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B.Z.Kopeliovich

NUCLEAR OPACITY FOR NEUTRINOS AT SMALL Q^2

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The striking result of the past year in the high-energy physics was the first observation of the nuclear shadowing in the neutrino-nucleus interactions at small Q^2 by BEBC WA59 Collaboration[1,2]. It has been predicted long ago in the pioneering paper[3] by Bell, who started from the Adler relation[4] (AR) connecting the neutrino and pion interactions. These ideas stimulated investigations[5,6] of photonuclear reactions, which have confirmed the shadowing of photon interactions. Though the detection of the axial current shadowing is last but not least. We discuss here some peculiarities of the rich pattern of the small Q^2 neutrino-nucleus interaction and present an adequate quantitative description.

Our principal observation is the following. The nuclear shadowing of axial current interaction has an origin quite distinct from that of the vector one. The latter comes from the vector meson dominance, and the energy scale for saturation of shadowing is determined by ρ-meson mass and is high: $2\nu/(Q^2+m_\rho^2)\gg\lambda$, where $-Q^2$ and ν are the four-momentum squared and the energy of the hadronic fluctuation, λ is the absorbtive length in nuclear medium.On the contrary, the axial current is characterized by early onset of nuclear screening at energies, determined by pion mass rather than mass of the axial-vector meson. This has been shown first by Bell[3] within his optical model, and it can be deduced immediately from the AR. This cannot be interpreted in the spirit of the pion dominance because pion spontaneous emission by neutrino in the vacuum is forbidden by the transversiality of lepton current[7,8]. Neutrino can only emit heavy hadronic fluctuation for a much shorter time interval. Thus, at first sight, at low energy the nuclear shadowing seems to disappear, i.e. the AR for νA scattering should be strongly violated. This conclusion doesn't depend on the pion mass. On the other hand, in the chiral limit[11], when pion is a true Golstone particle, the AR is exact for nuclear targets too.

The key to this puzzle is the following: the time of life of hadronic fluctuation is enlarged dramatically inside the nuclear matter due to interaction of neutrino with a medium and diffractive production of pions. Bell[7] has found an early nuclear shadowing within his optical model. We demonstrate this in the generalized Glauber-Gribov[9,10] theory and obtain more elaborate and accurate formulae, compared to given by the Bell's optical model, used in Refs.1,2. Two approaches differ considerably in the intermediate energy region, whereas both coincide at high energies if only pion is taken as an intermediate state. The latter is trivial as the answer is given simply by the AR for the neutrino-nucleus total cross section. The inclusion of other possible intermediate states results in visible deviation from the optical model predictions at high energies.

Let us start with contributions to the neutrino-nucleus total cross section originating from the graphs shown in fig.1. We consider the elastic scattering, bearing in mind the optical

Fig.1. The lowest order graphs containing diffractive production of pion by axial-current.

theorem. Fig.1a corresponds to the elastic scattering of weak axial current, J_A, on a bound nucleon. It is not screened by nucleus, due to smaliness of J_A-N cross section and produces a volume effect

$$\sigma^{(1)}_{tot}(\nu A) = A\sigma_{tot}(\nu N). \qquad (1)$$

The contribution shown in fig.1b is the first inelastic correction which is generated by the diffractive transition $\nu N \to l\pi N$. It equals to (compare with ref.[12])

$$\sigma^{(2)}_{tot}(\nu A) = -2|f_{j\pi}|^2 \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \rho(\vec{b},z_1) \int_{-\infty}^{z_1} dz_2 \rho(\vec{b},z_2) \exp[-iq^{\pi}_{L}(z_1 - z_2)]$$

$$\exp[-f_{\pi\pi} T(\vec{b},z_2,z_1)]. \qquad (2)$$

Here b,z are the impact parameter and the longitudinal coordinate; $\rho(b,z)$ is the nuclear density; $T(\vec{b},z_2,z_1) = \int_{z_2}^{z_1} dz \rho(\vec{b},z)$, $T(\vec{b},-\infty,\infty)$ is the nucleus profile function; $f_{\pi\pi}$ and $f_{j\pi}$ are the imaginary parts of $\pi N \to \pi N$ and of $\nu N \to l\pi N$ forward scattering amplitudes (the normalization $\sigma_{tot} = 2\mathrm{Im}f(0)$ is used); $q^{\pi}_{L} = (Q^2 + m^2_{\pi})/2\nu$ is longitudinal momentum transferred to the nucleon.

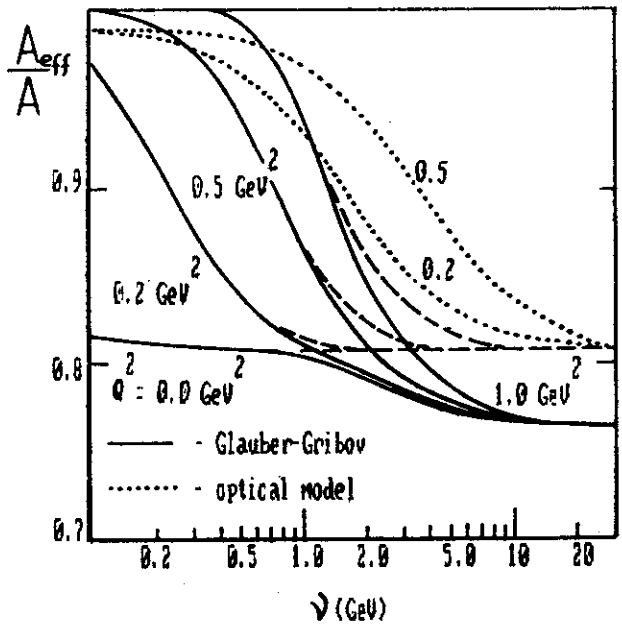

Fig.2. Cross section per nucleon, A_{eff}/A, as a function of the energy transfer ν, vs the four-momentum transfer squared Q^2. The full curves are the predictions based on the Glauber-Gribov theory. The dashed lines demonstrate the contribution of the graphs shown in fig.1. The dotted lines are the predictions derived from the Bell's optical model.

It is instructive to demonstrate the cancellation of the volume terms in the high-energy limit of $q_L^{\pi} \to 0$. In this case integrals in (2) are computed explicitly

$$\sigma_{tot}^{(2)}(\nu A) = - \frac{|f_{j\pi}|^2}{|f_{\pi\pi}|^2} \left\{ A\, \sigma_{tot}(\pi N) - \sigma_{tot}(\pi A) \right\} , \qquad (3)$$

where

$$\sigma_{tot}(\pi A) = 2\int d^2\vec{b} \left\{ 1 - \exp[-\tfrac{1}{2}\sigma_{tot}(\pi N) T(\vec{b},-\infty,\infty)] \right\} .$$

Now, it is time is ripe for AR enter the game: written in the form $\sigma_{tot}(\nu N)/|f_{j\pi}|^2 = \sigma_{tot}(\pi N)/|f_{\pi\pi}|^2$, it provides the cancellation of the volume terms in the sum of expressions (1) and (2).

The degree of nuclear shadowing of the neutrino interactions is demonstrated in fig.2. The value of $A_{eff} = \sigma_{tot}(\nu A)/\sigma_{tot}(\nu N)$ for nucleus Ne is computed in accordance with eqs. (1),(2) using nuclear density in the Woods-Saxon form. One sees that the larger is Q^2 the later on saturation of shadowing comes.

Let us compare the present approach with the Bell's optical model (OM). The equation[3,7] for the amplitude of the virtual hadron wave propagating through the nuclear matter, can be solved explicitly, resulting in following expression for the cross section

$$\sigma^{(OM)}_{tot}(\nu A) = 2f^2_{j\pi} \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \rho(\vec{b},z_1) \int_{-\infty}^{z_1} dz_2 \rho(\vec{b},z_2) \, \frac{q^{\pi}_L \exp[-f_{\pi\pi} T(\vec{b},z_2,z_1)]}{q^{\pi}_L - i f_{\pi\pi}\rho(\vec{b},z_2)}$$

$$+ \frac{f^2_{j\pi}}{f^2_{\pi\pi}} \sigma_{tot}(\pi A) . \qquad (4)$$

Numerical results are plotted in fig.2 by the dotted line. Comparison with the previous calculation shows that optical model underestimates considerably nuclear opacity for neutrinos at intermediate energies.

There are some other inelastic corrections as well. Some examples shown in fig.3 are connected with the possibility of the

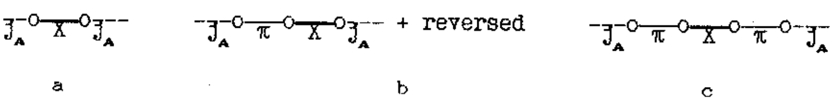

Fig.3. The graphs taking into account the pion diffraction dissociation in the intermediate state.

neutrino diffraction dissociation, i.e. the process $\nu N \to lXN$. It is interesting that volume terms corresponding to these graphs cancel each other. The rest can be written in the form

$$\sigma^{(3)}_{tot}(\nu A) = -4\pi \frac{f^2_{j\pi}}{f^2_{\pi\pi}} \int d^2\vec{b} \quad \exp[-f_{\pi\pi} T(\vec{b},-\infty,\infty)] \int_{-\infty}^{\infty} dz_1 \rho(\vec{b},z_1) \int_{-\infty}^{z_1} dz_2 \rho(\vec{b},z_2)$$

$$\int_{(3m_\pi)^2}^{\infty} dM^2 \left[\frac{d\sigma_{DD}(\pi N)}{dM^2 dt}\right]_{t=0} \exp[-i q^X_L (z_1 - z_2)] \qquad (5)$$

Here $d\sigma_{DD}(\pi N)/dM^2 dt|_{t=0}$ is the forward diffraction dissociation cross section; we put $f_{XX} = f_{\pi\pi}$ for the sake of simplicity; the

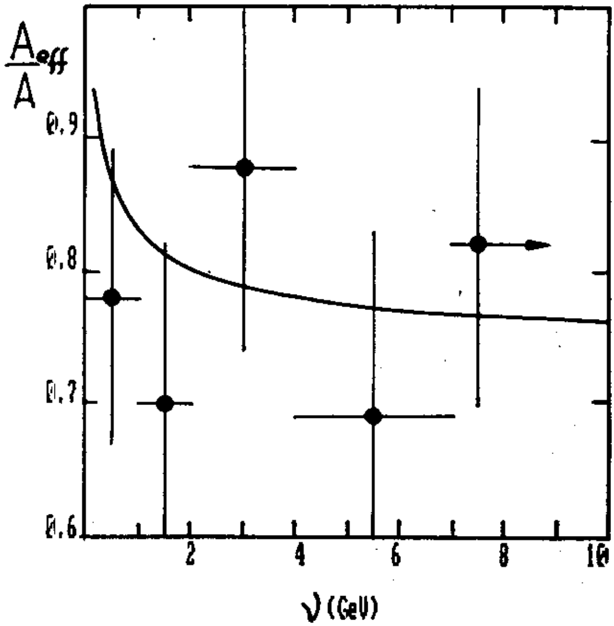

Fig.4. Neon/deuterium ratios of cross sections per nucleon, A_{eff}/A, with x below Ø.2 and Q^2 below Ø.2 $(GeV/c)^2$ shown as a function of the energy trasfer ν. The curve is a prediction of the Glauber-Gribov theory.

energy transferred, ν, is taken high enough in order to neglect q_L^{π}. Note that expression (5) coincides with the first inelastic correction[12] to $\sigma_{tot}(\pi A)$ up to a factor of $f^2_{j\pi}/f^2_{\pi\pi}$. It can be shown that consideration of all possible intermediate states in νA scattering is equivalent to summation to all orders of inelastic corrections to $\sigma_{tot}(\pi A)$ included in AR. This statement is a trivial consequence of AR in the asymptotics but it is true at any energy. Analogous conclusion was proved for the vector current in Ref.13.

To estimate correction (5) we have used the results of phenomenological fit[14] to the experimental data on $d\sigma_{DD}(\pi N)/dM^2dt$ in the resonance energy-range, supplemented by the triple-Regge tail. The solid and dashed curves in fig. 2 show the shadowing factor A_{eff}/A calculated with this correction and without it.

In order to compare the calculations with the experimental data[1] shown in fig.4, we added in a contribution of the vector current, and averaged both over the range $0<Q^2<0.2(\mathrm{GeV}/c)^2$. A good agreement is observed.

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References

1. BEBC WA59 Collaboration, Allport P.P. et al., paper submitted to the XIXth Int. Symp. on Muliparticle Dynamics, Arles, France, 1988
2. Marage P., report submitted to the XIIIth Int. Conf. on Neutrino Phys. and Astrophys., Boston, 1988
3. Bell J.S., Phys. Rev. Lett. 1964, 13, p.57
4. Adler S., Phys. Rev. 1964, 135, p.963
5. Ross M., Stodolsky L., Phys. Rev. 1966, 149, p.1172 .
6. Drell S.D., Trefil S. Phys. Rev. Lett. 1966, 16, p.552; ibid, p.832
7. Bell J., Lectures in Particles and Fields, edited by H.H.Aly, (New York, Gordon and Breach Science Publishers), 1969, p.323
8. Piketty C., Stodolsky L., Nucl. Phys., 1970, B15, p.571
9. Glauber R.J., Lectures in Theoretical Physics, Vol. 1, 1958, edited by W.E.Brittin and L.G.Dunham (New York, N.Y., 1959)
10. Gribov V.N., Zh.Eksp.Teor.Fiz., 1969, 56, p.892 ; Sov. Phys. JETP, 1969, 29, p.483
11. We ignore the lepton masses and the axial anomaly contributions. The former can be easily taken into account[7,8], the latter is negligibly small.
12. Karmanov V., Kondratyuk L.A., Pis'ma Zh.Eksp.Teor.Fiz. 1973, 18, p.266 ; Sov. Phys. JETP Lett. 1973, 18, p.451
13. Bertocchi L., Treleani D., Nuovo Cimento 1979, A 54, p.113
14. Dakhno L.G., Yad. Fiz. 1983, 37, p.993

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