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PHOTON ABSORPTION IN NUCLEI AND VECTOR-MESON DOMINANCE

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We show that in some applications of vector-meson dominance to photon reactions in nuclei the mass of the ρ meson cannot be neglected at photon energies of current interest. Thus, in calculation of the photon absorption cross section in the optical-model approximation, the effect of the ρ mass m_ρ is important for photon energies $\omega \lesssim m_\rho^2(R/\sigma N)^{1/2}$, where R and N are the radius and density of the nucleus, and σ is the total ρ-nucleon cross section.

It has been pointed out by Bell[1] and by Stodolsky[2] that vector-meson dominance implies hadronlike behavior for photons in interactions with nuclei. If nuclear reactions initiated by photons and ρ mesons are proportional, photons should appear to be strongly absorbed in photonuclear processes at high energies. For example, the total photoabsorption cross section should vary approximately as $A^{2/3}$ instead of as A, where A is the number of nucleons. If the ρ mass is neglected, the linear A dependence of this cross section does not occur because of destructive interference between the photon and ρ-meson waves in the nucleus. However, at photon energies ω such that the coherence length ω/m_ρ^2 between the photon and ρ-meson waves is comparable with or less than the radius R of the nucleus we expect that the ρ mass is important.[3] We will show that the volume contribution to the cross section is then not canceled by ρ-γ interference.

To illustrate the importance of the ρ-γ mass difference we calculate the scattering of photons using the optical model for the nucleus in the eikonal approximation. At impact parameter b, the photon wave ψ_γ and the ρ-meson wave ψ_ρ satisfy the following equations in the nucleus:

$$\partial\psi_\gamma/\partial z = ik_\gamma n_{\gamma\gamma}\psi_\gamma + ik_\gamma n_{\gamma\rho}\psi_\rho, \tag{1}$$

$$\partial\psi_\rho/\partial z = ik_\rho n_{\rho\gamma}\psi_\gamma + ik_\rho n_{\rho\rho}\psi_\rho, \tag{2}$$

where $n_{ij}=\delta_{ij}+2\pi N f_{ij}/k_i^2$ is the complex index of refraction in the nucleus in terms of the forward γ- and ρ-nucleon scattering amplitudes f_{ij}. For an incident photon of momentum k_γ on a nucleus of radius R the boundary conditions are

$$\psi_\gamma = \exp[-ik_\gamma(R^2-b^2)^{1/2}], \tag{3}$$

$$\psi_\rho = 0 \tag{4}$$

at $z=-(R^2-b^2)^{1/2}$.

The solution of these equations is elementary. If we keep only lowest order terms in the electromagnetic coupling we obtain for $-(R^2-b^2)^{1/2} \le z \le (R^2-b^2)^{1/2}$

$$\psi_\gamma = \exp[ik_\gamma z], \tag{5}$$

$$\psi_\rho = \frac{k_\rho n_{\rho\gamma}}{k_\gamma - k_\rho n_{\rho\rho}}\left[\exp(ik_\gamma z) - \exp\{ik_\rho n_{\rho\rho}[z+(R^2-b^2)^{1/2}] - ik_\gamma(R^2-b^2)^{1/2}\}\right]. \tag{6}$$

The forward elastic photon scattering $F_{\gamma\gamma}$ is then given by

$$F_{\gamma\gamma} = 2\pi N\int_0^R db\, b\int_{-(R^2-b^2)^{1/2}}^{(R^2-b^2)^{1/2}} dz\,[f_{\gamma\gamma}\psi_\gamma(z,b) + f_{\gamma\rho}\psi_\rho(z,b)]\exp(-ik_\gamma z), \tag{7}$$

and substituting Eqs. (5) and (6) in Eq. (7) we obtain

$$F_{\gamma\gamma}=\frac{4\pi}{3}R^3N\left\{f_{\gamma\gamma}+\frac{f_{\gamma\rho}n_{\rho\gamma}k_\rho}{k_\gamma-k_\rho n_{\rho\rho}}\right\}+2\pi iR^2N\frac{f_{\gamma\rho}n_{\rho\gamma}k_\rho}{(k_\gamma-k_\rho n_{\rho\rho})^2}\{\tfrac{1}{2}-g[-2iR(k_\gamma-k_\rho n_{\rho\rho})]\},\tag{8}$$

where $g(x)=[(x-1)e^x+1]/x^2$.

It is clear from the first term in Eq. (8) that in general $F_{\gamma\gamma}$ has a term proportional to the number of nucleons $A=\frac{4}{3}\pi R^3N$. This comes, in part, from the superposition of photon waves scattered from each nucleon, given by the amplitude $f_{\gamma\gamma}$. However, there is also a contribution from the coherently generated ρ-meson, given by $f_{\rho\gamma}$. If we make the assumption of vector-meson dominance:

$$f_{\gamma\gamma}=\left(\frac{e}{2\gamma_\rho}\right)^2f_{\rho\rho},\quad f_{\gamma\rho}=f_{\rho\gamma}=\left(\frac{e}{2\gamma_\rho}\right)f_{\rho\rho},\tag{9}$$

Eq. (8) becomes

$$F_{\gamma\gamma}=\left(\frac{e}{2\gamma_\rho}\right)^2\frac{\omega R^2}{1-m_\rho^2/4\pi Nf_{\rho\rho}}\left[-\frac{m_\rho^2R}{3\omega}+\frac{i}{1-m_\rho^2/4\pi Nf_{\rho\rho}}\left\{\frac{1}{2}-g\left[-\frac{iR}{\omega}(m_\rho^2-4\pi Nf_{\rho\rho})\right]\right\}\right].\tag{10}$$

Hence the volume contribution to $F_{\gamma\gamma}$ is also proportional to m_ρ^2 and can be neglected only when $\omega\gg m_\rho^2R$. As an example, for lead, $R=7$ F and $m_\rho^2R\sim21$ BeV. However, if we confine our attention to the total photoabsorption cross section σ_γ and assume that $f_{\rho\rho}$ is pure imaginary, i.e., $f_{\rho\rho}=i\omega\sigma/4\pi$ (σ is the total ρ-nucleon cross section), another criterion applies. In this case[4]

$$\sigma_\gamma=\left(\frac{e}{2\gamma_\rho}\right)^2\frac{4\pi R^2}{1+(m_\rho^2/\sigma N\omega)^2}\left[\frac{1}{3}\frac{m_\rho^4R}{\sigma N\omega^2}+\frac{1}{1+(m_\rho^2/\sigma N\omega)^2}\left\{\left[1-\left(\frac{m_\rho^2}{\sigma N\omega}\right)^2\right][\tfrac{1}{2}-\mathrm{Re}g(x)]-\frac{2m_\rho^2}{\sigma N\omega}\mathrm{Im}g(x)\right\}\right],\tag{11}$$

where $x=-R(\sigma N+im_\rho^2/\omega)$. The volume contribution to σ_γ becomes small compared with the surface term when $\omega\gg m_\rho^2(R/\sigma N)^{1/2}$, provided $\sigma NR\gtrsim1$. For[5] $\sigma\sim30$ mb, $N\sim1.5\times10^{38}$ cm^{-3}, and the lead radius $R=7$ F, we get $m_\rho^2(R/\sigma N)^{1/2}\sim12$.

Finally, we calculate the forward amplitudes for elastic ρ-nucleus scattering $F_{\rho\rho}$ and ρ photoproduction $F_{\rho\gamma}$. Assuming vector-meson dominance for nucleon scattering, Eq. (9), we obtain

$$F_{\rho\gamma}=\left(\frac{e}{2\gamma_\rho}\right)\frac{i\omega R^2}{1-m_\rho^2/4\pi Nf_{\rho\rho}}\left\{g\left[\frac{im_\rho^2R}{2\omega}\right]-g\left[\frac{iR}{\omega}\left(-\frac{m_\rho^2}{2}+4\pi Nf_{\rho\rho}\right)\right]\right\},\tag{12}$$

which corresponds to the result of Drell and Trefil,[6] and

$$F_{\rho\rho}=i\omega R^2\left\{\frac{1}{2}-g\left[\frac{iR}{\omega}4\pi Nf_{\rho\rho}\right]\right\}.\tag{13}$$

Hence the analog of the vector-meson–dominance relations, Eq. (9), applied to the nuclear scattering amplitudes F_{ij}, Eqs. (8), (12), and (13), is valid provided $\omega\gg m_\rho^2R$ and either $4\pi Nf\gg m_\rho^2$ or $\omega\gg4\pi Nf_{\rho\rho}R$. If we assume that $f_{\rho\rho}$ is imaginary the second condition becomes $\omega\gg m_\rho^2/\sigma N$ or $\sigma NR\ll1$.

To conclude, we note that recently discrepancies have been found in comparing some predictions of vector-meson dominance with experiment.[5,7-9] It is possible that a similar lower energy bound must be used before applying vector-meson dominance for photon-nucleon reactions, particularly if current ideas that the nucleon should be treated as a composite system are valid.

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EXPERIMENTS ON FORMING INTENSE RINGS OF ELECTRONS SUITABLE FOR THE ACCELERATION OF IONS*

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Electrons were injected from a 3.3-MeV 300-A accelerator into a circular orbit in a pulsed magnetic field. Trapped ring currents of 150 A were magnetically compressed from 19- to 3.5-cm radius and simultaneously accelerated from 3.3 to 18 MeV. The rms dimensions of the cross section of the ring after compression were $a = 2.3 \pm 0.2$ mm radially and $b = 1.6 \pm 0.2$ mm axially. The lifetime of the ring, typically 5.5 msec, was determined by the decay of the magnetic field after compression and could be decreased by the addition of hydrogen gas, indicating the focusing effect of the trapped positive ions.

In contrast to our present-day "single-particle" accelerators, in which the self-fields of the circulating particles can be treated as a negligible or minor perturbation, the basic concept of "collective-effect" accelerators involves use of self-fields larger than externally applied accelerating fields. Use of self-fields of intense clusters of electrons to accelerate beams of protons and ions, with advantages over other methods, has been speculated in the last two decades.[1-5]

One form of collective-effect accelerator creates an intense electron cluster, containing trapped ions, that can be accelerated electrically (or magnetically). Existing linear accelerating columns have typically achieved 1-2 MeV/m for protons; if sufficiently high electric holding fileds in the cluster can be maintained, this limit can be advanced by the factor (proton mass)/(electron mass). Using an electron ring as a possible vehicle is suggested in a sentence by Harvie,[1] and final stabilization of the ring by ion focusing is suggested by Veksler et al.[6] The latter work is especially significant in reporting experimental efforts to form electron rings with suitable holding power.

Problems of forming very intense rings have been studied intensively at this laboratory, possible instability problems uncovered, and a variety of solutions proposed.[7] Encouraged by earlier experimental results[6] and by calculations,[7] we undertook an experimental program to form rings, load them with ions, and study self-stabilization and acceleration. This note reports an experiment on the first two of these four objectives, with a ring-forming "compressor" that was used at the 300-A, 3.3-MeV Astron facility.[8] Other experiments addressed to the first objective only (albeit at low intensity) have recently been reported.[9,10]

The equipment is described in Ref. 9. The ring-forming apparatus, or compressor, is illustrated in Fig. 1. Alumina was chosen for the vacuum envelope because it is structurally strong and has good vacuum characteristics, but mostly because eddy-current effects precluded use of large areas of metal. Pumping by two 500-l/sec ion pumps achieved pressures between 10^{-8} and 10^{-7} Torr.

A pulsed weak-focusing magnetic field was generated by three nested coil pairs, pulsed sequentially. The magnetic field cycle, represented in Fig. 2, shows a rise from 660 G at injection to 17 kG after compression, in a time of 500 μsec. Electrons are injected on an orbit radius R of 19 cm. They are simultaneously accelerated azimuthally by betatron action from 3.3 to 18 MeV and compressed in radius to 3.5 cm. During this process the minor diameter of the ring damps adiabatically from a few centimeters to a few millimeters.

The beam was introduced into the compressor through a snout made of soft iron (to cancel the field inside) and plated with a graduated coating of copper to minimize (at the moment of injection) field perturbations of the pulsed field outside. The center of this snout was at a radius of $R = 21.4$ cm. The closed orbit at injection was