TeV γ-rays and neutrinos from nuclei photodissociation

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Abstract. In astrophysical sources, TeV gamma-rays may originate by means of two well-know mechanisms: via electromagnetic or hadronic processes. In this talk we discuss a third mechanism: the photodisintegration of nuclei at the source, followed by de-excitation of the daughter nuclei. We examine the conditions that need to be satisfied in the source so that a relevant contribution to the TeV gamma-ray flux may come from this mechanism and we also present the distinctive features of this dynamical framework, as is the absence of low energy counterparts. We also comment on the concomitant associated flux of antineutrinos coming from the β-decay of stripped neutrons, which turns out to be smaller than that of gamma-rays.

There are two well-known mechanisms for generating TeV γ-rays in astrophysical sources [1]. The first involves purely electromagnetic processes, including electron bremsstrahlung, synchrotron radiation and inverse Compton scattering. In the second, which may be termed hadronic, the γ-rays originate in π^0 decays, which in turn are produced in pp or $p\gamma$ interactions.

In this talk, based on Refs. [2, 3], we discuss a third dynamical framework which can lead to TeV γ-rays: the photodisintegration of nuclei at the source, followed by the photo-de-excitation of the daughter nuclei [4]. If a highly relativistic nucleus propagates in a photon background and its boost factor is such that photo-excitation via the Giant Dipole Resonance (GDR) is possible ($\epsilon_\gamma \sim 10$ MeV $-$ 30 MeV in the nucleus rest frame), then the emission of MeV gamma-rays (along with one or more nucleon) from the excited daughter nucleus (in the rest frame of the nucleus) may take place. The production of TeV γ-rays means that the GDR energy can only be reached if the ambient photons have energies in the far ultraviolet, which is expected from photons from the Lyman α emissions of hot stars.

Therefore, when a nucleus propagates in a photon background, there are two processes by which γ-rays may be produced: photo-disintegration of the nucleus followed by de-excitation of a daughter nucleus, or photopion production followed by decay of the neutral pions. The two processes have different thresholds and different signatures. Here we are concerned with the former mechanism, emphasized more than a decade ago by Moskalenko and collaborators [5], but largely ignored by the rest of the γ-ray community.

The interaction between photons and high energy nuclei results in the emission of nucleons. The relevant photonuclear interaction process for the relevant energies has been studied from the point of view of the collective model and the shell model [6]. It is shown that collective nuclear states dominate the interaction, with low angular momentum modes preferred. In the energy region which extends from threshold for single-nucleon emission ~ 10 MeV up to $\sim$ 30 MeV the GDR dominates. The GDR de-excites by the statistical emission of a single nucleon. Above the GDR region, and up to the photopion production threshold at $E_{\rm th}^{\pi} = m_\pi (1 + m_\pi/2m_N) \simeq 145$ MeV, the non-resonant processes provide a much smaller cross-section with a relatively flat dependence on energy.

The photo-disintegration rate for a highly relativistic nucleus with energy $E = \gamma A m_N$ (where γ is the boost factor) traversing a photon background with energy ϵ and spectrum $n(\epsilon)$, normalized so that the total number of photons in a box is $\int n(\epsilon) d\epsilon$, is given by [7]

$$R_A = \frac{1}{2} \int_0^\infty \frac{n(\epsilon)}{\gamma^2 \epsilon^2}\, d\epsilon \int_0^{2\gamma\epsilon} \epsilon' \, \sigma_A(\epsilon')\, d\epsilon' \,, \tag{1}$$

where $\sigma_A(\epsilon')$ is the cross section for photodisintegration of a nucleus of mass A by a photon of energy ϵ' in the rest frame of the nucleus.

For the considerations of the persent work, in the above expression, the total photoabsorption cross section can be approximated by a single pole, so the photodisintegration rate simplifies to

$$R_A \approx = \frac{\pi\, \sigma_0\, \epsilon'_0\, \Gamma}{4\gamma^2} \int_{\epsilon'_0/2\gamma}^\infty \frac{d\epsilon}{\epsilon^2}\; n(\epsilon)\,. \tag{2}$$

where ϵ'_0 is a central value of the GD energy band, Γ is a width and σ_0 is the normalization of the cross section. Their numerical values are given by $\sigma_0/A = 1.45 \times 10^{-27}{\rm cm}^2$, $\Gamma = 8$ MeV, and $\epsilon'_0 = 42.65 A^{-0.21}\, (0.925 A^{2.433})$ MeV, for $A > 4$ ($A \leq 4$) [8].

After the high energy nuclei interact with the photon field entering the GDR region, the nucleus is left in an excited state which will go over into an underlying state emitting γ-rays [5]. Some early semiquantitative statistical-model calculations for the production of γ-rays through the decay of the GDR in the ^{56}Fe nucleus showed that the mean energy of the γ-spectrum is $\overline{E'_{\gamma 56}} \sim 2-4$ MeV and the average multiplicity is $\overline{n_{56}} \sim 1-3$ [9]. Previous measurements showed that for the case of ^{16}O, the corresponding values are $\overline{E'_{\gamma 16}} \sim 5-7$ MeV and $\overline{n_{16}} \sim 0.3-0.5$ [10]. Hence, in the observer system, these relativistic nuclei are a source of directional γ-rays with energy of the order $\sim \gamma$ MeV.

The energy behavior for TeV γ-rays is a complex convolution of the energy distributions of the various nuclei participating in the photodisintegration, with the rate factors appropriate to the eV photon density for the various stellar populations. If we approximate the γ-ray spectrum as being monochromatic, with energy equal to its average value ($\overline{E'_{\gamma A}}$), the emissivity of γ-rays coming from nuclei de-excitation can be written as [5]

$$Q_\gamma^{\rm dis}(E_\gamma) = \sum_A \frac{\overline{n_A} m_N}{2\overline{E'_{\gamma A}}} \int_{\frac{m_N E_\gamma}{2\overline{E'_{\gamma A}}}} \frac{dn_A}{dE_N}(E_N)\, R_A\, \frac{dE_N}{E_N}\,. \tag{3}$$

where $\overline{n_A}$ is the mean γ-ray multiplicity for a nucleus with atomic number A and

$$\sum_A \frac{dn_A}{dE_N}(E_N) = \sum_A N_A \left(\frac{E_N}{E_0}\right)^{-\alpha} \,, \tag{4}$$

where N_A is a normalization constant, $E_0 = 1$ TeV and E_γ is the energy of the emitted γ-ray in the lab.

The γ-ray emissivity is related to the differential flux at the observer's site (assuming there is no absorption) as

$$\frac{dF_\gamma}{dE_\gamma}(E_\gamma) = \frac{V_{\rm dis}}{4\pi d^2}\, Q_\gamma^{\rm dis}(E_\gamma) \tag{5}$$

where V_{dis} is the volume of the source region and d is the distance to the observer.

It is clear that if the photodisintegration rate is weakly dependent on E_N, then the observed γ-ray flux will display the same power law behavior than the nuclei population. Haim Goldberg showed at this Conference, in the context of an explanation to the HEGRA data from the direction of Cygnus OB2 in terms of the mechanisms described here, that this occurs in this stellar association in the energy region 1 TeV $\lesssim E_\gamma < 10 \lesssim$ TeV corresponding to a boost factor $10^6 \lesssim \gamma \lesssim 10^7$.

Additionally, the important role played by the GDR in the photodisintegration effectively sets a *lower* limit on the resulting γ-ray energy, with no counterpart at lower energies, which is a distinctive feature of this mechanism.

On the other hand, the interaction of nuclei with the background photons also produces a beam of neutrons. The decay mean free path of a neutron is $c\,\gamma\,\overline{\tau}_n = 9.15\,(E_n/10^9$ GeV) kpc, the lifetime being boosted from its rest-frame value $\overline{\tau}_n = 886$ seconds to its lab value via $\gamma = E_n/m_n$. This means that for source distance $d \gtrsim 1$ kpc, practically all neutrons with $E_n \sim 10^6$ GeV will decay *en route* to Earth, producing a flux of directional antineutrinos. Approximating the antineutrino spectrum from β-decay by a monochromatic spectrum with energy equal to the average energy (ϵ_0) and the neutron decay probability by a step function at some energy $E_n^{\max} \sim \mathcal{O}(m_n\, d/\overline{\tau}_n) = (d/9.15$ kpc) $\times\, 10^9$ GeV, the expression that relates the neutron flux at the source (dF_n/dE_n) to the antineutrino flux observed at Earth ($dF_{\overline{\nu}}/dE_{\overline{\nu}}$) is simplified to [11]

$$\frac{dF_{\overline{\nu}}}{dE_{\overline{\nu}}}(E_{\overline{\nu}}) = \frac{m_n}{2\,\epsilon_0}\int_{\frac{m_n\,E_{\overline{\nu}}}{2\,\epsilon_0}}^{E_n^{\max}} \frac{dE_n}{E_n}\,\frac{dF_n}{dE_n}(E_n)\,. \tag{6}$$

The neutron emission can be related to the γ-ray flux only if photodeexcitation following photodissociation is unsuppressed. Thus, a *lower* bound for neutron emissivity (and resulting antineutrino flux) may be obtained by finding this relation. For a transition in which an average of $\overline{n_{30}}$ γ-rays are emitted during deexcitation, an average of $\sim 1/2$ neutron is emitted during the stripping (there is almost equal probability of emission of n and p). Thus the antineutrino emissivity at production can be related to the γ-ray emissivity as

$$Q_{\overline{\nu}_e}^{dis}(E_{\overline{\nu_e}}) = \frac{1}{2\,\overline{n}\,\alpha}\left(\frac{2\,\epsilon_0}{\overline{E'_\gamma}}\right)^{\alpha-1} Q_\gamma^{dis}(E_{\overline{\nu}_e}) \tag{7}$$

where α is the spectral index of the photon population. Bearing in mind that typically $\alpha \gtrsim 2$, $\overline{n} \sim \mathcal{O}(1)$ and $2\,\epsilon_0 \lesssim \overline{E'_\gamma}$, the antineutrino flux will render smaller than the associated γ-ray flux by about an order of magnitude.

On the other hand, as noted above, there are other ways of producing TeV γ-rays from a source of highly relativistic nuclei: photo-meson production and interactions with the cold ambient interstellar medium. In both cases, γ-rays (neutrinos) are produced after π^0 (π^+, π^-) decays. However, the former mechanism has a very high energy threshold, being only relevant for very high energetic beams or in very hot photon enviroments. Hence, it will be important to study when the mechanism described in this talk will be dominant over the case of nucleus-proton collisions.

It will be shown elsewhere that the ratio of the γ-ray emissivity due to these two mechanisms, for the particular case of a power-law index $\alpha = 2$, is given by

$$R^\gamma_{Ap/dis}(\alpha = 2) \equiv \frac{Q_\gamma^{Ap}(E_\gamma)}{Q_\gamma^{dis}(E_\gamma)} \simeq 0.1\left(\frac{n_H}{0.1\,\text{cm}^{-3}}\right)\left(\frac{A}{30}\right)^{3/4}\left(\frac{10^{-5}\,\text{yrs}^{-1}}{R_A}\right)\left(\frac{0.005}{Z_{A\gamma}(\alpha = 2)}\right) \tag{8}$$

where n_H is the interstellar medium density, A is the nuclei atomic number and $Z_{A\gamma}(\alpha)$ is the so-called Z-factor.

Hence, γ-rays produced by the de-excitation of nuclei after photodissociation in a photon background might well be the primary contribution to a TeV signal should a low density interstellar medium be present.

On the other hand, the ratios of antineutrinos (after taken into account oscillations) due to the two mechanisms are given by

$$R^{\nu_\mu}_{Ap/dis}(\alpha = 2) \simeq 4.2 \left(\frac{n_H}{0.1\,\mathrm{cm}^{-3}}\right) \left(\frac{A}{30}\right)^{3/4} \left(\frac{10^{-5}\,\mathrm{yrs}^{-1}}{R_A}\right) \tag{9}$$

$$R^{\nu_e}_{Ap/dis}(\alpha = 2) \simeq 1.8 \left(\frac{n_H}{0.1\,\mathrm{cm}^{-3}}\right) \left(\frac{A}{30}\right)^{3/4} \left(\frac{10^{-5}\,\mathrm{yrs}^{-1}}{R_A}\right) \tag{10}$$

which agrees with the prediction for the antineutrino population from neutron and pion decay, that leads to the flavor ratios $\sim$ 5:2:2 and $\sim$ 1:1:1, respectively. Therefore, even if the TeV γ-ray flux is dominated by de-excitation of daughter nuclei after photodissociation, the antineutrino population will be, in general, dominated by pion decay. Note that for typical values of the parameters, if the population of γ-rays is the same from both mechanism, the number of antineutrinos is ~ 40 times larger in the case of π decays.

To conclude, we have presented a mechanism for the generation of TeV γ-rays (and antineutrinos) based on nuclei photodissociation in a photon background (in regions rich in hot stars), which presents a sharp low energy cutoff, with no counterpart at lower energies, and that may dominate over the π production and decay mode in low density interstellar media. In addition, we have shown that the concomitant stripped neutrons will β-decay to give rise to an associated flux of TeV antineutrinos, which will be smaller than the flux of gamma-rays.

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