Title:
Coherent rho 0 photoproduction in bulk matter at high energies

Author:
Couderc, Elsa

Publication Date:
08-26-2009

Permalink:
http://escholarship.org/uc/item/88n0m5dk

Copyright Information:
All rights reserved unless otherwise indicated. Contact the author or original publisher for any necessary permissions. eScholarship is not the copyright owner for deposited works. Learn more at http://www.escholarship.org/help_copyright.html#reuse
Coherent $\rho^0$ photoproduction in bulk matter at high energies

Elsa Couderc and Spencer Klein

The IceCube Collaboration

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.
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 neutrinos 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 do not consider these effects may need to be revised.

In this letter, we discuss hadronic interactions of photons [3], and introduce a new effect: coherent photon to $\rho^0$ 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 $\nu$ 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 de-localized 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 $\rho$ conversion, constructive interference raises the cross section.

Photon to $\rho$ 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 [7]. As the photon energy $k$ rises, the required momentum transfer $\Delta k = M_\pi^2/2k$ decreases, and the coherence length $l_f = \hbar/\Delta k$ rises (we take $\hbar = c = 1$ throughout). Here $M_\pi$ is the final state mass. When $k > 3 \times 10^{14}$ eV (for $M_\pi = M_\rho = 778$ MeV/c², the $\rho$ 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 (|$\gamma_b$>), but with a $q\bar{q}$ component, |$q\bar{q}$> and heavier fluctuations (e.g. $q\bar{q}q\bar{q}$, and strange quark pairs):

$$|\psi> = e^{ikz} \left[ \sqrt{1 - F^2} |\gamma_b> + |q\bar{q}> + ... \right] \tag{1}$$

where $F = 6.0210^{-2}$ is the amplitude for the photon to fluctuate to a $q\bar{q}$ pair [7]. Heavier fluctuations are not relevant here, and will not be further considered.

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

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

The photon can be absorbed in the target, with absorption length $\alpha = 1/n[\sigma_{ee}(\gamma A) + \sigma_{hadr}(\gamma A)]$. Here $\sigma_{ee}(\gamma A)$ is the pair production cross section, $\sigma_{hadr}(\gamma A)$ is the photonnuclear cross section, and $n$ is the target density, in atoms/volume.
The $\rho$ can be lost by direct hadronic interaction, or by decay to $\pi^+\pi^-$, followed by $\pi$ interactions. The decay itself does not affect the coherence \[12\], but two $\pi$ interact differently from one $\rho$. For simplicity, we take $\beta = 1/\alpha\Gamma_{tot}(\rho A)$ where $\alpha_{tot}(\rho A)$ is the $\rho$ nucleus cross section. The factor of 2 difference between two $\pi$ and one $\rho$ 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

$$<\rho^0|\psi(L)> = nF\int_0^\infty \eta d\eta \int_0^{2\pi} d\psi \times \int_0^L dz e^{i(k-\frac{\eta^2}{2})z} f(\theta) e^{i(k'-\frac{\eta^2}{2})r'},$$

(3)

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

In an infinite medium only forward scattering, $f(0)$, contributes to coherent scattering \[10, 11, 13\]. We assume that the real part of $f$ contributes to coherent scattering \[10, 11, 13\]. We substitute $\eta d\eta = \eta' dr'$ where $\eta'$ is the distance between the scattering point ($\eta, z$) and the observer at $(0, L)$, to evaluate the integrals \[11\]:

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

(4)

where $A$ and $B$ are the energy-dependent amplitudes for $\rho$ and direct $\pi\pi$ production respectively \[13\], and the $\rho^0$ 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, $\sigma(\gamma p \rightarrow \rho p) = A^2$.

We substitute $\eta d\eta = \eta' dr'$ where $\eta'$ is the distance between the scattering point ($\eta, z$) and the observer at $(0, L)$, to evaluate the integrals \[11\]:

$$<\rho^0|\psi(L)> = 2\pi nF \int_{2m_\pi}^{M_\rho+5\epsilon_\rho} dM_{\pi\pi} f(0, M_{\pi\pi}) \times e^{i(k'-\frac{\eta^2}{2})L} e^{i(kL-\frac{\eta^2}{2})L - 1} \frac{(ik' - \frac{\eta^2}{2})}{(ik - \frac{\eta^2}{2})}$$

(5)

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

$$P_{\rho\rho}(L, M_{\pi\pi}) = 4\pi^2 |f(0)|^2 F^2 n^2 \times \frac{e^{-\alpha L + \epsilon - \beta L} + 2e^{-\frac{\alpha \eta^2}{2}} \cos(\Delta kL)}{(k^2 + \frac{\eta^2}{4})(\Delta k^2 + \frac{(\alpha - \beta)^2}{4})}$$

(6)

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

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

$$P(L) = \int_0^L dz |<\rho^0|\psi(z)>|^2 \over \beta$$

(7)

This equation is only properly normalized for $P(L) \ll 1$. The loss of photon intensity due to the coherent $\rho$ reaction is not included. For kaon regeneration, the analogous problem has been solved recursively \[14\]. Here, we normalize the probabilities to sum to one in thick targets.

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

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

(8)

We determine these using two different methods: a Glauber calculation based on HERA data on $\gamma p \rightarrow \rho p$, 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 \[17\].

We consider three materials: water, standard rock \[9\] and lead. For water, we add the amplitudes for the cross sections for hydrogen and oxygen.

The Glauber calculation uses the optical theorem \[18\] and vector meson dominance model to link the total $pp$ cross section to the differential $\gamma p$ cross section:

$$\sigma_{tot}(\rho p) = 4\sqrt{\pi F} \int \frac{d\sigma(\gamma p \rightarrow pp)}{dt}|_{t=0}$$

(9)

where $t$ is the squared momentum transfer. $d\sigma/dt(\gamma p \rightarrow pp)$ comes from a fit to HERA data \[19\].

The cross sections for nuclear targets are found with a quantum Glauber calculation \[20\]:

$$\sigma_{tot}(\rho A) = 2 \int d^2 \vec{r} \frac{1 - e^{-\sigma_{tot}(\rho p)T_A(\vec{r})}}{2}$$

(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, Rauft and Roessler (ERR) \[17\]. It uses GVMD plus direct photon-quark interactions, to determine $\sigma_{hadr}(\gamma A)$. 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 $\sigma(\gamma \text{Pb}) = 15 \text{ mb}$ at low energies. Again, $\sigma_{\text{tot}}(\rho A) = \sigma_{\text{had}}(\gamma A)/F^2$. The ERR cross sections are similar to a newer result that computed photon cross sections using a dipole model [21].

Figure 1 compares 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).

In conclusion, photons with energies above $10^{20} \text{ eV}$ 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 $10^{23} \text{ eV}$, photons are most likely to interact by coherently converting into a $\rho$, and then interacting hadronically in the target. This is a
FIG. 4: The normalized probabilities for a photon to interact as an $e^+e^-$ pair, via incoherent hadronic interaction (‘hadron’), or as an elastically produced $\rho$ (‘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.

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 ultra-high energy electromagnetic showers, altering the radio and acoustic emission. It should be included in the models used in searches for ultra-high energy astrophysical $\nu_e$.

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 number DE-AC-76SF00098.

[1] D. Saltzberg, Phys. Scripta T121, 119 (2005); C. W. James et al., Mon. Not. Roy. 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, astro-ph/0412546 (2004).
[5] J. Alvarez-Muniz and E. Zas, Phys. Lett. B434, 396 (1998).
[6] J. Ralston, S. Razaque and P. Jain, astro-ph/0209455.
[7] T. Bauer et al., Rev. Mod. Phys. 50, 261 (1978).
[8] A. Migdal, Phys. Rev. 103, 1811 (1956); T. Stanev et al., Phys. Rev. D25, 1291 (1982).
[9] S. Klein, Rev. Mod. Phys. 71, 1501 (1999).
[10] K. Kleinhecht, Forschr. Physik 21, 57 (1973).
[11] J. Liu, Phys. Rev. D45, 1428 (1992).
[12] S. Klein, nucl-ex/0402007; S. Klein and J. Nystrand, Phys. Rev. Lett. 84, 2330 (2000); S. Klein and J. Nystrand, Phys. Lett. A308, 323 (2003).
[13] M. Lax, Rev. Modern Phys. 23 287 (1951).
[14] P. Söding, Phys. Lett. 19, 702 (1966).
[15] S. Klein and J. Nystrand, Phys. Rev. C60 014903 (1999).
[16] W. Fetscher et al., Z. fur. Physik C72, 543 (1996).
[17] R. Engel, J. Ranft and S. Roesler, Phys. Rev. D55, 6957 (1997).
[18] J. Blatt and V. Weisskopf, Theoretical Nuclear Physics (Wiley, New York, 1952).
[19] J. A. Crittenden, Exclusive Production of Neutral Vector Mesons at the Electron-Proton Collider HERA (Springer-Verlag, Berlin, 1997).
[20] S. Drell, Phys. Rev. Lett. 16, 552 (1966); erratum in Phys. Rev. Lett. 16, 832 (1966).
[21] T. Rogers and M. Strikman, J. Phys. G32, 2041 (2006).