Coherent ρ^0 Photoproduction in Bulk Matter at High Energies

Elsa Couderc
Lawrence Berkeley National Laboratory, Berkeley, California, 94720 USA and Département de Physique, Ecole Normale Supérieure, Paris, France

Spencer Klein
Lawrence Berkeley National Laboratory, Berkeley, California, 94720 USA and Department of Physics, University of California, Berkeley, California, 94720 USA
(Received 8 January 2009; published 6 August 2009)

The momentum transfer Δk required for a photon to scatter from a target and emerge as a ρ^0 decreases as the photon energy k rises. For $k > 3 \times 10^{14}$ eV, Δk is small enough that the interaction cannot be localized to a single nucleus. At still higher energies, photons may coherently scatter elastically from bulk matter and emerge as a ρ^0, in a manner akin to kaon regeneration. Constructive interference from the different nuclei coherently raises the cross section and the interaction probability rises linearly with energy. At energies above 10^{23} eV, coherent conversion is the dominant process; photons interact predominantly as ρ^0. We compute the coherent scattering probabilities in slabs of lead, water, and rock, and discuss the implications of the increased hadronic interaction probabilities for photons on ultrahigh energy shower development.

DOI: 10.1103/PhysRevLett.103.062504 PACS numbers: 13.60.−r, 25.20.−x, 95.55.Vj

An understanding of the cross sections for photon interactions is important in many areas of physics. For example, several groups have searched for radio waves [1] or acoustic pulses [2] produced by interactions of astrophysical ν_e with energies up to 10^{25} eV. The radio and acoustic frequency spectra and angular distribution depend on the distribution of moving electric charges (for radio) and energy deposition (for acoustic). These distributions are controlled by the particle interactions that govern shower development. The experimental flux limits depend on the assumed character of these interactions.

In this Letter, we discuss hadronic interactions of photons [3] and introduce a new effect: coherent photon to ρ^0 conversion in bulk matter. These effects become important at energies above 10^{20} eV, but are not in many current calculations [4]. With these effects, photons produce hadronic showers, rather than electromagnetic showers. Since hadronic showers are much less affected by the Landau-Pomeranchuk-Migdal (LPM) effect [5], they are much more compact; the presence of hadronic interactions alters both the frequency spectrum and angular distribution of the electromagnetic and acoustic radiation from neutrino induced showers. Published limits that do not consider these effects may need to be revised.

Besides its importance for ν searches, coherent conversion is very interesting in its own right, as one of a handful of examples where particles interact very differently in bulk matter than with isolated atoms; interactions with individual targets are replaced by distributed interactions which are delocalized over multiple atoms [6]. The other prominent examples are LPM suppression of bremsstrahlung and pair production [7,8], kaon regeneration [9], and coherent neutrino forward scattering [10]. The LPM effect decreases the cross section for pair production, due to destructive interference. In contrast, in the other examples, including coherent ρ conversion, constructive interference raises the cross section.

Photon to ρ conversion occurs when a photon fluctuates to a virtual $q\bar{q}$ pair which then scatters elastically from a target nucleus, emerging as a vector meson [11]. As the photon energy k rises, the required momentum transfer $\Delta k = M_{\pi\pi}^2/2k$ decreases, and the coherence length $l_f = \hbar/\Delta k$ rises (we take $\hbar = c = 1$ throughout). Here, $M_{\pi\pi}$ is the final state mass. When $k > 3 \times 10^{14}$ eV (for $M_{\pi\pi} = M_\rho = 778$ MeV$/c^2$, the ρ pole mass), $l_f > 0.2$ nm, the typical internuclear spacing, and coherence over multiple nuclei becomes possible.

We consider a high-energy plane-wave photon traveling in the $+z$ direction. The photon wave function is mostly bare photon ($|\gamma_b\rangle$), but with a $q\bar{q}$ component, $|q\bar{q}\rangle$ and heavier fluctuations (e.g., $q\bar{q}q\bar{q}$, and strange quark pairs)

$$|\psi\rangle = e^{ikz}[\sqrt{1-F^2}|\gamma_b\rangle + F|q\bar{q}\rangle + \ldots] \quad (1)$$

where $F = 6.02 \times 10^{-2}$ is the amplitude for the photon to fluctuate to a $q\bar{q}$ pair [11]. Heavier fluctuations may become significant at high enough energies. However, these fluctuations will have a much shorter coherence length, and therefore will not be subject to coherent enhancement at significantly higher energies.

The $|q\bar{q}\rangle$ scatters from nuclei at positions $\vec{r}_i$, with scattering amplitude $f(\theta)$, emerging with momentum $\vec{k}_i'$. Neglecting photon or ρ absorption, and photon scattering (so $q\bar{q}$ do not scatter and then fluctuate back to a photon), the wave function at a depth L in the material is

$$|\psi(L)\rangle = \sqrt{1-F^2}e^{ikL}|\gamma_b\rangle + F\sum_i e^{ikz_i} f(\theta)\frac{e^{i\vec{k}_i'\cdot(\vec{L}-\vec{r}_i)}}{|\vec{L}-\vec{r}_i|}|\rho\rangle. \tag{2}$$

The photon can be absorbed in the target, with absorption length $\alpha = (1/n)[\sigma_{ee}(\gamma A) + \sigma_{\rm hadr}(\gamma A)]$. Here, $\sigma_{ee}(\gamma A)$ is the pair production cross section, $\sigma_{\rm hadr}(\gamma A)$ is the photonuclear cross section, and n is the target density, in atoms/volume.

The ρ can be lost by direct hadronic interaction, or by decay to $\pi^+\pi^-$, followed by π interactions. The decay itself does not affect the coherence [12], but two π interact differently from one ρ. For simplicity, we take the ρ absorption length $\beta = (1/n)\sigma_{\rm tot}(\rho A)$ where $\sigma_{\rm tot}(\rho A)$ is the ρ nucleus cross section. The factor of 2 difference between two π and one ρ is small compared to the other uncertainties. This also applies for direct $\pi^+\pi^-$ production, discussed below.

Including these absorption factors, and treating the target as a homogenous medium with constant density n, the wave function at depth L in the slab is

$$\langle\rho^0|\psi(L)\rangle = nF\int_0^\infty \eta d\eta \int_0^{2\pi} d\psi \int_0^L dz e^{[ik-(\alpha/2)]z} f(\theta) \times \frac{e^{[ik'-(\beta/2)]r'}}{r'}, \tag{3}$$

for an incident plane wave moving along the $+z$ axis. The integral over the target volume is in cylindrical coordinates where η is the radial distance from the z axis and ψ is the azimuthal angle. We neglect scattering effects at large distances since absorption limits the effective size of the target.

In an infinite medium forward scattering, $f(0)$, is the main contributor to coherent scattering [9,10,13]. There is also a contribution from inelastic diffraction [14], where the photon interacts diffractively with one nucleon, where it is excited to a higher-mass state. This excited state can then interact with a second nucleon, emerging as a ρ^0. If the two nucleons are in the same nucleus, this effect is similar to that due to nuclear shadowing, which accounts for multiple inelastic interactions in a single nucleus; this will be discussed later. However, the two nucleons might be in different nuclei. Since the intermediate state has a shorter coherence length than the ρ^0, it does not make a large contribution to coherent photoproduction and we neglect it here. We assume that the real part of $f(0)$ is small [11], corresponding to nearly complete absorption. Then, from the optical theorem, $|f(0)| = \sigma_{\rm tot}(\rho A)k/4\pi$.

After scattering, the system has the momentum $k' = k - \Delta k$. Since $\Delta k \propto M_{\pi\pi}^2$, the ρ width affects the calculation. The photon may also fluctuate directly into an $\pi^+\pi^-$ pair [15]; these two processes interfere and the mass spectrum is a Breit-Wigner spectrum. Then,

$$f(0, M_{\pi\pi}) = \frac{k}{4\pi}\left|A\frac{\sqrt{M_{\pi\pi}m_\rho\Gamma_\rho}}{M_{\pi\pi}^2 - m_\rho^2 + im_\rho\Gamma_\rho} + B\right|^2 \tag{4}$$

where A and B are the energy-dependent amplitudes for ρ and direct $\pi\pi$ production, respectively, [16], and the ρ^0 width $\Gamma_\rho = 150$ MeV. We assume that B/A is independent of photon energy and target material. Integrating $\int dM_{\pi\pi} f(0, M_{\pi\pi})$ returns the traditional $f(0)$. With this, $\sigma(\gamma p \to \rho p) = A^2$.

We substitute $\eta d\eta = r'dr'$ where r' is the distance between the scattering point (η, z) and the observer at $(0, L)$, to evaluate the integrals [10]

$$\langle\rho^0|\psi(L)\rangle = 2\pi nF\int_{2m_\pi}^{M_\rho+5\Gamma_\rho} dM_{\pi\pi} f(0, M_{\pi\pi})\frac{e^{[ik'-(\beta/2)]L}}{(ik'-\frac{\beta}{2})}\frac{e^{[i\Delta kL-(\alpha-\beta/2)]L}-1}{(i\Delta k - \frac{\alpha-\beta}{2})}. \tag{5}$$

For simplicity, we give here the probability for a fixed $M_{\pi\pi}$ (although the full calculations include the wide ρ)

$$P_{\rho^0}(L, M_{\pi\pi}) = 4\pi^2|f(0)|^2F^2n^2\frac{e^{-\alpha L} + e^{-\beta L} - 2e^{-(\alpha+\beta/2)L}\cos(\Delta kL)}{(k'^2 + \frac{\beta^2}{4})(\Delta k^2 + \frac{(\alpha-\beta)^2}{4})}. \tag{6}$$

Equation (6) illustrates some of the features of the system. When $\Delta kL \gg 1$, the cosine fluctuates rapidly, leading to incoherent ρ production. However, when the coherence condition $\Delta kL \ll 1$ is fulfilled, the scattering amplitudes add in phase, and production is coherent.

A ρ inside a target is not directly observable. However, the way it interacts—electromagnetically, hadronically, or through ρ conversion—is indirectly observable, by studying the shower development. The probability that an incident photon interacts as a real ρ is the integrated probability for finding a ρ, multiplied by the probability for a ρ to interact hadronically in length dz, or dz/β

$$P(L) = \int_0^L \frac{dz|\langle\rho^0|\psi(z)\rangle|^2}{\beta}. \tag{7}$$

This equation is only properly normalized for $P(L) \ll 1$. The loss of photon intensity due to the coherent ρ reaction is not included. For kaon regeneration, the analogous problem has been solved recursively [17]. Here, we normalize the probabilities to sum to one in thick targets.

The numerical values of $P(L)$ depend on $\sigma_{\rm tot}(\rho A)$ and the cross section for a photon to interact hadronically (as a ρ), $\sigma_{\rm hadr}(\gamma A)$. They are related via

$$\sigma_{\rm hadr}(\gamma A) = F^2\sigma_{\rm tot}(\rho A). \tag{8}$$

We determine these using two different methods: a Glauber calculation based on HERA data on $\gamma p \to \rho p$, using a soft Pomeron model to extrapolate the cross sections to higher energies, and a second calculation that includes generalized vector meson dominance (GVMD) plus a component for direct photon interactions [18].

We consider three materials: water, standard rock [8], and lead. For water, we add the amplitudes for the cross sections for hydrogen and oxygen.

The Glauber calculation uses the optical theorem [19] and vector meson dominance model to link the total ρp cross section to the differential γp cross section

$$\sigma_{\rm tot}(\rho p) = \frac{4\sqrt{\pi}}{F}\sqrt{\frac{d\sigma(\gamma p \to \rho p)}{dt}\bigg|_{t=0}} \qquad (9)$$

where t is the squared momentum transfer. $d\sigma/dt(\gamma p \to \rho p)$ comes from a fit to HERA data [20].

The cross sections for nuclear targets are found with a quantum Glauber calculation [21]

$$\sigma_{\rm tot}(\rho A) = 2\int d^2\vec{r}\left(1 - e^{-[\sigma_{\rm tot}(\rho p)T_A(\vec{r})/2]}\right) \qquad (10)$$

where $T_A(\vec{r})$ is the nuclear thickness function for a material with atomic number A, calculated from a Woods-Saxon nuclear density, with a skin thickness of 0.53 fm and density $\rho_0 = 1.16A^{1/3}(1 - 1.16A^{-2/3})$.

The second approach follows Engel, Ranft, and Roessler (ERR) [18]. It uses GVMD plus direct photon-quark interactions to determine $\sigma_{\rm hadr}(\gamma A)$. ERR predict a steeper rise in the cross section than the Glauber calculation. We parameterize their results. For $W_{\gamma p} < 10^{11}$ eV, the cross section is constant, while at higher energies, it rises as $W_{\gamma p}^{0.2}$. The cross section scales as $A^{0.887}$, normalized so that $\sigma(\gamma\text{Pb}) = 15$ mb at low energies. The difference from A^1 scaling is due to nuclear shadowing, which accounts for the possibility of multiple photon-nucleon interactions within the nucleus; this correction should also hold for inelastic diffraction. Again, $\sigma_{\rm tot}(\rho A) = \sigma_{\rm hadr}(\gamma A)/F^2$. The ERR cross sections are similar to a newer result that computed photon cross sections using a dipole model [22].

Figure 1 compares the cross sections for e^+e^- production and the two photonuclear models. $\sigma_{ee}(\gamma A)$ is constant at low energies, but falls at higher energies when the LPM effect becomes important [3,7]. The hadronic cross sections rise slowly with energy. The hadronic curves agree at low energies, but diverge as the energy rises; the difference is about a factor of 5 at 10^{23} eV. This difference shows the range of variation in hadronic models; other uncertainties in this calculation (including the effects of heavier states, etc.) should have a smaller effect.

In the ERR (Glauber) model, above 5×10^{19} eV (5×10^{20} eV), photonuclear interactions predominate, and photons produce hadronic showers. The crossover energy is almost material-independent for solids.

Figure 2 shows the probability of finding a ρ^0, Eq. (6), as a function of depth in a thick target. As with K_s from kaon regeneration [9], the amplitudes add and the probability initially rises as the square of the depth. After reaching a maximum, the probability decreases slowly as ρ absorption competes with ρ production, and then drops rapidly as the bare photons are absorbed.

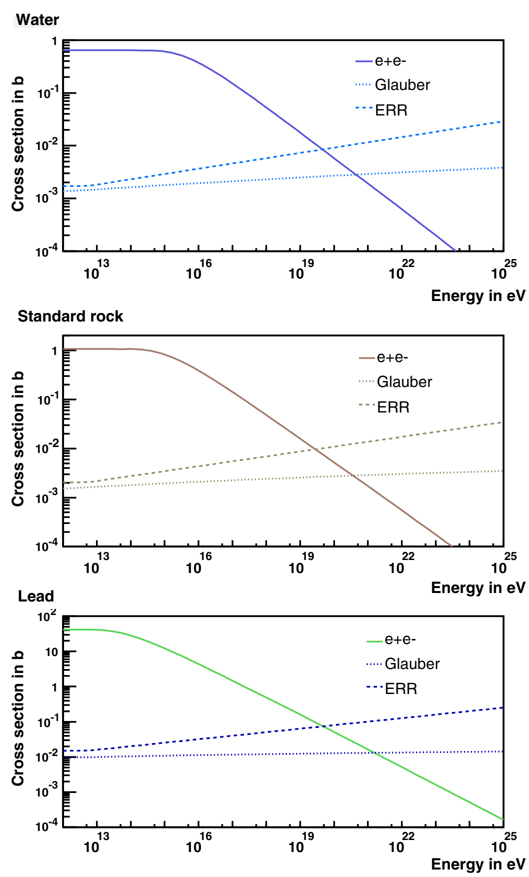

FIG. 1 (color online). The cross sections for photon interactions to e^+e^- pairs, and for incoherent photonuclear interactions in the Glauber and ERR models, for water (top), standard rock (middle), and lead (bottom).

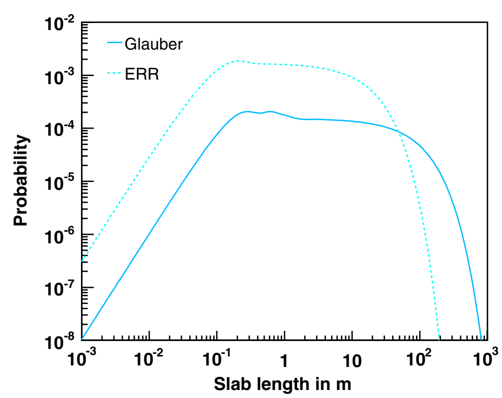

FIG. 2 (color online). ρ probability as a function of depth in a slab for a 10^{23} eV photon incident on a water target. The two broad peaks around 20 and 40 cm correspond to $\Delta kL = 2n\pi$ at the ρ pole mass.

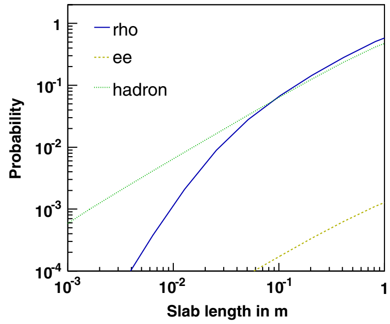

FIG. 3 (color online). The probability of a 10^{24} eV photon interacting electromagnetically (dashed blue line), in an incoherent hadronic interaction (dotted line), or as a coherently produced ρ (solid line), as a function of target depth in a lead target.

Figure 3 shows the probability for a 10^{24} eV photon to interact as a function of target thickness L. For $L < 10$ cm, the probability of a photon interacting as a coherently produced ρ is quite small. For $L > 10$ cm, the probability is higher than for photonuclear interactions and e^+e^-; it is the dominant interaction.

Figure 4 shows the probabilities for incident photons to interact electromagnetically ($\gamma \rightarrow e^+e^-$ pair), via incoherent hadronic interactions, and as coherently produced ρ, as a function of energy, in a 100 m thick slab; in the displayed energy range, 100 m is effectively infinite thickness. At energies above 10^{23} eV (for ERR) to 10^{24} eV (for the Glauber calculation), coherently produced ρ interactions dominate. This dominance will reduce the interaction length of photons. The reduction in shower length will have consequences for searches for ultrahigh energy astrophysical ν_e [1,4].

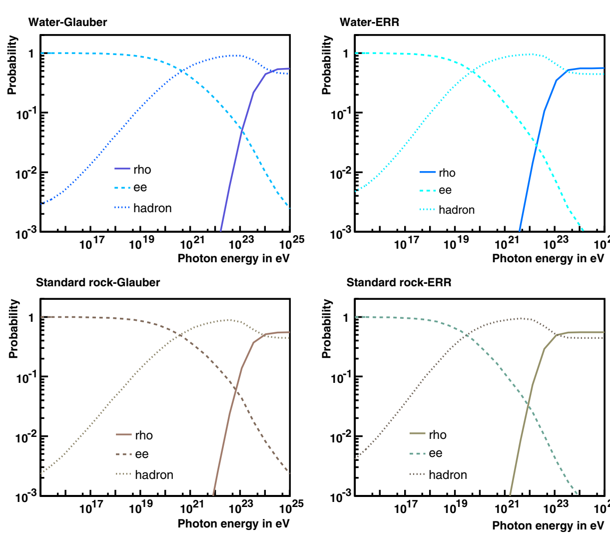

FIG. 4 (color online). The normalized probabilities for a photon to interact as an e^+e^- pair, via incoherent hadronic interaction ("hadron"), or as an elastically produced ρ ("rho") in a 100 m thick water or standard rock target. This is thick enough for almost total absorption, so these results apply for an infinitely thick target.

In conclusion, photons with energies above 10^{20} eV in solids or liquids are more likely to interact hadronically rather than electromagnetically. These hadronic showers are not subject to the LPM effect and so are considerably more compact than purely electromagnetic calculations would predict. At energies above 10^{23} eV, photons are most likely to interact by coherently converting into a ρ, and then interacting hadronically in the target. This is a new example of a coherent process in bulk matter, similar to kaon regeneration or coherent neutrino scattering. This coherent interaction further shortens the shower development. The reduction in photon interaction length will shorten ultrahigh energy electromagnetic showers, altering the radio and acoustic emission. It should be included in the models used in searches for ultrahigh energy astrophysical ν_e.

We thank Volker Koch for useful comments. This work was funded by the U.S. National Science Foundation and the U.S. Department of Energy under Contract No. DE-AC-76SF00098.

[1] D. Saltzberg, Phys. Scr. **T121**, 119 (2005); C. W. James *et al.*, Mon. Not. R. Astron. Soc. **379**, 1037 (2007); P. W. Gorham *et al.*, Phys. Rev. Lett. **93**, 041101 (2004).
[2] J. Vandenbroucke, G. Gratta, and N. Lehtinen, Astrophys. J. **621**, 301 (2005).
[3] S. Klein, Radiat. Phys. Chem. **75**, 696 (2006).
[4] S. Klein, arXiv:astro-ph/0412546.
[5] J. Alvarez-Muniz and E. Zas, Phys. Lett. B **434**, 396 (1998).
[6] J. Ralston, S. Razzaque, and P. Jain, arXiv:astro-ph/0209455.
[7] A. Migdal, Phys. Rev. **103**, 1811 (1956); T. Stanev *et al.*, Phys. Rev. D **25**, 1291 (1982).
[8] S. Klein, Rev. Mod. Phys. **71**, 1501 (1999).
[9] K. Kleinknecht, Fortschr. Phys. **21**, 57 (1973).
[10] J. Liu, Phys. Rev. D **45**, 1428 (1992).
[11] T. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978).
[12] B. I. Abelev *et al.*, Phys. Rev. Lett. **102**, 112301 (2009); S. Klein and J. Nystrand, Phys. Rev. Lett. **84**, 2330 (2000); S. Klein and J. Nystrand, Phys. Lett. A **308**, 323 (2003).
[13] M. Lax, Rev. Mod. Phys. **23**, 287 (1951).
[14] D. Diamond and B. Margolis, Phys. Rev. D **16**, 1365 (1977).
[15] P. Söding, Phys. Lett. **19**, 702 (1966).
[16] S. Klein and J. Nystrand, Phys. Rev. C **60**, 014903 (1999).
[17] W. Fetscher *et al.*, Z. Phys. C **72**, 543 (1996).
[18] R. Engel, J. Ranft, and S. Roesler, Phys. Rev. D **55**, 6957 (1997).
[19] J. Blatt and V. Weisskopf, *Theoretical Nuclear Physics* (Wiley, New York, 1952).
[20] J. A. Crittenden, *Exclusive Production of Neutral Vector Mesons at the Electron-Proton Collider HERA* (Springer-Verlag, Berlin, 1997).
[21] S. Drell and J. Trefil, Phys. Rev. Lett. **16**, 552 (1966); Phys. Rev. Lett. **16**, 832(E) (1966).
[22] T. Rogers and M. Strikman, J. Phys. G **32**, 2041 (2006).