national accelerator laboratory

THY-14
1971

SEARCH FOR NEW VECTOR MESONS BY DIFFRACTIVE PHOTOPRODUCTION AT NAL

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Operated by Universities Research Association Inc. Under Contract with the United States Atomic Energy Commission

ABSTRACT

If yet unobserved vector meson existed, it can be seen most easily by diffractive-photoproduction on nuclei using photon beam at the National Accelerator Laboratory. We have considered the problem of coherent production of such a particle on nuclei, taking into account the mixing between ρ and the new vector meson to arbitrary order. The method used here can be generalized to describe coherent scattering of hadrons and nuclei. It will be shown that the interference effect reduces the production of the new vector meson considerably and that A dependence of the production cross section plays an important role.

INTRODUCTION

In order to formulate the concept of vector meson dominance, it is crucial to know whether or not there are other vector mesons besides ρ, ω, and ϕ through which photon interacts with hadrons. Since ρ, ω, and ϕ are produced diffractively when a high-energy photon beam strikes a nucleus, we expect such mesons to be also photoproduced diffractively. The diffractive production has the advantage that the produced particle must have similar quantum numbers as the photon and, furthermore, nondiffractive background is orders of magnitude smaller in the forward direction. We shall call the new vector meson v. An attempt to photoproduce v was made and no such meson was found with its mass $m_v \lesssim 2$ GeV.[1,2] At presently available energies, 2 GeV is an upper limit on the mass for diffractive production.

Since a photon beam with energy as high as 300 GeV will be available at National Accelerator Laboratory, questions on the existence of v with $m_v \lesssim 7$ GeV will be settled soon. Some theoretical investigations must be made before such an experiment to look for v is planned since there are effects which may greatly reduce chances of detecting v even if it existed. For example,

(1) Absorption effect. Since v is a strong-interacting particle, the final-state interaction will decrease probability of observing v. Such an effect is seen in ρ photoproduction.[3]

(2) Interference effect. Since ρ and v have the same quantum

numbers, these two states will mix with each other.[4] This effect may be such that probability for observing v is greatly reduced.

Since the dynamics of v is unknown, we shall not be able to give an absolute statement on these possibilities. We are able, however, to express the cross section for

$$\gamma + \text{nucleus} \rightarrow v + \text{nucleus}$$

in terms of four unknown parameters m_v, f_v,

$$\sigma_v = v + p \text{ total cross section, and}$$

$$\frac{ik}{4\pi}\ \Sigma = v + p \rightarrow \rho + p \text{ forward scattering amplitude,}$$

where p stands for a proton and k is the incident momentum of the photon. We expect Σ to be real constants at high energy. Result of the calculation indicates that for any value of Σ, the interference effect reduces the diffractive production of v considerably and, depending on the value of σ_v, the absorption effect will be appreciable. It also indicates, however, that if v existed with $m_v \lesssim 7$ GeV, we should be able to observe them at the National Accelerator Laboratory.[5]

FORMULATION

The theory of photoproduction on nucleus is a many-body body problem and is very complex depending on the detail required to describe the theory. Therefore, the main problem is to realize the limitation placed on the experimental measurement which is to be compared with the theory and reduce the complexity of the problem by well chosen series of approximations. The general treatment of the scattering theory at high energy is given by Glauber[6] and subsequent application to photo-ρ production on nuclei neglecting all correlation of nucleons has been shown to be quite adequate for explaining present experimental data. The basic set of assumptions successfully used in ρ production, therefore, should also be applicable in photo-v production.

Let us consider the process of photo-ρ production in absence of v and compare the problem with that of photo-v production. In Fig. 1 we have drawn diagrams for ρ production. The time runs from left to right. The solid line corresponds to various nucleons in the nucleus. Note the diffractive production implies that a majority of scattering is forward, $\theta \sim 1/ka$ being the width of the forward peak, where a is the effective radius of a nucleon, k is the momentum of the photon beam. Taking k to be 200 GeV/c, a to be 1 fermi, $1/ka \sim 1/40$. So, to a good approximation, we can take each scattering of ρ on nucleon to be forward. Thus, for each impact parameter of the photon, we have a one-dimensional problem. To show this, nucleons are drawn in a straight line. Since the backward direction is negligible, each nucleon participates in the scattering once. The break in the solid line indicates that they are different nucleons.

Now consider the v-photo production. The photon creates either ρ or v (we denote it by α) at $\vec{R} = (\vec{b}, z)$ by scattering diffractively with one of the nucleons, where $\vec{b}$ denotes the impact parameter and the z axis is in the direction of the beam. To lowest order in $e^2/4\pi$, the photon no longer enters into the problem. Then α scatters diffractively with each of the other nucleons in the nucleus, but we must consider the possibility that v and ρ are mixed arbitrarily many times. The processes mentioned here are shown in Fig. 2.

For simplicity let us consider a problem in which the photon scatters diffractively with the nucleon j at r_j, α is created at $\vec{R} = (\vec{b}, z)$ and in turn scatters with nucleon i at r_i and turns into β, where α and β again stand for either ρ or v. This process is shown in Fig. 3. Let $f_{\alpha\beta}(\vec{q})$ denote the scattering amplitude for $\alpha + p \to \beta + p$ with momentum transfer $\vec{q}$ and $\Gamma_{\alpha\beta}(\vec{r})$ to be its Fourier transform.

$$\Gamma_{\alpha\beta}(\vec{r}) = \frac{1}{(2\pi)^{3/2} ik} \int e^{-i\vec{q}\cdot\vec{r}} f_{\alpha\beta}(\vec{q})\, d^3\vec{q} \tag{1}$$

$$f_{\alpha\beta}(\vec{q}) = \frac{ik}{(2\pi)^{3/2}} \int e^{i\vec{q}\cdot\vec{r}} \Gamma_{\alpha\beta}(\vec{r})\, d^3\vec{r}\,. \tag{2}$$

The scattering amplitude for the event is

$$f^{ji}_{\alpha\beta}(Q) = \frac{ik}{(2\pi)^{3/2}} \int d^3\vec{R} \prod_{k=1}^{A} d^3\vec{r}_k \times$$
$$\times\, e^{i\vec{Q}\cdot\vec{R}} U(r_1, \ldots, r_A)^* \Gamma_{\gamma\alpha}(\vec{R} - \vec{r}_j)\, e^{i\chi^{i}_{\alpha\beta}(b, z, q^{\parallel}_{\alpha\beta})} U(r, \ldots, r_A), \tag{3}$$

where $\vec{Q}$ is the momentum transfer between γ and β, $\chi^{i}_{\alpha\beta}(b, z, q^{\parallel}_{\alpha\beta})$ is the phase function describing α + ith nucleon $\rightarrow \beta$ + ith nucleon scattering. $q^{\parallel}_{\alpha\beta}$ is the longitudinal momentum transfer

$$\left[\vec{q}_{\alpha\beta}\right]_{\text{forward direction}} = \frac{m_\beta^2 - m_\alpha^2}{2k}\,\hat{z}.$$

The state of the nucleus is $U(r_1, \ldots r_A)$. To obtain Eq. (3), first note that $\Gamma_{\gamma\alpha}(\vec{R} - \vec{r}_j) \exp\, i\chi^i_{\alpha\beta}(b, z, q^{\parallel}_{\alpha\beta})$ describes the double scattering $\gamma + p \rightarrow \alpha + p$ and $\alpha + p \rightarrow \beta + p$ as a function of $\vec{r}_j$, $\vec{r}_i$, and $\vec{R}$. We then sandwich the above expression by the state of the nucleus, integrate over all the internal nuclear coordinates $\vec{r}_k$ and finally take the Fourier transform to obtain the scattering amplitude. To find $\chi^i_{\alpha\beta}(b, z, q^{\parallel}_{\alpha\beta})$, we write the α + ith nucleon $\rightarrow \beta$ + ith nucleon scattering amplitude

$$f^i_{\alpha\beta}(\vec{q}) = \frac{ik}{(2\pi)^{3/2}} \int e^{i\vec{q}\cdot\vec{b}}\, d^2\vec{b} \;\times$$
$$\times\, e^{iq^{\parallel}_{\alpha\beta} z'}\, U(r_1, \ldots, r_A)^* \,\Gamma_{\alpha\beta}(b - b_i, z' - z_i) U(r_1, \ldots, r_A) dz' \prod_{k=1}^{A} d^3\vec{r}_k. \tag{4}$$

In terms of the phase $\chi^i_{\alpha\beta}(b - b_i, q^{\parallel}_{\alpha\beta})$, the same amplitude can be written as

$$f^i_{\alpha\beta}(\vec{q}) = \frac{ik}{2\pi} \int d^2\vec{b}\, e^{i\vec{q}\cdot\vec{b}} \;\times$$
$$\times\; U(r_1, \ldots, r_A)^* \left[\delta_{\alpha\beta} - e^{i\chi^i_{\alpha\beta}(b - b_i, q^{\parallel}_{\alpha\beta})}\right] U(r_1, \ldots, r_A) \prod_{k=1}^{A} d\vec{r}_k. \tag{5}$$

Comparing Eqs. (4) and (5), we obtain

$$e^{i\chi^i_{\alpha\beta}(b - b_i, q^{\parallel}_{\alpha\beta})} = \delta_{\alpha\beta} - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{iq^{\parallel}_{\alpha\beta} z'}\, \Gamma_{\alpha\beta}(b - b_i, z' - z_i)\, dz'. \tag{6}$$

The $\chi^{i}_{\alpha\beta}(b, q^{\parallel}_{\alpha\beta})$ of Eq. (6) is the phase for the process in which α is present at the entire range of z', $-\infty < z' < \infty$. But, infact, in our process α is created at $\vec{R} = (\vec{b}, z)$, so z' runs for $z < z' < \infty$ and we must cut off the z' integration at z. Then Eq. (3) becomes

$$f^{ji}_{\gamma\beta}(\vec{Q}) = \frac{ik}{(2\pi)^{3/2}} \int e^{i\vec{Q}\cdot\vec{R}}\, U(r_1, \ldots, r_A)^* \, \Gamma_{\gamma\alpha}(\vec{R} - \vec{r}_j) \times$$

$$\times \left[\delta_{\alpha\beta} - \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{iq^{\parallel}_{\alpha\beta} z'}\, \Gamma_{\alpha\beta}(b - b_i, z' - z_i)\, dz' \right] U(r_1, \ldots, r_A) \prod_{k=1}^{A} d^3\vec{r}_k . \quad (7)$$

Using the fact that

$$\int U(\vec{r}_1, \ldots, \vec{r}_A)^* \, U(\vec{r}_1, \ldots, \vec{r}_A) \prod_{k=1}^{A} d^3\vec{r}_k = 1$$

$$\int U(\vec{r}_1, \ldots, \vec{r}_A)^* \, U(\vec{r}_1, \ldots, \vec{r}_A) \prod_{\substack{k=1 \\ k\neq i}}^{A} d^3\vec{r}_k = \rho_i(r_i) \qquad (8)$$

and

$$\int U(\vec{r}_1, \ldots, \vec{r}_A)^* \, U(\vec{r}_1, \ldots, \vec{r}_A) \prod_{\substack{k=1 \\ k\neq i,\, k\neq j}}^{A} d^3\vec{r}_k = \rho_{ij}(r_i, r_j) ,$$

where $\rho_i(r_i)$ is the distribution function for the ith nucleon and $\rho_{ij}(r_i, r_j)$ is the distribution function for jth and ith nucleon, we can rewrite Eq. (7)

$$f^{ji}_{\gamma\beta}(\vec{Q}) = \frac{ik}{(2\pi)^{3/2}} \int d^3R\, d^3r_j\, e^{i\vec{Q}\cdot\vec{R}}\, \Gamma_{\gamma\alpha}(\vec{R} - \vec{r}_j) \times$$

$$\times \left[\delta_{\alpha\beta}\rho_j(r_j) - \frac{1}{\sqrt{2\pi}} \int_z^{\infty} \Gamma_{\alpha\beta}(b - b_i, z' - z_i)\, e^{iq^{\parallel}_{\alpha\beta} z'}\, dz' \rho_{ij}(r_i r_j) d^3r_i \right], \quad (9)$$

where we have integrated over the spectator nucleons, $k = 1, \ldots, A$ $k \neq i,j$. We now make an approximation that $\rho_j(r_j) = \rho(r_j)$ for all j. We have neglected all correlation effect between nucleons. The correlation effect may not be negligible. The accuracy of the experimental measurement, however, does not seem to require nuclear physics considerations at least for low energy photo-ρ production and therefore, we will adopt this approximation. The $\rho(r_i)$ is equal to the average density of the nucleus and
$U(r_1,\ldots Jr_A)^* \; U(r_1,\ldots,r_A) = \prod_{k=1}^{A} \rho(r_k)$. Since
$\Gamma_{\alpha\beta}(\vec{b}-\vec{b}_i z'-z_i) \neq 0$ only in the immediate neighborhood of i th nucleon, for large A, $\rho(r_i)$ varies little over the same region. Then we may make an approximation

$$\int d^3\vec{x}\; d^3\vec{y}\; e^{i\vec{k}.\vec{x}}\; \Gamma_{\alpha\beta}(\vec{x}-\vec{y})\; \rho(\vec{y}) = \int d^3\vec{x}\; e^{i\vec{k}.\vec{x}}\; \rho(\vec{x}) \int d^3y \Gamma_{\alpha\beta}(\vec{x}-\vec{y})$$

$$= \frac{(2\pi)^{3/2}}{ik}\; f_{\alpha\beta}(0) \int d^3\vec{x}\; e^{i\vec{k}.\vec{x}}\; \rho(\vec{x}).$$

Using this, we can rewrite Eq. (9)

$$f^{ji}_{\alpha\beta}(\vec{Q}) = f_{\gamma\alpha}(0)\int d^3\,\vec{R}\;\; e^{i\vec{Q}\cdot\vec{R}}\rho(R)\left[\delta_{\alpha\beta} - \frac{2\pi}{ik}\, f_{\alpha\beta}(0)\int_z^\infty dz'\; e^{iq^{\parallel}_{\alpha\beta}z}\rho(b_1 z')\right]. \quad (10)$$

So far we have been considering a hypothetical problem in which we have turned off interaction of α with all nucleons except the i th nucleon. The 2×2 matrix

$$T^i_{\alpha\beta}(\vec{R}\,) = \begin{pmatrix} 1 - \frac{2\pi}{ik} f_{\rho\rho}(0)\int_z^\infty \rho(b, z')dz', & -\frac{2\pi}{ik} f_{\rho v}(0)\int_z^\infty e^{iq^{\parallel}_{\rho v}z'}\rho(b, z')dz' \\ -\frac{2\pi}{ik} f_{\rho v}(0)\int_z^\infty e^{-iq^{\parallel}_{\rho v}z'}\rho(b, z')dz', & 1 - \frac{2\pi}{ik} f_{vv}(0)\int_z^\infty \rho(b, z')dz' \end{pmatrix} \quad (11)$$

describes the scattering between α and the i th nucleon. Note that $T^{i}_{\alpha\beta}(\vec{R})$ does not depend on "i". That is, it does not depend on which nucleon α scatters from once the nuclear correlation is neglected. The time ordering for interaction with different nucleons does not occur since interaction operations all commutes with each other. We have $f_{\rho v}(0) = f_{v\rho}(0)$ using time reversal invariance. Furthermore, if we assume that all $f_{\alpha\beta}(0)$ become purely imaginary at high energy, $T^{i}_{\alpha\beta}(R)$ is Hermitian. Then, when we include the effect of α scattering with all other nucleons, $T_{\alpha\beta}(R)$ is replaced by $[T(\vec{R})^{A-1}]_{\alpha\beta}$. Let $\chi^{\pm}(\vec{R})$ be the eigen vector for $T(R)$ with eigen value $\lambda^{\pm}(R)$. Denoting

$$T(R)=\begin{pmatrix} a\,, & b \\ b^{*}, & d \end{pmatrix},$$

$$\lambda^{\pm} = 1/2\left(a + d \pm \sqrt{(a-d)^{2} + 4\,|b|^{2}}\right)$$

and interms of eigen vectors $|\chi^{\pm}>$, ρ and v can be written as

$$|\rho> = \frac{(a-\lambda^{-})\sqrt{|b|^{2}+(a-\lambda^{+})^{2}}}{(\lambda^{+}-\lambda^{-})\;b}\,|\chi^{+}> + \frac{(a-\lambda^{+})\sqrt{|b|^{2}+(a-\lambda^{-})^{2}}}{(\lambda^{+}-\lambda^{-})\;b}\,|\chi^{-}>$$

$$|v> = \frac{\sqrt{|b|^{2}+(a-\lambda^{+})^{2}}}{\lambda^{+}-\lambda^{-}}\,|\chi^{+}> + \frac{\sqrt{|b|^{2}+(a-\lambda^{-})^{2}}}{\lambda^{+}-\lambda^{-}}\,|\chi^{-}> \qquad (12)$$

When the state $\chi^{\pm}(R)$ interacts with a nucleon it becomes $\lambda^{\pm}(R)\ \chi^{\pm}(R)$. The influence of A-1 nucleons will be $(\lambda^{\pm}(R))^{A-1}\chi^{\pm}(R)$. Thus effects of all the nucleons can be treated in a trivial way when the nuclear correla- effect is neglected.

The amplitude for photo production of β on a nucleus with the momentum transfer $\vec{Q}$ can be obtained by generalizing Eq. (10).

$$f_{\gamma A\to\beta A(\vec{Q})} = \sum_{\alpha=\rho,v}\ \sum_{j=1} f_{\gamma\alpha}(0)\int d^3\vec{R}\ e^{i\vec{Q}\cdot\vec{R}}\ \rho(R)\left[T(R)^{A-1}\right]_{\alpha\beta}$$

$$= 2\pi A \sum_{\alpha=\rho,v} f_{\gamma\alpha}(0)\int e^{iQ_\beta^{\parallel}z} J_o(kb\Theta)\rho(bz)\left[T(R)^{A-1}\right]_{\alpha\beta} bdbdz \tag{13}$$

where $Q_\beta^{\parallel} = \frac{m_\beta^2}{2k}$, Θ is the angle β makes with respect to the incident photon beam. The second expression is obtained by integrating over the azimuthal angle taking advantage of the cylindrical symmetry.[7]

Denoting

$$\begin{aligned} |\rho> &= E\,|\chi^+> + B\,|\chi^-> \\ |v> &= C\,|\chi^+> + D\,|\chi^-> \end{aligned} \tag{14}$$

where the coefficients stand for those given in Eq. (12), we obtain expressions for photo production of ρ and v on a nucleus from Eq. (13).

$$f_{\gamma A\rightarrow vA}(\Theta) = 2\pi A\int bdbdz\ e^{iq_v^{\parallel}z}\ \rho(b,z)\ J_o(kb\Theta)\ \times \tag{15}$$
$$\times\left\{f_{\gamma\rho}(0)\left[(\lambda^+)^{A-1}E^*C + (\lambda^-)^{A-1}B^*D\right] + f_{\gamma v}(0)\left[(\lambda^+)^{A-1}C^*C+(\lambda^-)^{A-1}D^*D\right]\right\}$$

$$f_{\gamma A\rightarrow\rho A}(0) = 2\pi A\int bdbdz\ e^{iq_\rho^{\parallel}z}\ \rho(b,z)\ J_o(kb\Theta)\ \times$$
$$\times\ \left\{f_{\gamma\rho}(0)\left[(\lambda^+)^{A-1}\,|E|^2 + (\lambda^-)^{A-1}\,|B|^2\right] + f_{\gamma v}(0)\left[(\lambda^+)^{A-1}C^*E+(\lambda^-)^{A-1}D^*B\right]\right\} \tag{16}$$

A similar technique can be used to derive the expression,

$$f_{\rho A\rightarrow vA}(\Theta) = \frac{k}{i}\int bdb\ J_o(k\Theta b)\ (\lambda^{+A}\ \tilde{E}^*\tilde{C} + \lambda^{-A}\ \tilde{B}^*\ \tilde{D}). \tag{17}$$

where $\tilde{E}, \tilde{B}, \tilde{C}, \tilde{D}$ are calculated in the similar way as E, B, C, D respectively with an exception that the lower limit of the integral in the matrix element of Eq. (11), z, is replaced by $(-\infty)$.

II. PARAMETERS

Eqs. (15) and (16) contains parameters, $f_{\gamma\rho}(0)$, $f_{\gamma v}(0)$, $f_{\rho v}(0) = f_{v\rho}(0)$, $f_{\rho\rho}(0)$, $f_{vv}(0)$ where $f_{\alpha\beta}(0)$ is $\alpha + p \rightarrow \beta + p$ scattering amplitude at zero momentum transfer. For $\alpha \neq \beta$, $f_{\alpha\beta}(0)$ is an un-physical amplitude which is obtained by extrapolation from the physical region where $|\vec{q}\,| \geq \left|\frac{m_\beta^2 - m_\alpha^2}{2k}\right|$. $f_{\gamma\rho}(0)$ and $f_{\gamma v}(0)$ can be written in terms of $f_{\rho\rho}(0)$, $f_{vv}(0)$, $f_{\rho v}(0)$ using vector-dominance model as shown in Fig. 4.

$$f_{\gamma\rho}(0) = \frac{e}{f_\rho} f_{\rho\rho}(0) + \frac{e}{f_v} f_{v\rho}(0)$$

$$f_{\gamma v}(0) = \frac{e}{f_\rho} f_{\rho v}(0) + \frac{e}{f_v} f_{vv}(0) \tag{18}$$

Since existence of v is not required by the usual vector-dominance model at present energies we expect $1/f_\rho >> 1/f_v$.

The simplest kind of diffraction theory (scattering from a black disk or simple Pomeranchuck Regge pole exchange) predicts that $f_{\alpha\beta}(0)$ is purely imaginary at high energy. Photo-ρ production data seems to require $\mathrm{Re}\, f_{\gamma\rho}(0)/\mathrm{Im}\, f_{\gamma\rho}(0) \approx .2$ at $k \lesssim 15$ GeV/c. If we were interested only in order of magnitude prediction for the v production, we can set the amplitude to be purely imaginary. Thus using the optical theorem,

$$\frac{4\pi}{ik} f_{\rho\rho}(0) = \sigma_\rho, \quad \frac{4\pi}{ik} f_{vv}(0) = \sigma_v \text{ and define } \frac{4\pi}{ik} f_{\rho v}(0) \equiv \Sigma\,. \tag{19}$$

where σ_ρ and σ_v are ρ p and v p total cross sections respectively. We take σ_ρ, σ_v, and Σ to be independent of energy. This is consistent with the approximation of settting the amplitude to be purely imaginary. From photo-ρ production,[8] we have $\sigma_\rho \approx 26$ mb. Therefore, we have σ_v, Σ, $f_v(0)$ and m_v as unknown parameters.

III Small Σ and Large k Limit

Although we can not apriori restrict ourselves to small Σ and large k, by studying these limits, we gain insights into our general result. In this section we intend to show that, (a) if the absorption of the vector mesons due to scattering with nucleons is very small, i.e., σ_ρ and σ_v is small, the A dependence of the cross section for photoproduction of both ρ and v goes as A^2, (b) if the absorption is large, with ρ dominance $1/f_v = 0$, the A dependence of the cross section for the ρ production is $A^{4/3}$ while A dependence of v-production cross section may be quite different depending on the value for σ_v. On the other hand, if $1/f_v \neq 0$, v-production cross section will have a term which behaves as $A^{4/3}$. We expect therefore that study of A dependence of v-production will be a very sensitive way to measure the parameters f_v and Σ.

As $\Sigma \to 0$, $b \to 0$. To first order in b, we have, from Eq. (12), $\lambda^+ \cong a$, $\lambda^- \cong d$,

$$E^* C = \frac{b}{a-d}\ , \ B^* D = \frac{-b}{a-d}\ , \ |C|^2 \cong 0,\ |D|^2 = 1.\ \text{Then } (\lambda^+)^{A-1} =$$

$$\left(1 - \frac{\sigma_\rho}{2} \int_z^\infty \rho\,(b,z)\,dz\right)^{A-1} \cong e^{-\frac{\sigma_\rho A}{2}\int_z^\infty \rho(b,z')dz'}.$$

Substituting these into Eq. (15), we obtain

$$f_{\gamma A \to vA}(\Theta) = 2\pi A \int bdb\ dz\ e^{iq_v^{\parallel} z} \rho(b,z) J_0(kb\Theta)\ X$$

$$\times \left\{ f_{\gamma\rho}(0) \frac{-\Sigma \int_z^\infty e^{iq_v^{\parallel} z'} \rho(b,z')dz'}{\left(\sigma_v-\sigma_\rho\right)\int_z^\infty \rho(b,z')dz'} \times \right.$$

$$\times \left(e^{-\frac{\sigma_\rho A}{2}\int_z^\infty \rho(b,z')dz'} - e^{-\frac{\sigma_v A}{2}\int_z^\infty \rho(b,z')dz'} \right) \tag{20}$$

$$\left. + f_{\gamma v}(0)\; e^{-\frac{\sigma_v A}{2}\int_z^\infty \rho(b,z')dz'} \right\} .$$

In the limit as $k\to\infty$, $q_v^{\parallel} = 0$ and Eq.(20) simplifies considerably. z integration can be performed and obtain

$$f_{\gamma A\to vA}(\Theta) = 4\pi \int bdb\; J_0(kb\Theta) \left\{ \frac{f_{\gamma\rho}(0)\Sigma}{\sigma_\rho-\sigma_v} \times \right.$$

$$\times \left[\frac{\left(1-e^{-\frac{\sigma_\rho A}{2}\int_{-\infty}^\infty \rho(b,z')dz'}\right)}{\sigma_\rho} - \frac{\left(1-e^{-\frac{\sigma_v A}{2}\int_{-\infty}^\infty \rho(b,z')dz'}\right)}{\sigma_v} \right] \tag{15'}$$

$$\left. + \frac{f_{\gamma v}(0)}{\sigma_v} \left(1-e^{-\frac{\sigma_v A}{2}\int_{-\infty}^\infty \rho(b,z')dz'}\right) \right\}$$

Similarly in this limit, Eq.(16) becomes

$$f_{\gamma A\to\rho A} = \frac{4\pi}{\sigma_\rho} f_{\gamma\rho}(0) \int bdb\; J_0(kb\Theta) \left(1-e^{-\frac{\sigma_\rho A}{2}\int_{-\infty}^\infty \rho(b,z')dz'}\right) \tag{16'}$$

and Eq. (17) becomes

$$f_{\rho A\to vA} = \frac{-4\pi f_{\rho v}(0)}{\sigma_v - \sigma_\rho}\int bdbJ_0(kb\Theta)\left[e^{-\frac{\sigma_v A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'} - e^{-\frac{\sigma_\rho A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'}\right] \tag{17'}$$

Eq. (17') is the result obtained previously by other authors.[9] In Eq. (17'), replace ρ by γ and v by ρ then setting $\sigma_\gamma = 0(\alpha^2) \ll \Sigma$, σ_ρ, we obtain Eq. (16'). By comparing the second term of Eq. (15') with Eq. (16') we see that this term is direct photoproduction of v. Diagramatically, it is shown in Fig. (2a). It can also be shown that the first term of Eq. (15') corresponds to the diagram shown in Fig. (2b). Therefore, $\Sigma\to 0$ limit given in Eq. (15') corresponds to the first order perturbation expansion in Σ. Finally under ρ dominance assumption $\frac{1}{f_v} = 0$, we expect $f_{\gamma A\to vA}(\Theta) = \frac{1}{f_\rho} f_{\rho A\to vA}(\Theta)$ to hold. This is indeed satisfied as shown below.

(a) Consider the limit of small σ_ρ and σ_v. This limit corresponds to the nucleus being transparent to ρ and v. Taking $\Theta = 0$, expanding the exponentials and performing the integration over b, we obtain

$$\begin{aligned} f_{\gamma A\to vA}(0) &= Af_{\gamma v}(0) \\ f_{\gamma A\to \rho A}(0) &= Af_{\gamma \rho}(0) \\ f_{\rho A\to vA}(0) &= Af_{\rho v}(0) \end{aligned} \tag{21}$$

The cross section, therefore, goes as A^2 as expected from the coherent scattering.

(b) Consider large σ_ρ and σ_V. This limit corresponds to the nucleus being black. Since the exponential is negligible compared to 1 in Eqs. (16′) it becomes

$$f_{\gamma A\to\rho A}(0) \to \frac{1}{\sigma_\rho} f_{\gamma\rho}\, 2\pi R^2 = \frac{e}{f_\rho}\, \frac{ik}{4\pi}\, 2\pi R^2 \tag{22}$$

to the zeroth order in Σ.

Since $2\pi R^2$ is the total cross section for diffractive scattering from a black disc, using optical theorem, it is consistent with $\rho A\to\rho A$ diffraction scattering from a black disc. In order to understand these result interms of well known diffraction concepts consider

$$f_{\alpha A\to\beta A}(q) = \frac{ik}{2\pi}\int e^{i\vec{q}\cdot\vec{b}}\left(\delta_{\alpha\beta} - e^{i\chi_{\alpha\beta}(b)}\right) d^2\vec{b} \tag{23}$$

Then the phase function in this limit is

$$\begin{aligned} e^{i\chi_{\rho\rho}(b)} &= 1 \quad \text{for } b > R \\ &= 0 \quad \text{for } b < R. \end{aligned} \tag{24}$$

The limit for Eq. (17′) is $f_{\rho A\to vA}(0) \to 0$. In terms of Eq. (23), the phase function in this limit is

$$e^{i\chi_{\rho v}(b)} = 0 \text{ for all } b.$$

This is because for $b > R$, there are no mechanism which transforms ρ to v and for $b < R$, all v created is absorbed in the nucleus and is never detected.

The behavior of Eq. (15′) is our main interest. In this limit, the first term of Eq. (15′) $\rightarrow -2\pi f_{\gamma\rho}(0) \dfrac{\Sigma}{\sigma_\rho - \sigma_v}\left(\dfrac{1}{\sigma_v} - \dfrac{1}{\sigma_\rho}\right) R^2$

$$= -\frac{ike}{2}\frac{1}{f_\rho}\frac{\Sigma}{\sigma_v}$$

the second term of Eq. (15′) $\rightarrow 2\pi \dfrac{f_{\gamma v}(0)}{\sigma_v} R^2$

$$= \frac{ike}{2}\left(\frac{1}{f_\rho}\frac{\Sigma}{\sigma_v}\right) R^2; \text{ assuming } \frac{1}{f_v} = 0 \ .$$

If we assume ρ dominance, $\frac{1}{f_v} = 0$, the first and second terms cancel with each other. That is, in the lowest order in Σ, the diagrams shown in Fig. 2a and 2b interfere destractively to cancel out the $A^{4/3}$ behavior. Substituting Eq. (18) into Eq. (15′) we obtain

$$f_{\gamma A \rightarrow vA}(\Theta) = \tag{25}$$
$$\frac{e}{f_\rho}\frac{4\pi f_{\rho v}(0)}{\sigma_v - \sigma_\rho}\int bdb\, J_0(kb\Theta)\left[e^{-\frac{\sigma_\rho A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'} - e^{-\frac{\sigma_v A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'}\right]$$
$$+ \frac{e}{f_v}\frac{4\pi f_{vv}(0)}{\sigma_v}\int bdb\, J_0(kb\Theta)\left(1 - e^{-\frac{\sigma_v A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'}\right)$$

If $\frac{1}{f_v} = 0$, comparing Eq. (25) with Eq. (17') we obtain

$$f_{\gamma A \to vA}(0) = \frac{e}{f\rho} f_{\rho A \to vA}$$

which is consistent with ρ dominance.

Let us examine the A dependence of Eq. (25) in some detail. For this purpose, it is convenient to take a cylindrical model for the density function $\rho(r)$.

$$\rho(r) = \frac{1}{2\pi R^3} \quad \text{for} \quad -R<z<R, \quad b<R \qquad (26)$$

$$R = CA^{1/3} \quad \text{where } C = 1.14 \text{ fermi.}$$

then

$$f_{\gamma A \to vA}(0) = + \frac{e}{f\rho} \frac{4\pi f_{\rho v}(0)}{\sigma_v - \sigma_\rho} \frac{1}{2} R^2 \left[e^{-\frac{\sigma_\rho A}{2\pi R^2}} - e^{-\frac{\sigma_v A}{2\pi R^2}} \right]$$

$$+ \frac{e}{f_v} \frac{4\pi f_{vv}(0)}{\sigma_v} \frac{1}{2} R^2 \left[1 - e^{-\frac{\sigma_v A}{2\pi R^2}} \right]$$

The most extreme case if $\sigma_v >> \sigma_\rho$ then we obtain

$$f_{\gamma A \to vA}(0) = + \frac{e}{f_\rho} \frac{2\pi f_{\rho v}(0)}{\sigma_v - \sigma_\rho} C^2 A^{2/3} e^{-\frac{\sigma_\rho A^{1/3}}{2\pi C^2}}$$

$$+ \frac{e}{f_v} \frac{2\pi f_{vv}(0)}{\sigma_v} C^2 A^{2/3} \qquad (27)$$

$A^{2/3} e^{-\left(\sigma_\rho A^{1/3} / 2\pi C^2\right)}$ increases by factor of 7 while A varies from A = 1 to A = 240. Therefore, study of A dependence of the cross section in v-photoproduction is a very sensitive measurement of relative strength of the two terms in Eq. (25).

IV SMALL COUPLING MODEL[10]

Let us suppose that v is not seen in the experimental search. In such a case we can only place an upperlimit on the coupling of γ and ρ with v. Let us introduce the coupling F and define the coupling between ρ and v to be $\dfrac{m_v^2 - m_\rho^2}{F}$ where we take $\dfrac{m_v^2 - m_\rho^2}{F} << \dfrac{m_\rho^2}{f_\rho}$. Then interms of F, we have

$$\frac{f_\rho}{f_v} = \frac{1}{F}\left(1 - \frac{m_\rho^2}{m_v^2}\right)$$

$$\Sigma = \frac{\sigma_v - \sigma_\rho}{F}$$

where we have considered the process only to the first order in $\frac{1}{F}$ as shown in Fig. 5. Furthermore, since σ_v is associated with the area of proton as seen by v, we expect it to be of same order of magnitude as that of σ_ρ. The small coupling model is a special case of $\Sigma \to 0$ limit. In this model, Eq. (25) becomes

$$f_{\gamma A\to vA}(0) = \frac{ik}{F}\,\frac{e}{f_\rho}\int J_o(kb\Theta)\left(1-2e^{-\frac{\sigma_v A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'} + e^{-\frac{\sigma_\rho A}{2}\int_{-\infty}^{\infty}\rho(b,z')dz'}\right)bdb$$

where we have also assumed $m_\rho^2 << m_v^2$ and $m_v^2 R << k$. Note that A dependence is very sensitive to σ_v/σ_ρ. In fact if $\sigma_v \approx 10$ mb, the destructive interference occurs and there is a dip near $A \approx 65$. Therefore, it is quite important to vary the target nucleus to cover the wide range of A.

V. RESULTS

We now summarize the predictions of Eq. (15). Since we are only interested in the order of magnitude predictions, we will use the cylindrical model with uniform density for the nucleus. This is given in Eq. (26). This model is highly unrealistic and the results deviates from more realistic model when $q^{\parallel}R$ becomes sufficiently large. We restrict ourselves to the kinematical region such that the deviation from more realistic model is small. Also, if there is any deviation, this model will tend to under estimate the v production.

(1) To answer the questions of absorption effect raised in the introduction we have plotted $\frac{1}{A}\,\frac{d\sigma}{dt}(\gamma A\to vA) \,/\, \frac{d\sigma}{dt}(\gamma p\to vp)$ as function of A in Fig. 6. We have set $\Sigma = 20$ mb, $f_\rho/f_v = 0$ and considered various m_v and σ_v. The behavior shown in Fig. 6 also holds for other values of the parameters. Therefore, the absorption effect similar to

that of ρ production occurs for v-production.

(2) The question on interference effect was answered in Section III in the small Σ limit. The fact that v and ρ can be transformed to each other by diffractive scattering will decrease the cross section considerably. To show this we have plotted $\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow \rho A) / \frac{d\sigma}{dt}(\gamma p \rightarrow \rho p)$ as function of A in Fig. 7. This is to be compared with those of Fig. 6. Note that the interference effect also changes the A dependence.

(3) Let us now be pessimistic and assume that no evidence for v meson were found. Then the small coupling model of Sec. IV is applicable. In Fig. 8 we have plotted $\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow vA)$ as function of F for various (A, M_v, σ_v). The upper limit on F can be read off considering the experimental limitations. Although we expect $\sigma_v \approx \sigma_\rho$ and therefore the variation of σ_v in Fig. 8 should be sufficient, we have shown $\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow vA)$ as function of A for σ_v = 10 mb in Fig. 9 in order to illustrate the effect due to interference between various diagrams shown in Fig. 4. The F dependence is similar to those shown in Fig. 8. The origin of the dip is discussed in Section IV. It is, therefore, quite important to consider the photoproduction from various nucleus in case of a null result.

(4) For reference purposes, we have presented the result for various values of the parameters. They are shown in Fig. 10. Examination of these results show that, if v is found, A dependence of $\frac{d\sigma}{dt}(\gamma A \rightarrow vA)$ can be used to obtain the parameters f_ρ / f_v and σ_v.

On the other hand, the A dependence is quite insensitive to Σ.

ACKNOWLEDGEMENTS

We would like to thank Professor W. Lee for discussion on the experimental aspects of the problem. One of the authors (AIS) wishes to thank Professor T. D. Lee for getting him interested in the subject.

NOTE ADDED IN PROOF

Recently JPC = 1-- particle has been claimed to be observed in $K_L K_S$ resonance in $P\overline{P}$ reaction. (A. Benvenuti, et. al. Phys. Rev. Letters 27 , 283, (1971).

It will be quite interesting to look for this resonance in the photo production.

REFERENCES

[1] N. Hicks et al., Physics Letters 29B, 602 (1969).

P. Mostek et al., Physicsl Review Letters, 23, 718 (1969).

[2] It is quite interesting to consider the possibility that there are vector mesons whose conventional quantum numbers JPC = 1 -- are same as those for photon but they do not couple to the photon due to yet unknown selection rule. For example, according to the quark model, recently discovered $R_\alpha(1632)$ has quantum numbers JPC = 1--.

[3] If there is no absorption, the rate for the coherent ρ photoproduction on various nucleus should behave as A^2 where A is the atomic number of nucleus. On the other hand, if there is strong absorption, only those ρ which are created at the back face of the nucleus are seen. For the case, the rate behaves as $A^{4/3}$. Experimentally, the photo-production of ρ on various nucleus behaves as A^n where $2 > n > 4/3$.

[4] In this paper, we will be concerned with only the photoproduction of isovector particles. If the leptonic decay mode of the new vector mesons are detected for example, e^+e^-, then such an experiment will be sensitive to the isoscalar vector mesons.

[5] This experiment has been approved at NAL. W. Lee, M. Tannenbaum D. Yount, A. Wattenberg, T. O'Halloran, M. Gormley, and L. Read.

[6]The approximations used here are discussed by R. Glauber, Boulder Lectures in Theoretical Physics, Vol. 1 (1958), Inter-Science Publications, Inc., New York 1959.

[7]After the work has been completed it was pointed out to the authors that the coupled channel formalism developed in this paper has also been developed by M. Ross and L. Stodolsky, Phys. Rev. Letters 17, 563 (1966); S. J. Brodsky and J. Pumplin, Phys. Rev. 182, 1794 (1969); G. V. Bochmann and B. Margolis, Nuclear Physics B14, 609 (1969).

[8]If v meson exists, the determination of σ_ρ must in principle be modified. But we have seen that ρ production, and therefore σ_ρ, is quite insensitive to existence of v. We therefore take $\sigma_\rho = 26$ mb.

[9]K. Kölbig and B. Margolis, Nuclear Physics B6, 85, 1968.

[10]We thank Professor T. D. Lee for suggesting this possibility.

FIGURE CAPTIONS

Fig. 1 The diagram for ρ production. The solid line corresponds to various nucleons.

Fig. 2a A diagram for the v production corresponding to the ρ production of Fig. 1. The checked blob corresponds to elastic diffractive scattering.

Fig. 2b A diagrams for the v production including one $\rho \sim v$ transition. The black blob corresponds to diffractive $\rho p \rightleftarrows vp$ scattering.

Fig. 2c Set of diagrams for the v including arbitrary number of ρ - v transitions.

Fig. 3 Photon enters a nucleus scatters diffractively with j th nucleon at $\vec{r}_j$ to create α at $\vec{R}$. α intern scatters diffractively with ith nucleon at $\vec{r}_i$ and create β at $\vec{R}$. The ladder corresponds to interaction.

Fig. 4 Diagrams for $f_{\gamma v}$ and $f_{\gamma \rho}$.

Fig. 5 Diagrams relevant in the weak coupling model.

Fig. 6 $\frac{1}{A} \frac{d\sigma}{dt} (\gamma A \to vA) \ / \ \frac{d\sigma}{dt} (\gamma p \to vp)$ as function of A.

Fig. 7 $\frac{1}{A} \frac{d\sigma}{dt} (\gamma A \to \rho A) \ / \ \frac{d\sigma}{dt} (\gamma p \to \rho p)$ as function of A.

Fig. 8 $\frac{1}{A} \frac{d\sigma}{dt} (\gamma A \to vA)$ as function of F, m_v in GeV, and σ_v in mb.

Fig. 9 $\frac{1}{A} \frac{d\sigma}{dt} (\gamma A \to vA)$ see text.

Fig. 10 $\frac{1}{A} \frac{d\sigma}{dt} (\gamma A \to vA)$ as function of A.

a. m_v = 2GeV

b. m_v = 5GeV

c. m_v = 6GeV.

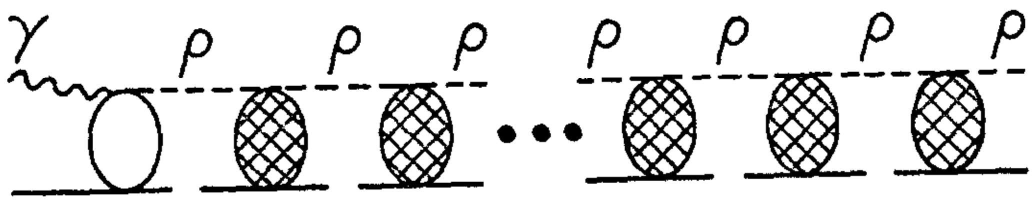


Fig 1

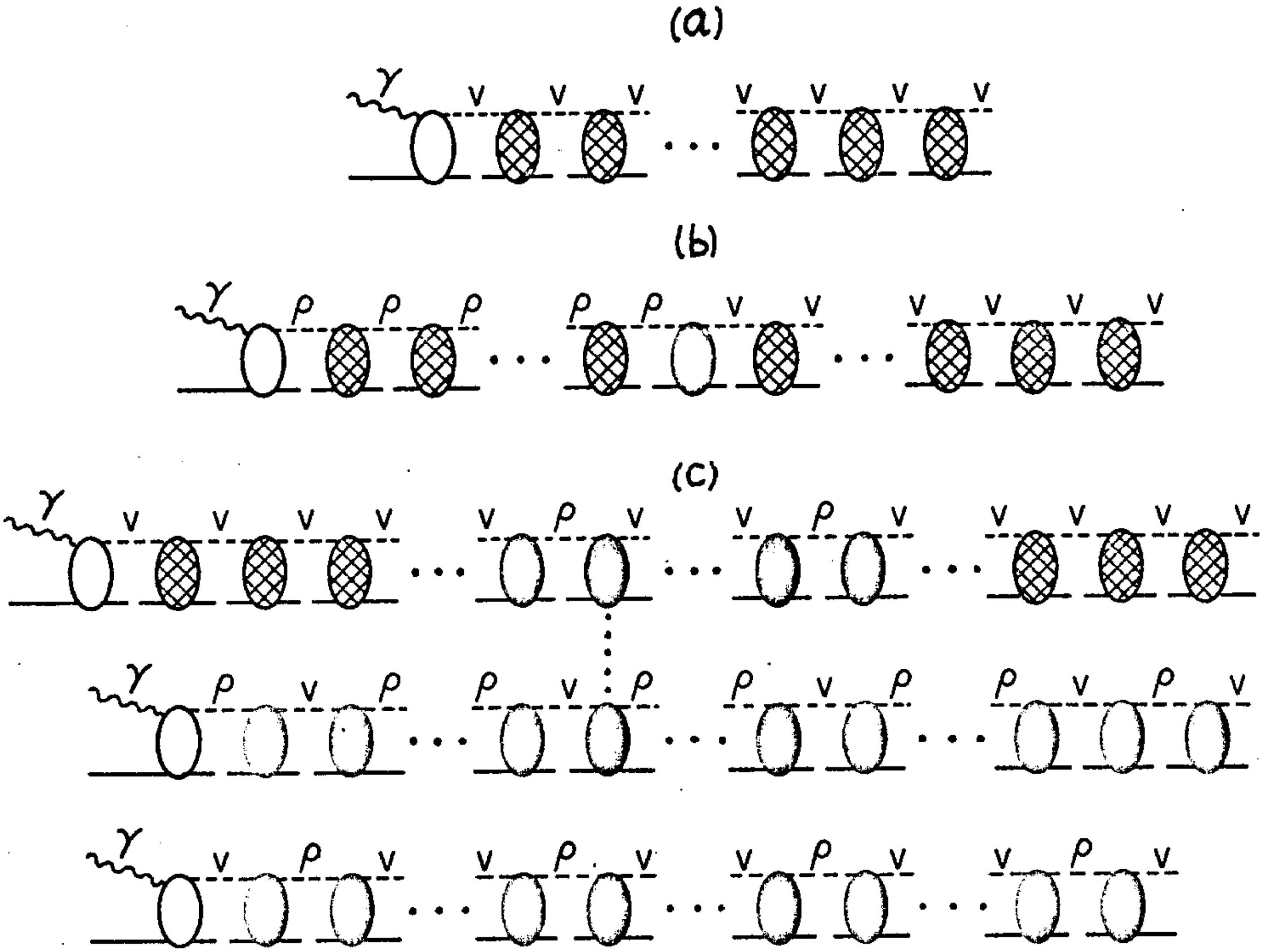


Fig. 2

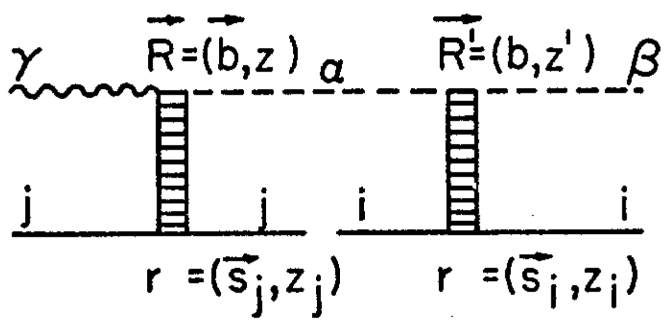
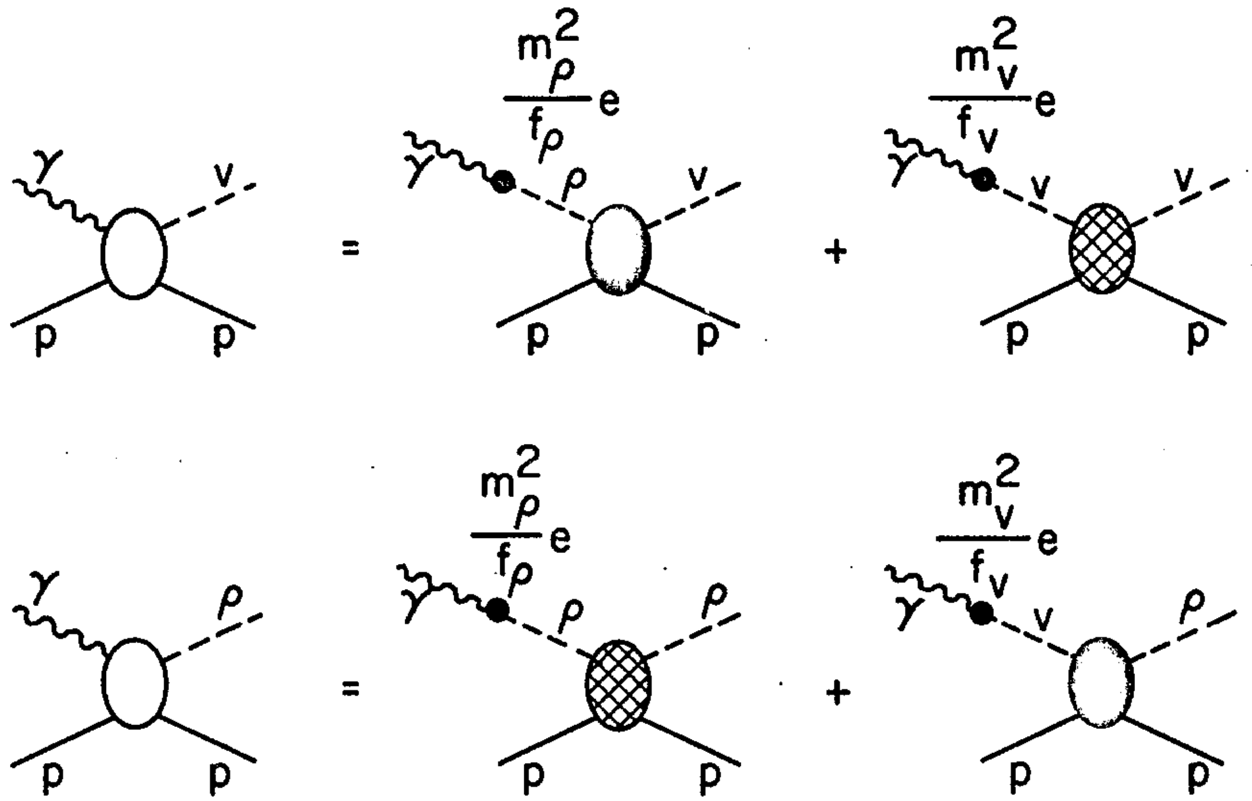


Fig. 3



γ
V
p
p
=
$\frac{m_\rho^2}{f_\rho}e$
γ
ρ
V
p
p
+
$\frac{m_V^2}{f_V}e$
γ
V
V
p
p
γ
ρ
p
p
=
$\frac{m_\rho^2}{f_\rho}e$
γ
ρ
ρ
p
p
+
$\frac{m_V^2}{f_V}e$
γ
V
ρ
p
p

Fig. 4

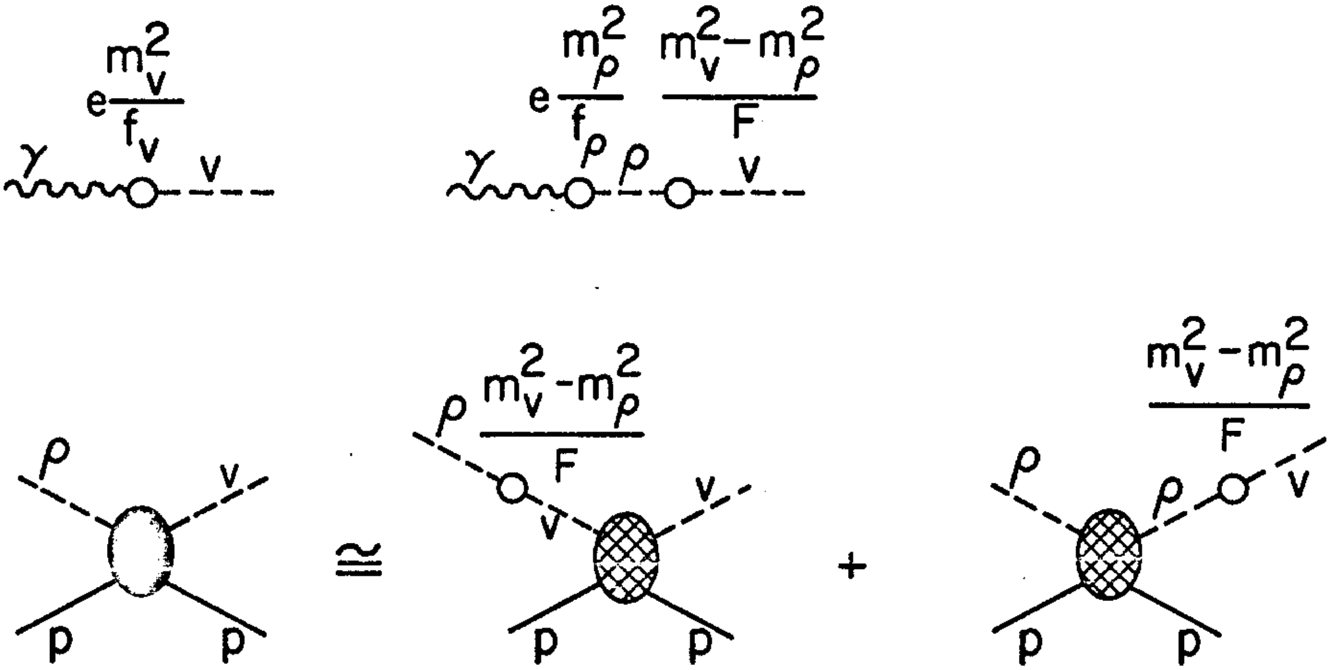
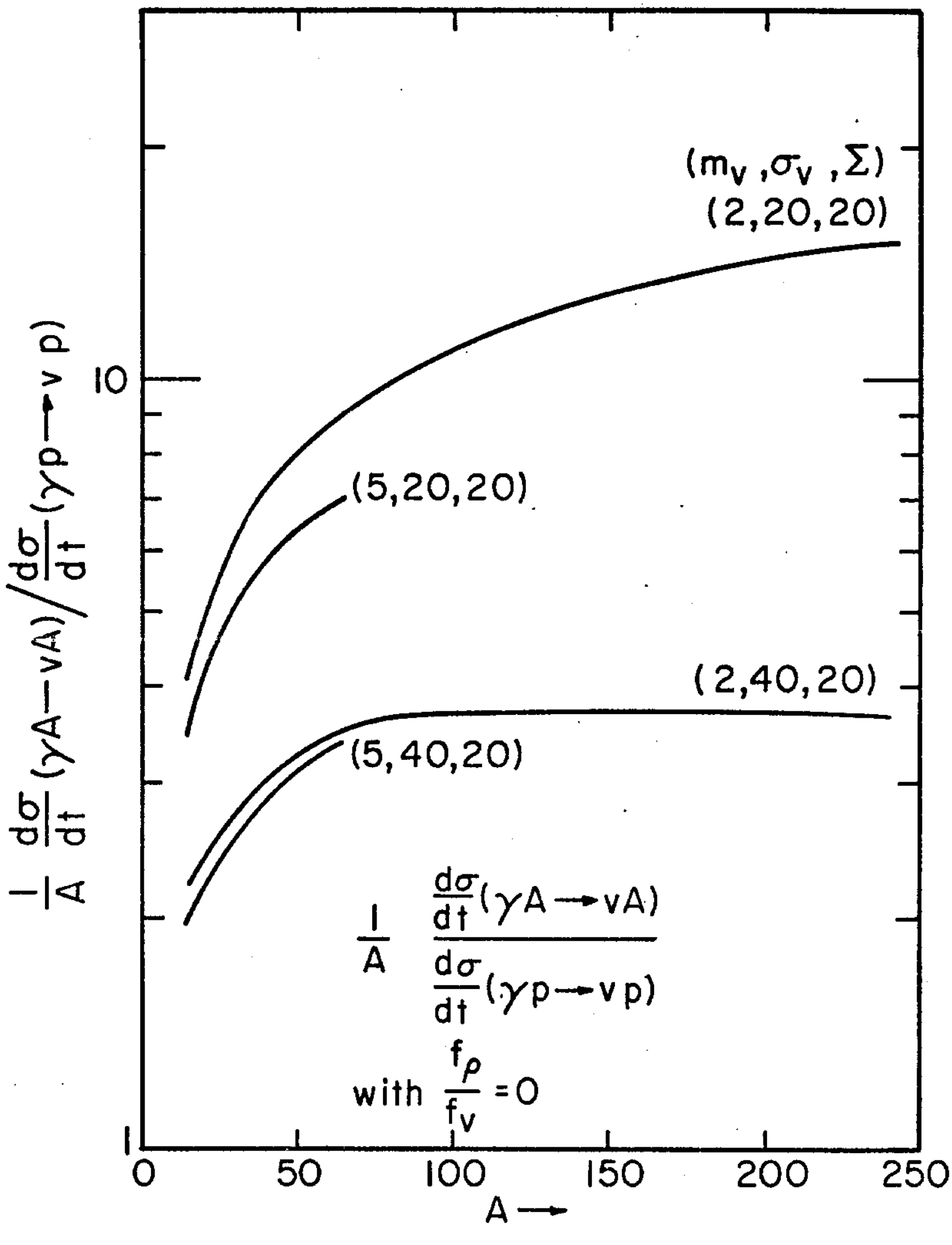
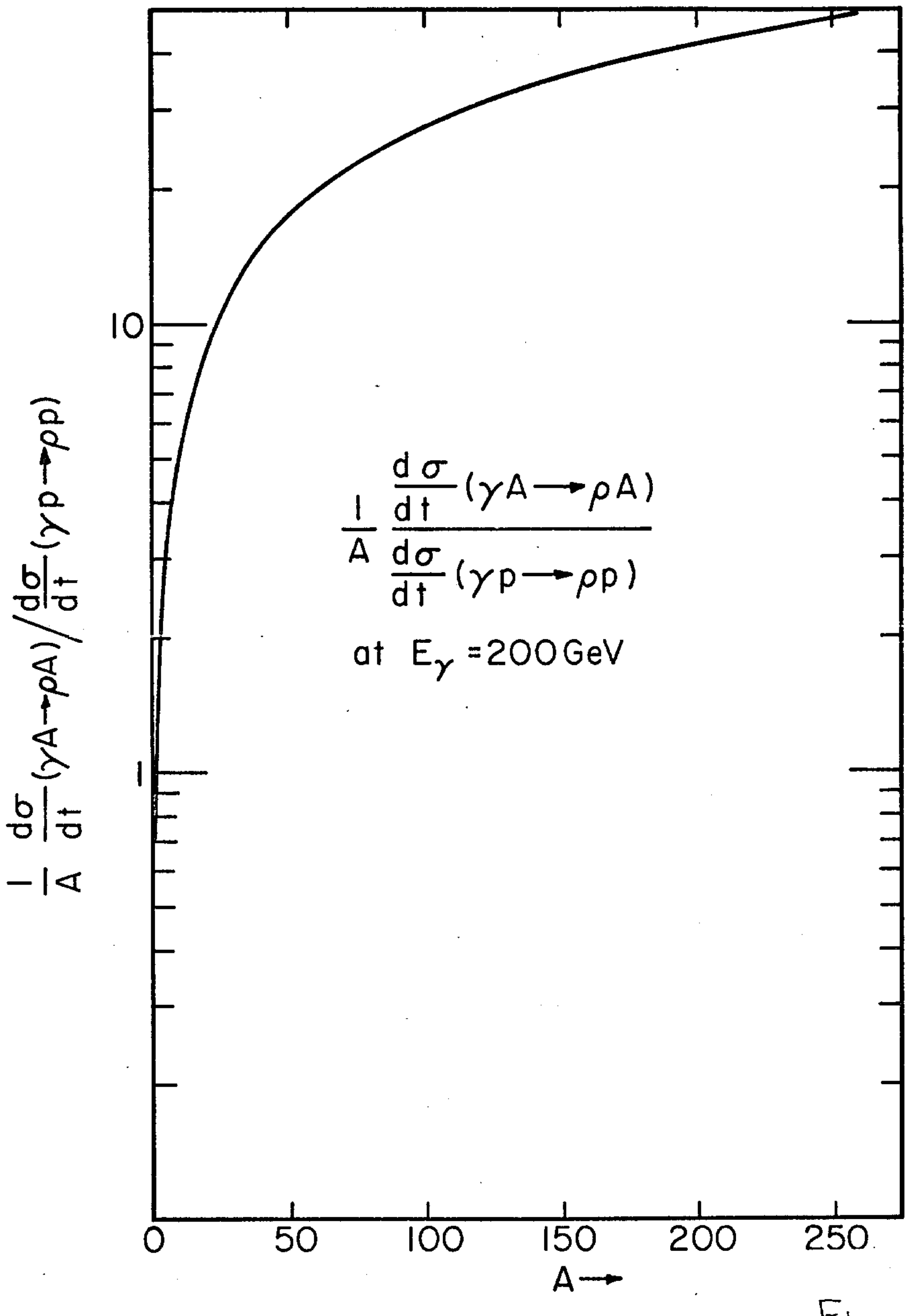


Fig. 5



(m_V, σ_V, Σ)
(2,20,20)
(5,20,20)
(2,40,20)
(5,40,20)
$\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \to vA) / \frac{d\sigma}{dt}(\gamma p \to vp)$
$\frac{1}{A} \frac{\frac{d\sigma}{dt}(\gamma A \to vA)}{\frac{d\sigma}{dt}(\gamma p \to vp)}$
with $\frac{f_\rho}{f_V} = 0$
10
1
0
50
100
150
200
250
A →

Fig. 6



$\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \to \rho A) / \frac{d\sigma}{dt}(\gamma p \to \rho p)$
10
1
0
50
100
150
200
250
A →
$\frac{1}{A}\frac{\frac{d\sigma}{dt}(\gamma A \to \rho A)}{\frac{d\sigma}{dt}(\gamma p \to \rho p)}$
at $E_\gamma = 200$ GeV

Fig 7

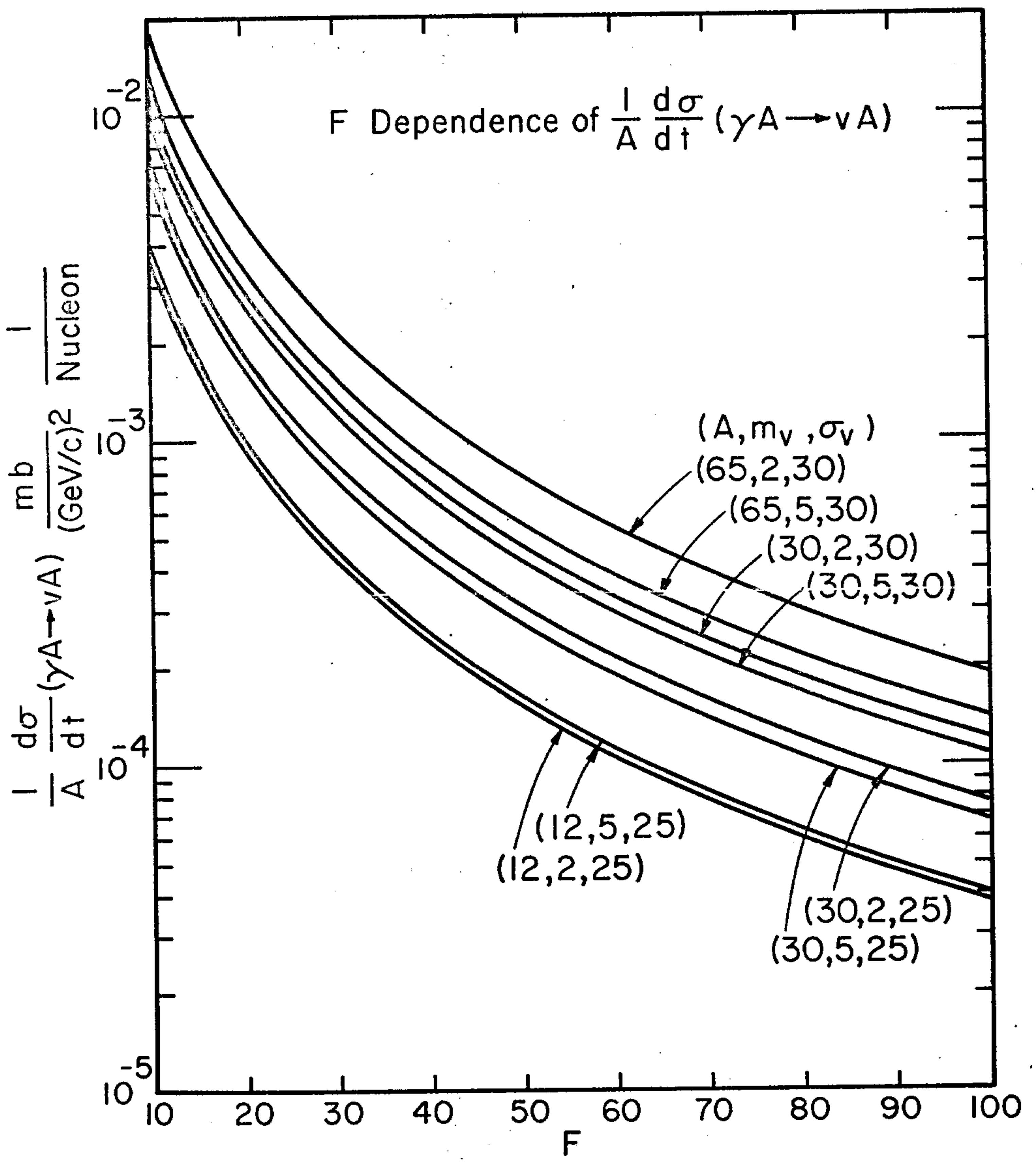
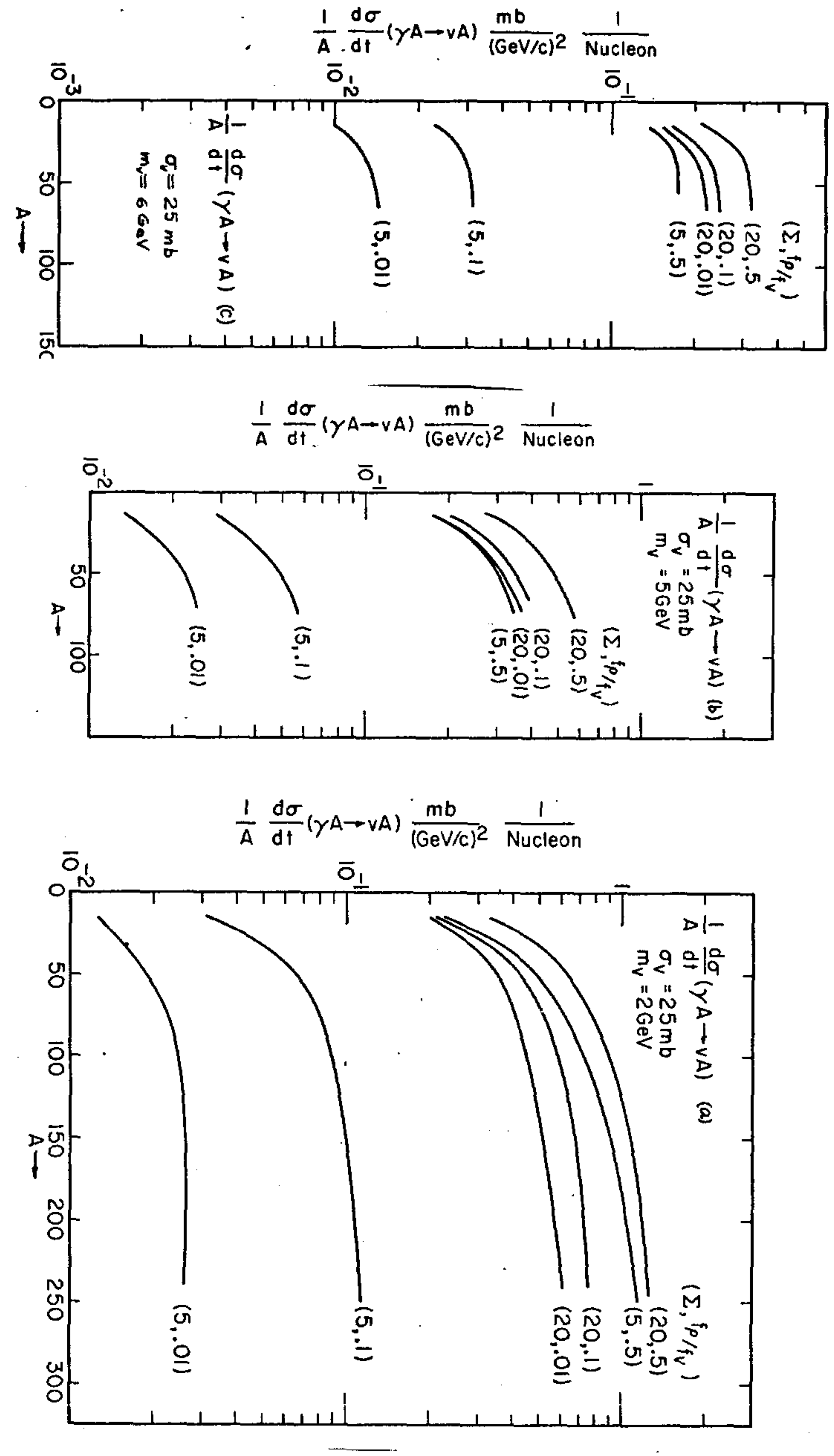
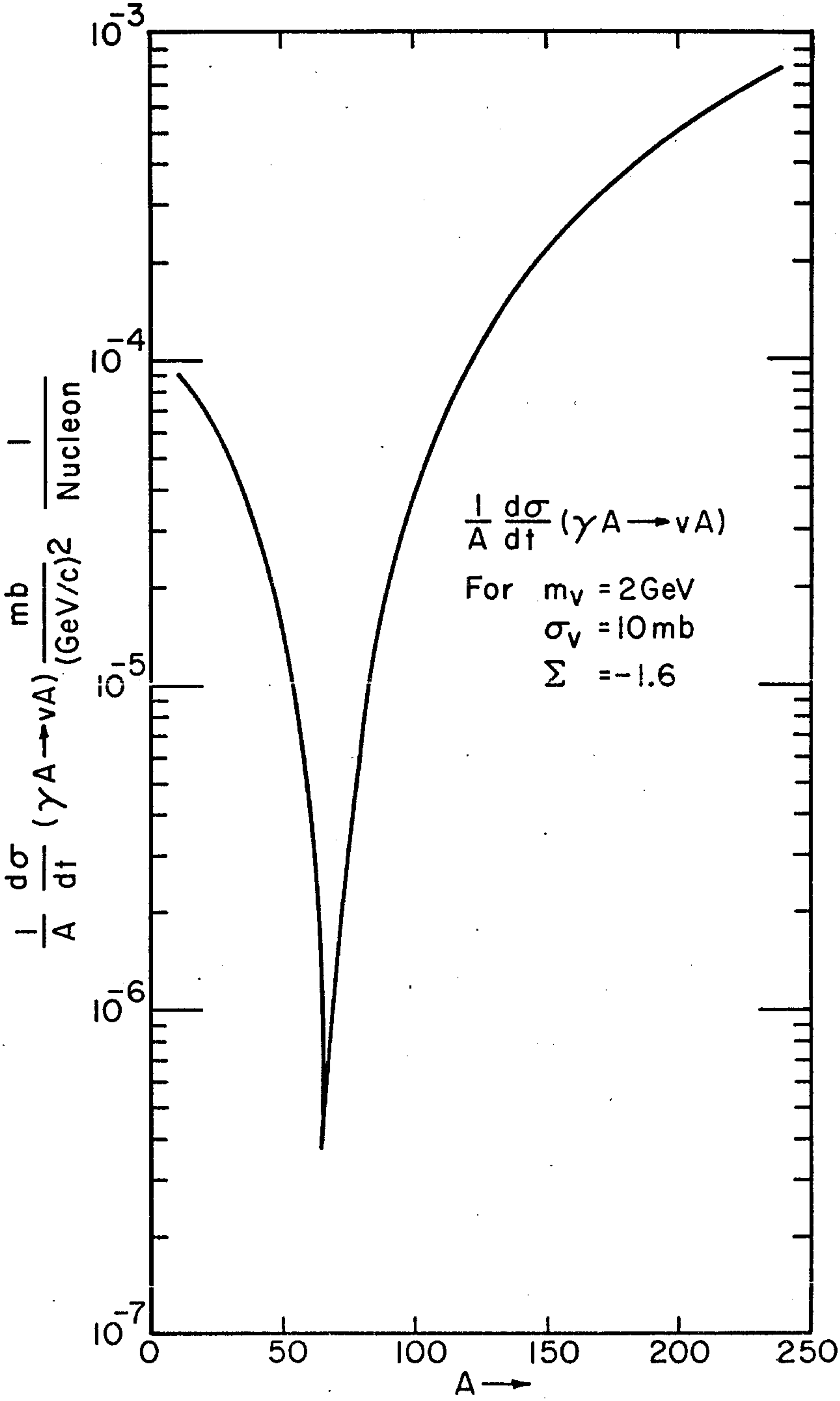

F Dependence of $\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow vA)$
$\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow vA)$ $\frac{mb}{(GeV/c)^2}$ $\frac{1}{Nucleon}$
(A, m_V, σ_V)
(65,2,30)
(65,5,30)
(30,2,30)
(30,5,30)
(12,5,25)
(12,2,25)
(30,2,25)
(30,5,25)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10
20
30
40
50
60
70
80
90
100
F

Fig 8



(a)
(b)
(c)
$\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \to vA)$ $\frac{mb}{(GeV/c)^2}$ $\frac{1}{Nucleon}$
A →
$\sigma_v = 25$ mb
$m_v = 2$ GeV
$m_v = 5$ GeV
$m_v = 6$ GeV
$(\Sigma, f_\rho/f_v)$
(20,.5)
(5,.5)
(20,.1)
(20,.01)
(5,.1)
(5,.01)

Fig. 9



10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow vA)\ \frac{mb}{(GeV/c)^2}\ \frac{1}{Nucleon}$
$\frac{1}{A}\frac{d\sigma}{dt}(\gamma A \rightarrow vA)$
For $m_v = 2$ GeV
$\sigma_v = 10$ mb
$\Sigma = -1.6$
0
50
100
150
200
250
A ⟶

Fig 10