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Angular Distribution of Gray Particles in High Energy $\nu\mu$- Ne Interaction

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التوزيع الزاوي للجسيمات الرمادية فى تفاعل $\nu\mu$- Ne ذي الطاقة العالية

تم بحث التوزيع الزاوي للجسيمات الرمادية(بروتونات تتراوح طاقتها بين ٣٠ –٤٠٠ ميف) المنبعثة من تفاعل الهيدرون بالنواة عند طاقة عالية . وقد افترض أن الجسيمات الرمادية ناتجة من الشلال الداخلي للنواة عن مرور هيدرون ساقط على النواة. وقد ركزنا دراستنا على الشلال الناتج من اصطدام وحيد لقذيفة ساقطة، كتفاعل النيترينو بالنواة عند طاقة عالية، حيث إن هذا التفاعل خال من مزيد من التصادمات للقذائف مع النويات داخل النواه . وقد استخدمنا تقريب جلوبر فى صياغة نموذجنا المقترح لتفسير هذه الظاهرة. وقد وجدنا ان الجسيمات الرمادية تظهر فقط من الجيلين الاول والثاني من أجيال الشلال ، وقد تم حساب التوزيع الزاوي لها.كما توافق حساب <θ> و <cosθ> مع البيانات المعملية المتاحة بشكل مرض .

400 MeV) $\leq E \leq$The angular distribution of the gray particles (protons in the energy range 30 emitted in the interaction of high energy hadrons with nuclei are investigated here. Gray particles"g particles" are assumed to result from the intranuclear cascade initiated by the passage of the incident hadron through the nucleus. We focus our study on the case where the cascade results from a single collision suffered by the projectile. Such reaction,which are free from higher successive projectile target nucleon collisions, are believed to occur in high energy neutrino-nucleus interaction. The proposed model is formulated in the frame work of Glauber approximation.It is found that the grey is particles arise only from the first two generations of the cascade, their angular distribution calculated here .The $< \theta >$ and $<\cos\theta>$ are found to agree satisfactorily with available experimental data .

Key words : Angular distribution, Glauber,intranuclear cascade, gray particles, GN1, GN2.

INTRODUCTION

Over the past few years interest has been growing in high energy hadron nucleus (hA) interaction and a vast amount of experimental data has already been accumulated. The reason is that , the mechanism of the particle production in nuclei is still in much debate(Tosson *et al.* 1994).Many theoretical models picture the hA interaction as a sequence of independent hA collisions inside the nucleus. Thus the number of collisions, ν , encountered by the incident hadron is used in these models as a basic parameter to describe the particle production on nuclei. The commonly known approach is to deduce ν from the number of produced "gray particles" N_g. These are mainly recoil target protons in the momentum range 0.2 ÷ 1 GeV/c (energy range $30 \leq E \leq 400$MeV). Their angular distribution peaks in the forward direction, and they are emitted during or shortly time after the passage of the leading hadron. They are therefore close to the primary sequence (pre-equilibrium stage) of the interaction and thus reflcted to bear important information about the interaction mechanism. To be more specific if the N_g distribution for a single colision (ν =1) is known , then the distribution for any other ν value can be constructed in an incoherent manner. Morover , the final state hadronic system in the single collision will reflect only the interanuclear cascade and thereby eases the interpretation of the peocess.

In this paper the charge current neutrino-nucleus (ν_μ A) interaction is foucused ,e.g

$$\nu_\mu + A \rightarrow \mu^- + \text{hadrons}, \qquad (1)$$

and the intranuclear cascade model is developed to calculate the angular distribution of g particles. In the following the description of the proposed model formulated in the frame work of Glauber approximation (Gliauber 1959) is pesented. Results of calculations and comparison with the experimental data as well as previous theoretical approches are clarified.

MODEL AND FORMULATION

The subsequent intranuclear cascade of ν_μ A interaction can be pictured as follows :

(i) The incident high energy neutrino approches the target nucleus at an impact prameter $\bar{b}$. As it passses through the nucleus, it may interact with a nucleon and disappears. The resulting muon does not reinteract in the nucleus (Griffiths 1987). The final state will thus reflect the intranuclear cascade. In such a reaction,neutrion interacts with a quark in a target nucleon via weak interaction basis. The resulting quark, considered as a leading particle system (LPS) may rescatter in the nucleus as a single quark befor it disintegrate into a meason. This LPS is estimated to have a negligable effect on the Ng production (Enaiah 2000). We are thus left with the struck nucleon which recoils inside the nucleus. This nucleon constitutes the primary of the first generation "GN1". It has a 50% chance to pass the velocity window $0.3 < \beta < 0.7$ for gray particles.It is , therefore, rather fast and travels mostlly in the forward direction. We shall assume for simplicity that they travel along the same impact parameter $\bar{b}$ as the projectile.

(ii) The primary nucleon rescatters with other nucleons yielding the second generation "GN2" . All protons from this generation are counted as gray particles. Pions from the decay of the probably excited primary nucleon are usually too slow to produce gray particles in a meson-nucleon collision.

(ii) The secondaries collide with other target nucleons to produce the third generation and so until a compond nucleus is formed and decay from energy degredation estimates (Hufner 1987) . It can be shown that the third and higher order generations contribute only to the black particles ($\beta < 0.3$) resulting from the final stage of the reaction (evaporation of the final nucleus). They are therefore also left out.

The visulization of the $\nu_\mu A$ interaction is represented schematiclly in Fig (1).

The above model can be formulated mathematically for $\nu_\mu A$ interaction as follows: The projectile neutrino characterized by the trajectory $\bar{r} = (\bar{b}, z)$ interacts with a target nucleon at z_1, $(-\infty < z_1 < \infty)$ and vanishes . The probability that this nucleon will emerge as a gray proton will be noted as P_γ . It is just the product of the probability P_p that it will recoil as a proton and the probability P_g (~ 0.5) that it will be gray (Enaiah 2000).

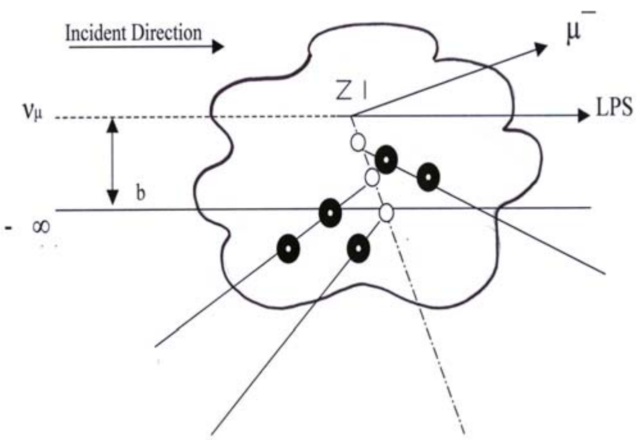

Fig.1 : The intranuclear cascade intiated by a very high energy neutrino.The incident neutrino strikes at Z1 . The recoiling primary nucleon(------)collide with secondary nucleons (○) . Tertiary collisions are denoted by (◉) .

$$P_\gamma = P_p P_g \qquad (2)$$

To determine P_p oneshould notice that the final state nucleon is a proton in 50% of charge-current interactions with an neutrino and in 100 % of the interaction with proton ,i.e

$$p_p = \frac{q\sigma_{\nu p} + 0.5(1-q)\sigma_{\nu n}}{\sigma_{\nu p} + \sigma_{\nu n}} \qquad (3)$$

which gives P_p =1/3 for q = charge Z/A ,i.e. for Z = A/2 nuclei (light nuclei) . Thus the number of the gray proton,n, from GN1 is either zero or one. The primary nucleon rescatters from N1 target nucleons GN2 of which N2 are gray protons. The number of gray particles from this event is therefore

$$N_g = n + N_2 \qquad (4)$$

The probability for this event is

$$I(\bar{b}, N_1, n, N_2) = \int e^{-\sigma_\nu T(-\infty, z_1)} \frac{dz_1}{\lambda_\nu} Q_1(n)\, I_{N1, N2}(\bar{b}, z_1) \qquad (5)$$

The first factor, under the integration sign ,represents the probability for no projectile interaction uptill z_1. The second factor namely dz_1/λ_ν is the probability that the neutrino nucleon interaction takes place between z_1 and z_1+dz .The main-free-path of λ_ν at the point ($\bar{b}$,z) is given by

$$\frac{1}{\lambda} = \sigma_\nu \rho(\bar{r}) \qquad (6)$$

where $\rho(\bar{r})$ is the target nuclear density normalized to the mass number A, and nuclear thickness

$$T(\bar{b}) = T(-\infty,z_1)+T(z,\infty) = \int_{-\infty}^{\infty} dz/d\lambda \qquad (7)$$

The third factor, $Q_1(n)$,is the probability of whether the struck nucleon will recoil as a gray proton or not (n= 0,1).

The final factor, gives the probability that the recoiling struck nucleon travelling from z_1 to ∞ (with impact parameter $\bar{b}$) will collide N_1 times , out of which N_2 are gray protons (Enaiah 2000, Tosson *et al.* 1994),i.e,

$$I_{N1,N2}(\bar{b},z_1)=\left\{\left(\frac{[\sigma T(z_1,\infty)]^{N1}}{N_1!}\right)e^{-\sigma T(z1,\infty)}\right\}\binom{N1}{N2}q^{N_2}(1-q)^{(N_1-N_2)} \qquad (8)$$

where σ is considered as an effective cross-section which was found from fitting the experimental <N_g> values in high-energy hA interaction (Tosson *et al.* 1994)

$$\sigma = 30 \pm 3 \text{ mb} \qquad (9)$$

The probability for N_g gray particles to be observed in the interaction along an impact parameter $\bar{b}$ is thus :

$$H(N_g,\bar{b}) = \sum_{N_1,n,N_2} \delta(N_g-n-N_2) I(\bar{b},n,N_1,N_2) \qquad (10)$$

Carrying out the summation over N_1 and N_2 one gets

$$H(N_g,\bar{b}) = \sum_{n=0,1}^{Min(Ng,1)} Q(n)\int \exp[-\sigma_v T(-\infty,Z1)]\frac{dz1}{\lambda_v}\frac{(q\sigma T(z1,\infty))^{Ng-n_o}}{(Ng-n_o)!} \exp[-q\sigma T(z1,\infty)]$$

(11)

As mention above $\sum_{n=0,1}^{Min(Ng,1)} Q(n)$ will equal 1. Now let ,

$$N_g - n_o = \mu$$

equation (11) will take a form

$$\mathrm{H}\,(\mathrm{Ng},\, \bar{b}) = \int e^{-\sigma T(-\infty, z1)} \frac{dz_1}{\lambda_\nu} \frac{\left[\sigma_N T(z_1,\infty)\right]^{\mu}}{\mu!} e^{-\sigma_N T(z_1,\infty)}$$

(12)

The partial cross section (geometrical factor) for primary struck nucleon to suffer μ secondery collisions for the single neutrino interaction G_μ is ginen by

$$G_\mu = \int d^2 b\ \ \mathrm{H}\,(\mathrm{Ng},\, \bar{b}) \tag{13}$$

Similary the geometrical factor Gμη represents the partial cross section for μth secondary to suffer η tertiary collisions is given by

$$G_{\mu\eta} = \mu I_\eta G_\mu \tag{14}$$

where,

$$I_\eta \cong \frac{\left[0.5\sigma T(b=0)\right]^{\eta}}{\eta!} e^{-\frac{1}{2}\sigma T(b=0)} \tag{15}$$

The inclusive cross-section for the production of gray particl "g" of momentum $\bar{p}$ in the ν_μ A reaction may be decomposed in to the sum

$$\frac{d^3\sigma}{d\bar{p}^3} = p_p \sum_\mu G_\mu D(\bar{p}) + \sum_\mu \sum_\eta G_{\mu\eta} D_{\mu\eta}(\bar{p}) \tag{16}$$

where Dμ (Dμη)gives the corresponding dynamical factor in the first(second) generation.The former is taken to be a Poisson like form,while the latter is taken to Gaussian as in Ref.(Hufner & Knoll 1977) (see the Appendix).

$$R(\bar{p}) = \frac{1}{(2\pi)^{\frac{3}{2}}} \frac{1}{\langle\sigma_{11}{}^2\rangle^{\frac{1}{2}}} \frac{1}{\langle\sigma_\perp{}^2\rangle^{-}} \exp\left(\frac{-(p_{11} - \langle p_{11}{}^2\rangle)}{2\langle\sigma_{11}{}^2\rangle} - \frac{p_\perp{}^2}{2\langle\sigma_\perp{}^2\rangle}\right)$$

(17)

where

$$p_{11} = p\cos(\theta) \qquad , \qquad p_{\perp} = p\sin(\theta)$$

When this equation is integrated over the momentum values,gives the angular distribution.i.e,

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\frac{d\sigma}{d(\cos\theta)}$$
$$= \sum_{\mu} G_{\mu} \int_{0}^{\infty} R_{\mu}(\overline{p}) p^2 dp + \sum_{\mu}\sum_{\eta} \mu I_{\eta} G_{\mu} \int_{0}^{\infty} R_{\mu\eta}(\overline{p}) p^2 dp$$
$$= \sum_{\mu} G_{\mu}[R(\theta) + \mu \sum_{\eta} I_{\eta} R_{\mu\eta}(\theta)] \qquad (18)$$

where,

$$R(\theta) = \int_{0}^{\infty} R_{\mu\eta}(\overline{p}) p^2 dp$$

In the integration over momentum values,care should be taken that momentum ranges 0.2 ÷ 1 GeV/c (energy range 30≤ E ≤ 400 Mev).

COMPARISON WITH EXPERIMENT

The calculations for the angular distibution of g particles produced in νμA reaction is shown in Fig. (2), (notice that the angular distribution is practically dominated by secondaries).This Fig. represents a comparison of the present calculation with those of the Monte Carlo cluster model (Bogatskaya *et al.* 1977).

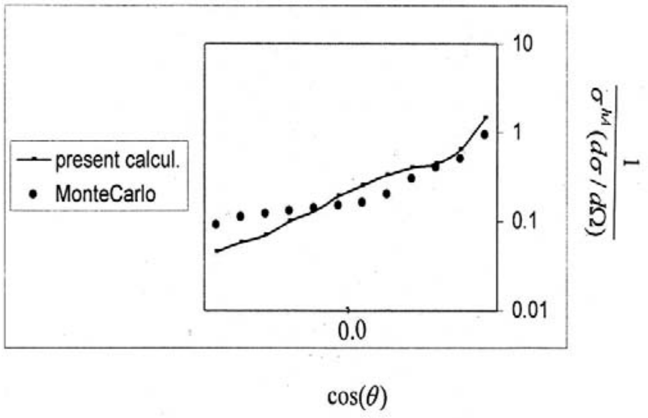

Fig. 2 : Angular distribution of g particles in ν_μ-Ne interaction.Data taken from Ref.[3].

On the whole, the present approach gives the best obtained agreement (in the shape and magnitude) with the experiment (Bogddanowicz *et al.* 1963). I condider this agreement is an additional justification that g particles are only produced from the first and second generation and mostly second generation. Table 1 summarizes the present calculation of the mean emission angle $<\theta>$ and $<\cos\theta>$ for the g particles from GN1 and GN2 with the corresponding experimental average values.

Table 1. The present calculation with corresponding experimental values

	Present calculation	Experiment
$<\theta>$(total) (GN2)	58.5° 76.5°	67± 2°
$<\cos\theta>$ (total) (GN2)	0.44 0.20	0.32±0.01

Appendix
The Dynamic Factirs Dμ And Dμη

Guided by the Gluber result (Hufner & Knoll 1977) , the factor D_μ(**p**) and $D_{\mu\eta}$ (**p**) describing the momentum distributions for GN1 and GN2 are taken to be Gaussian,

$$D_i(\vec{p}) = \left[(2\pi)^{3/2} \langle \sigma_{11}^2 \rangle_i^{\frac{1}{2}} \langle \sigma_\perp^2 \rangle_i \right]^{-1} \exp\left[-\frac{\left(p_{11} - \langle p_{11} \rangle_i\right)^2}{2\langle \sigma_{11}^2 \rangle_i} - \frac{p_\perp^2}{2\langle \sigma_\perp^2 \rangle_i} \right] \qquad \text{(A-1)}$$

Where the subscript i stands for either μ or $\mu\eta$. The mean momenta for the first and second generations satisfy,

$$\langle P_\| \rangle_\mu = (1 - \phi_1)^\mu \langle P_\| \rangle_o$$

$$\langle P_\| \rangle_{\mu\eta} = (1 - \phi_2)^\eta \langle P_\| \rangle_{\mu o} \qquad \text{(A-2)}$$

where,

$$\langle P_\| \rangle_{\mu o} = \phi_1 (1 - \phi_1)^{\mu-1} \langle P_\| \rangle_o \qquad \text{(A-3)}$$

The parameter $\phi_1(\phi_2)$is the fraction of momentum lost by the primary (secondary) recoiling nucleon in a collision with a secondary (tertiary) nucleon. The recursion relations for the widths are rather more complicated,

$$\langle \sigma_\|^2 \rangle_\mu = (1 - \phi_1 - \beta_1) \langle \sigma_\|^2 \rangle_{\mu-1} + (\phi_1 - \beta_1)(k_F^2/5)$$
$$+ \beta_1 [\langle \sigma_\perp^2 \rangle_{\mu-1} + (k_F^2/5)]$$
$$+ (\phi_1 - \phi_1^2 - \beta_1) \langle P_\| \rangle_{\mu-1}^2 \qquad \text{(A-4a)}$$

$$\langle \sigma_\perp^2 \rangle_\mu = (1 - \phi_1 - (\beta_1/2)) \langle \sigma_\perp^2 \rangle_{\mu-1} + (k_F^2/5)(\phi_1 - (\beta_1/2))$$
$$+ (\beta_1/2)[\langle \sigma_\|^2 \rangle_{\mu-1} + (k_F^2/5) + \langle P_\|^2 \rangle_{\mu-1}] \qquad \text{(A-4b)}$$

$$\langle \sigma_\|^2 \rangle_{\mu\eta} = (1 - \phi_2 - (\beta_2)\langle \sigma_\|^2 \rangle_{\mu,\eta-1} + (k_F^2/5)(\phi_2 - \beta_2)$$
$$+ (\beta_2[\langle \sigma_\perp^2 \rangle_{\mu,\eta-1} + (k_F^2/5)]$$
$$+ (\phi_2 - \phi_2^2 - \beta_2) \langle P_\| \rangle_{\mu,\eta-1}^2 \qquad \text{(A-4c)}$$

$$\left\langle \sigma_{\perp}^{2} \right\rangle_{\mu\eta} = (1 - \phi_2 - (\beta_2/2)) \left\langle \sigma_{\parallel}^{2} \right\rangle_{\mu,\eta-1}$$

$$+ (k_F^2/5)(\phi_2 - \beta_2/2) + (\beta_2/2)[\left\langle \sigma_{\parallel}^{2} \right\rangle_{\mu,\eta-1}$$

$$+ (k_F^2/5) + \left\langle P_{\parallel} \right\rangle_{\mu,\eta-1}^{2}] \qquad \text{(A-4d)}$$

where k_F is the Fermi momentum (~260 MeV).

The initial values for Eqs. (A-2 and A-4) are,

$$\left\langle P_{\parallel} \right\rangle_{o} \cong 0.5 \div \text{GeV}/c,\ \left\langle \sigma_{\parallel}^{2} \right\rangle_{o} = k_F^2/5,$$

$$\left\langle \sigma_{\perp}^{2} \right\rangle_{o} \cong 0.08\ (\text{GeV}/c)^2 \qquad \text{(A-5)}$$

and,

$$\left\langle \sigma_{\parallel}^{2} \right\rangle_{\mu o} = (k_F^2/5)\ (1 - \phi_2 - \beta_1)(\phi_1 - \beta_1)\left\langle \sigma_{\parallel}^{2} \right\rangle_{\mu,\eta-1}$$

$$+ \beta_1[\left\langle \sigma_{\perp}^{2} \right\rangle_{\mu-1} + (k_F^2/5)]$$

$$+ (\phi_2 - \phi_1^2 - \beta_2)\left\langle P_{\parallel} \right\rangle_{\mu-1}^{2} \qquad \text{(A-6)}$$

$$\left\langle \sigma_{\perp}^{2} \right\rangle_{\mu o} = (k_F^2/5)(1 - \phi_1 - (\beta_1/2)) + (\phi_1 - (\beta_1/2))\left\langle \sigma_{\perp}^{2} \right\rangle_{\mu-1}$$

$$+ (\beta_2/2)[\left\langle \sigma_{\parallel}^{2} \right\rangle_{\mu-1} + (k_F^2/5) + \left\langle P_{\parallel} \right\rangle_{\mu-1}^{2}] \qquad \text{(A-7)}$$

In our calculations we have taken,

$$\phi_1 = \phi_2 = 0.25 \quad \text{and} \quad \beta_1 = \beta_2 = (2\phi/3). \qquad \text{(A-8)}$$

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