}He (4.5A GeV/c) with emulsion for the group of events having Q = 0, Q = 1 and Q ≥ 1. The experimental data are compared with the theoretical predictions of the modified cascade model (parentheses).

Projectile	Q	$< N_g^f >$	$< N_g^b >$	(F / B)
^{3}He	0	3.28±0.11 (2.57)	1.06±0.05 (0.58)	3.09±0.34 (4.43)
	1	1.39±0.06 (1.05)	0.43±0.03 (0.21)	3.23±0.47 (5.00)
	≥ 1	1.20±0.05 (0.92)	0.38±0.02 (0.18)	3.16±0.44 (5.11)
^{4}He	0	3.12±0.14 (3.12)	1.13±0.08 (0.67)	2.76±0.36 (4.66)
	1	1.56±0.11 (1.18)	0.54±0.05 (0.25)	2.89±0.62 (4.72)
	≥ 1	1.22±0.07 (1.02)	0.40±0.03 (0.22)	3.05±0.56 (4.64)

The strong effect of the target size on the grey particles production is obvious in both hemispheres, especially in the BHS, where the multiplicity range increases with target size (for AgBr longer than CNO). The probability changes linearly with N_g^b multiplicity on a semi log scale, i. e., the change is an exponential decay at different targets. Hence, the system responsible for emitting grey particles looks like that of the radioactive decay. A similar conclusion was extracted by using heavy projectile ^{32}S [9] at 4.5A GeV/c. Meanwhile, in the FHS the change is not the same. Therefore, the mechanism of producing grey particles in the FHS is different from that in the BHS. We use the two helium isotopes for comparison, to note that, in Figures 1., 2. and 3c. and 3d. the distributions are similar for the two isotopes at each target. This indicates that the projectile size is not an effective factor in the BHS. In Figures 1. and 2a. and 2b., for the interactions with the targets CNO and Em, the multiplicity of forward grey particles excesses slightly for ^{3}He than for ^{4}He. Meanwhile, in Figures 3a. and 3b. for heavier target AgBr, ^{4}He contributes forward grey particles more than ^{3}He. This may be due to the excess neutron in ^{4}He nucleus that will be more probable to suffer cascading process with the heavier targets (AgBr dominates the region of central collisions). The average values of the grey particles multiplicity in the FHS $< N_g^f >$ and that in the BHS $< N_g^b >$ for the interactions of the two helium isotopes with different emulsion target nuclei are used to confirm the obtained results, as shown in Table 1. The values listed in the table have the same trend for the two isotopes as that observed in the multiplicity distributions. On the other hand, the model can describe the multiplicity distributions for ^{3}He and ^{4}He in the FHS. In BHS, the model systematically underestimates the distributions except for lower targets (CNO, $N_g^b < 2$) in Figures 1., 2., 3c. and 3d. The experimental values of $< N_g^b >$ at CNO in Table 1. agree with the model. This may confirm that, the mechanism responsible for production of grey particles in the FHS is different from that in the BHS.

In Table 2. one can show the multiplicity dependences of the grey particles on the quantity Q representing the centrality of interactions. That quantity measures the total charge of non–interacting projectile fragments per event. Q = 0 identifies events without any projectile fragment in the fragmentation cone. Such events are characterized by a central collision. Q = 1 identifies projectile fragments with singly charged particles. In Q ≥ 1 category one or more projectile fragments may be found in the fragmentation cone. As seen from Table 2., for both isotopes the values of $< N_g^f >$ are nearly the same at each channel of Q irrespective of the projectile size. A similar behavior is clear for $< N_g^b >$. In both hemispheres, the average values increase with centrality of interactions i.e. with decreasing Q value. The ratio between $< N_g^f >$ and $< N_g^b >$ denoted by (F / B) has a constant value within experimental errors ≈ 3. Hence, the emission of the grey particles both in forward and backward directions has the same trend at each channel of Q independent of the projectile. The model nearly tends to underestimate the average multiplicities of grey particles in the forward and backward hemisphere for both helium isotopes.

Correlations

The study of correlations of different multiplicities in forward and backward directions is of great interest in nucleus–nucleus interactions. Of course, both, strong and weak correlation may be considerably important to understand the mechanism of particles production in both hemispheres.

In Figure 4. we can show the dependence of $< N_g^f >$ and $< N_g^b >$ on the Q values as well as on the used targets mass numbers A_T through the interactions of ^{3}He and ^{4}He with emulsion nuclei at 4.5A GeV/c.

From the figure, it can be observed that, in the FHS the emission of the grey particles grows exponentially with the target size. In the BHS it increases linearly with nearly the same line for both projectiles. Thus, the dependence of the backward grey particle emission on the target is stronger than the forward ones. The dependence of the grey particles in both hemispheres on Q i.e. on the centrality decays exponentially, while, the effect of varying the projectile size is small. The experimental fittings of the data run by the regression analysis are illustrated by the dashed and solid curves. The corresponding fitting parameters and equations are listed in Table 3.

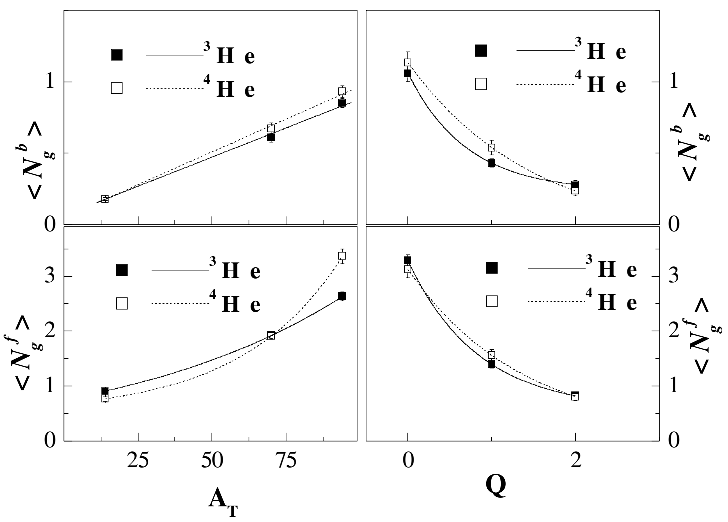

Figure 4. The experimental dependences of the average grey particle multiplicity in the forward and backward directions due to the interactions of ^{3}He and ^{4}He (4.5A GeV/c) with emulsion, on the different emulsion components mass number A_T and the striped charges Q, together with the experimental fitting (curves).

The total number of heavily ionizing particles in emulsion N_h representing the target size, strongly can deal with the impact parameter. Hence, the correlations in Figure 5. displays the dependence of the grey particles in the FHS and BHS on N_h. The histograms illustrate the predictions of the MCM. From Figure 5. one can observe that, the grey particles emitted in both hemispheres increase with N_h i.e. with the target. The saturation effect (which is a characteristic of heavy target fragmentation in central events) appears in the region of N_h > 10. The model somewhat, agrees with the measured correlations for $<N_g^f>$ and $<N_g^b>$ with N_h.

Table 3. Fitting relations and parameters characterizing the effect of target size A_T and the centrality (Q) on the emission of grey particles in the FHS and BHS through the interactions of ^{3}He and ^{4}He with emulsion at 4.5A GeV/c.

Projectile	^{3}He	^{4}He
FHS	Exponential growth of the form, $< N_g^f >= y_0 + a.e^{A_T/t}$ y_0 = –0.053 a = 0.805 t = 78.085	Exponential growth of the form, $< N_g^f >= y_0 + a.e^{A_T/t}$ y_0 = 0.499 a = 0.180 t = 33.957
	Exponential decay of the form, $< N_g^f >= y_0 + a.e^{-Q/t}$ y_0 = 0.579 a = 2.699 t = 0.835	Exponential decay of the form, $< N_g^f >= y_0 + a.e^{-Q/t}$ y_0 = 0.116 a = 3.005 t = 1.364
BHS	Linear relation of the form, $< N_g^b >= a + b.A_T$ a = 0.065±0.013 b = 0.008	Linear relation of the form, $< N_g^b >= a + b.A_T$ a = 0.051±0.010 b = 0.009
	Exponential decay of the form, $< N_g^b >= y_0 + a.e^{-Q/t}$ y_0 = 0.232 a = 0.826 t = 0.702	Exponential decay of the form, $< N_g^b >= y_0 + a.e^{-Q/t}$ y_0 = –0.088 a = 1.221 t = 1.504

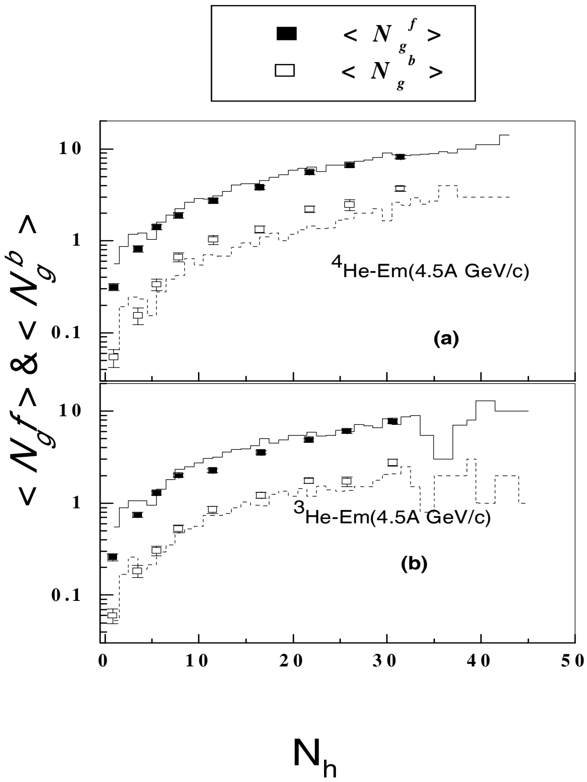

Figure 5. The experimental dependences of the average grey particle multiplicity in the forward and backward directions due to the interactions of ^{3}He and ^{4}He (4.5A GeV/c) with emulsion, on the heavily ionizing particle multiplicity, compared with the theoretical predictions of the MCM (histograms).

CONCLUSION

From the experimental data on grey particle production in the forward and backward hemispheres using ^{3}He and ^{4}He projectiles interactions with emulsion at 4.5A GeV/c the following conclusion may be drawn,

The target size is a strong factor affecting the grey particles production. That effect is more obvious in the BHS. The system emitting backward grey particles works like that of nuclear radioactive decay. The mechanism of grey particle production in the FHS is different from that in the BHS. The projectile size is not an effective factor in the grey particle production especially in the BHS. The (F / B) ratio for the emitted grey particles has a constant value ≈ 3, at different centrality for both He isotopes. The values of $<N_g^f>$ and $<N_g^b>$ can be correlated well with that of Q and the target masses A_T, where the dependence of $<N_g^b>$ on A_T is strong. The dependences of $<N_g^f>$ and $<N_g^b>$ on the target parameter N_h show a saturation effect at $N_h > 10$. This effect is a characteristic of heavy target fragmentation in the central events. The prediction of MCM can agree with the experimental data somewhat, specially in the FHS where the agreement is well.

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دراسة متعددة على إنتاج الجسيمات الرمادية في تفاعلات هيليوم-٣ وهيليوم-٤ مع المستحلب النووي عند٤,٥ جيجا إلكترون فولت لكل نيكليون لكل وحدة سرعة ضوء

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لقد أتاحت النتائج المعملية لنظيرين من نظائر أنوية ذرة الهيليوم عند نفس كمية التحرك، التعرف على الاتجاهات العديدة لإنتاج الجسيمات الرمادية و على هذا فقد أستعرضت نتائج تفاعلات هيليوم– ٣ و هيليوم– ٤ مع أنوية المستحلب النووي عند ٤,٥ جيجا الكترون فولت لكل نيكليون لكل وحدة سرعة نسبية كما تم تحليل تلك النتائج. أما بالنسبة لعملية انبعاث الجسيمات في الاتجاه الخلفي للتفاعل – و التي تعد محظورة الا بشروط في ضوء القواعد الكاينماتيكية – فقد نوقش مدى اعتماد هذا الانبعاث عمليا على حجم نواة الهدف و القذيفة و في الوقت نفسه قورن بعملية الانبعاث في الاتجاه الأمامي. كما أظهرت قيم المتوسطات العددية للجسيمات الرمادية امكانية الربط بينها و بين كتلة نواة الهدف و كذلك بارامتر مركزية التفاعل. و قد نوقش مدى اتفاق النتائج المعملية مع مثيلاتها المحسوبة نظريا من خلال نموذج التبخر المتسلسل المعدل. و أخيرا فان هذه الدراسة قد أتاحت إمكانية للتعرف على ميكانيكية إنتاج الجسيمات عند الطاقات العالية.