

TeV γ -rays via nuclei de-excitation: HEGRA source

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Abstract. It is possible that TeV γ rays can originate in the photo-deexcitation of a PeV nucleus following photodisintegration via the Giant Dipole Resonance in an environment rich in Lyman alpha photons. This mechanism is examined as a candidate explanation of the recently discovered HEGRA source. The ultra-violet photon background results from the rich O and B star environment of the CygnusOB2 association. A signature of the mechanism is the existence of a lower limit ~ 500 GeV on the γ -ray spectrum. The conditions for an measurable accompanying neutrino flux from neutron decay are assessed.

[This talk is based on a manuscript in preparation, in collaboration with L. Anchordoqui, J. Beacom, S. Palomares-Ruiz and T. Weiler.]

In a previous talk at this Conference, Sergio Palomares-Ruiz has introduced a dynamical framework for source of TeV γ -rays with no apparent radio counterpart: the photodisintegration of nuclei at the source, followed by the photo-de-excitation of the daughter nuclei [1]. In order to generate TeV γ -rays as a result of emission of MeV γ -rays in the rest frame of the de-exciting nucleus, the Lorentz factor of the boosted nucleus must be $\sim 10^6$. For this boost factor, excitation via the “Giant Dipole resonance” (~ 10 MeV – 30 MeV in the nucleus rest frame) is obtained with ambient photons with energies in the far ultraviolet. Photons of these energies are expected from the Lyman α emissions from hot stars. The important role played by the Giant Dipole resonance in the photodisintegration effectively sets a *lower* limit on the resulting γ -ray energy. In this talk, the viability of these ideas will be tested in providing a dynamical framework for the recently reported and previously unidentified HEGRA source [2].

The HEGRA experiment [2] has reported significant activity (at the 7σ level) in the TeV region from an unidentified source which is within 0.5° of the Cygnus X-3 X-ray binary. The strength of the source, and the distinct absence of an X-ray counterpart, make this source a good candidate for probing the nucleus photodisintegration \rightarrow deexcitation model for producing TeV γ -rays. Especially intriguing is the possible association of the TeV HEGRA source with Cygnus OB2, a cluster of about 2600 ± 400 OB stars [3], ≈ 5000 light years from Earth. The cluster shows no evidence of supernova remnants, and is estimated to have a wind mechanical luminosity budget $L_w \sim (1 - 2) \times 10^{39}$ erg s $^{-1}$. The recently observed TeV γ -rays originate in the northeast boundary of the association [2]. In this talk, I present a model for explaining the HEGRA observations, in which trapped high energy nuclei undergo stripping on the starlight background and their surviving fragments emit γ -rays in transition to their ground states.

The observation of the Cygnus region by the HEGRA IACT-system [4] has allowed the serendipitous discovery of a TeV source with hard injection spectrum on the outskirts of the

core of Cygnus OB2 [5]. The energy spectrum is characterized by a hard photon index,

$$\frac{dF_\gamma}{dE_\gamma} = 6.2 (\pm 1.5_{\text{stat}} \pm 1.3_{\text{sys}}) \times 10^{-13} \left(\frac{E_\gamma}{\text{TeV}} \right)^{-1.9(\pm 0.1_{\text{stat}} \pm 0.3_{\text{sys}})} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}. \quad (1)$$

So far no clear counterparts at other wavelengths have been identified, and moreover, the observed spectrum is not easily accommodated with synchrotron radiation by electrons [5]. The difficulty to accommodate the spectrum by conventional electromagnetic mechanisms has been exacerbated by the failure of CHANDRA and VLA to detect X-rays or radiowaves signaling acceleration of any electrons [6], although a displaced jet mechanism is still viable [5]. A hadronic explanation is difficult in the face of low estimates for ambient proton densities [7]. With no single compelling explanation for the various characteristics of this source, we present a new mechanism for explaining the HEGRA data.

The interaction between photons and high energy nuclei results in the emission of nucleons. In the energy region which extends from threshold for single-nucleon emission ~ 10 MeV up to ~ 30 MeV the Giant Dipole resonance (GDR) dominates. The GDR de-excites by the statistical emission of a single nucleon.

The photo-disintegration rate for a highly relativistic nucleus with energy $E = \gamma Am_N$ (where γ is the Lorentz factor) propagating through a photon background with energy ϵ and spectrum $n(\epsilon)$, normalized so that the total number of photons in a box is $\int n(\epsilon)d\epsilon$, has been obtained by Stecker [8]. If one roughly approximates the cross sections found by a direct fit to data [9] by a single pole, one obtains a simple expression for the disintegration rate

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

where the ϵ'_0 is the central value of the GD energy band, and σ_0 , Γ are A -dependent cross section pole residues and widths, with numerical values taken from [9].

The ingredients necessary for calculating the photodisintegration rate from a given region of the OB association are (i) an ambient photon distribution in order to obtain the rate R_A^* due to starlight and (ii) an initial population density of \sim PeV nuclei n_A in the region. Energies of \mathcal{O} (PeV/nucleon) are achieved through re-acceleration in strong winds of the OB stars. The calculation of the disintegration rate to lowest order will be justified *a posteriori*, where it will be seen that *at most one nucleon will be stripped in the region of interest during the diffusion time within the association*.

The photon background will be assumed to result from the thermal emission of the stars in the region R . The average density in the region will reflect both the temperatures due to emission from O and B stars, and the dilution resulting from inverse square law considerations. Details will be given in the completed manuscript.

In Fig. 1 we show the dependence on the Lorentz factor of R_{56}^* , R_{30}^* and R_4^* . In all cases, the disintegration time exceeds the diffusion time ($\sim 10^4$ yr [11]) of the nucleus in the association. Thus, the *a priori* assumption of a lowest order calculation has been justified.

The low energy cutoff on R_A^* seen in Fig. 1 will be mirrored in the resulting photon distribution. The E^{-2} energy behavior of the various nuclear fluxes will not substantially affect this low energy feature, and it is a robust consequence of the model.

After the high energy nuclei interact with the photon field entering the giant resonance region, the nucleus is left in an excited state which will go over into an underlying state emitting γ -rays [12]. Following various analyses for iron [13] and oxygen [14], we interpolate and take for mean energy of of the γ -spectrum of Si ($A = 30$) to be $E'_{\gamma 30} \sim 1$ MeV and for the average multiplicity $\overline{n_{30}} \sim 2$. Hence, in the observer system, these relativistic nuclei are a source of directional γ -rays with energy of the order $\sim \gamma$ MeV.

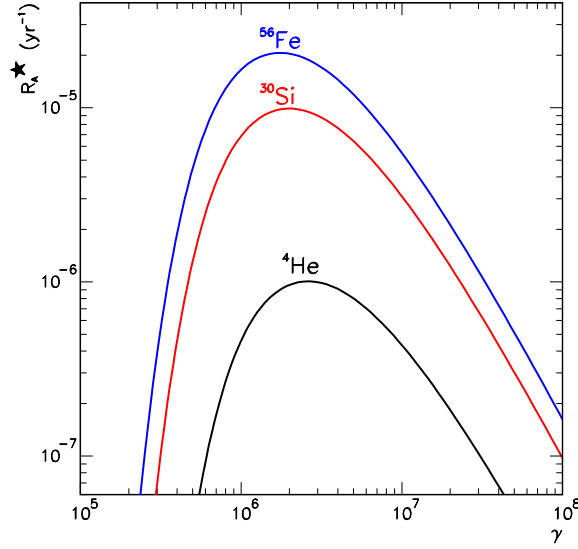


Figure 1. Photo-disintegration rate of ^{56}Fe , ^{30}Si , and ^4He on the Cygnus OB2 starlight.

We now proceed to find the nuclear population necessary to account for the HEGRA flux. The flux is given by

$$\frac{dF_\gamma}{dE_\gamma}(E_\gamma) = \frac{V_{\text{dis}}}{4\pi D^2} Q_\gamma^{\text{dis}}(E_\gamma) \quad (3)$$

where V_{dis} is the volume of the source region, D is the distance to the observer. The photon emissivity $Q_\gamma^{\text{dis}}(E_\gamma)$ is in turn given by

$$Q_\gamma^{\text{dis}}(E_\gamma) = \sum_A \frac{\bar{n}_A m_N}{2\bar{E}'_{\gamma A}} \int_{\frac{m_N E_\gamma}{2\bar{E}'_{\gamma A}}} \frac{dn_A}{dE_N}(E_N) R_A \frac{dE_N}{E_N}. \quad (4)$$

with $\bar{E}'_{\gamma A}$ (\bar{n}_A) the mean gamma ray energy (multiplicity), and dn_A/dE_N the population density. It is clear from Eq. (4) that if R_A^* is weakly dependent on E_N then the observed γ -ray flux will display the same power law behavior than the nuclei population. The HEGRA data shows an approximate E^{-2} behavior for $1 \text{ TeV} \lesssim E_\gamma \lesssim 10 \text{ TeV}$ corresponding to a boost factor $10^6 \lesssim \gamma \lesssim 10^7$. Remarkably, as can be seen in Fig. 1, R_A^* varies by a factor of only 2 precisely in this region, far less than the 2 orders of magnitude of the primary nucleus flux. Therefore, in the presently proposed model the photon flux follows the parent population of nuclei in the PeV/nucleon energy region.

Saturation with a single nucleus species (say Si) and matching with the HEGRA data (with an E^{-2} power law) yields a Si density at the source, at an energy of 1 PeV. When compared with the observed diffuse cosmic ray nuclear density $dn_{\text{CR,Si}}/dE$ in this energy region [15], we find that the latter is a factor of 10^5 smaller than the required density. This shows explicitly that the required population density at PeV/nucleon must arise from acceleration of much more plentiful nuclei that are trapped at much lower energies. One can also show that, accumulated over the diffusion time of 10^4 yr, the required power density is 2 orders of magnitude smaller than the kinetic energy budget of the entire association.

We have presented in detail the criteria for the model to be viable. There is of course one issue that needs to be addressed – the signal was observed only in a 3 pc radius cell at the edge

of the association. We can only offer the obvious possibility – an increased density of very hot OB stars in the cell of the HEGRA source which provide more efficient trapping and accelerating conditions, as well as a hotter photon background. More understanding can only come with a full Monte Carlo simulation.

Neutrinos

Preceding the deexcitation process which spawns the gamma-ray flux, a PeV-scale neutron flux is generated during the initial photodisintegration. The decay of these neutrons will in turn generate an initial electron antineutrino flux in the TeV range. The details of the calculation of the neutron flux will be presented elsewhere; the antineutrino flux is then obtained in a manner similar to that described in [16]. After allowing for flavor mixing, and carrying out the semi-analytic acceptance analysis described in [17], one finds that for either tracks or showers, the accumulated 15-yr signal from the entire CygnusOB2 region at the IceCube neutrino telescope (now under construction) is well below atmospheric background.

In this context, a critical role may be played by helium. Its much larger prevalence in cosmic rays more than compensates for its smaller stripping rate. Stripping to ^3He with emission of a neutron (but not of a photon) will provide a yield of antineutrinos about a factor of 10 larger than our prediction from silicon or iron, enough to provide a signal at IceCube.

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