TeV gamma-rays from photo-disintegration/de-excitation of cosmic-ray nuclei

L. A. Anchordoqui, J.F. Beacom, H. Goldberg,
S. Palomares-Ruiz, T.J. Weiler

astro-ph/0611580

Masaki Mori

ICRR CANGAROO group Internal seminar, December 28, 2006

Gamma-ray generation processes

- Electromagnetic (EM)
  - Synchrotron, inverse Compton
- Hadronic (PION)
  - $p + p$ (or $p + \gamma$) $\rightarrow$ ($\pi^0 \rightarrow \gamma\ \gamma$) + X
- **Photo-disintegration/de-excitation (*A**)**
  - Photonuclear process $A + \gamma \rightarrow A'^{*} + X$
  - De-excitation $A'^{*} \rightarrow A' + \gamma$
  - "Double-boost" by $\Gamma_A = E_A^{LAB}/m_A > 10^6$ (eV starlight $\rightarrow$ TeV gamma-ray)
  - Ref. F. Stecker, Phys.Rev.180, 1264 (1969)

F. Stecker, Phys.Rev.180, 1264 (1969)

Photo-disintegration cross section

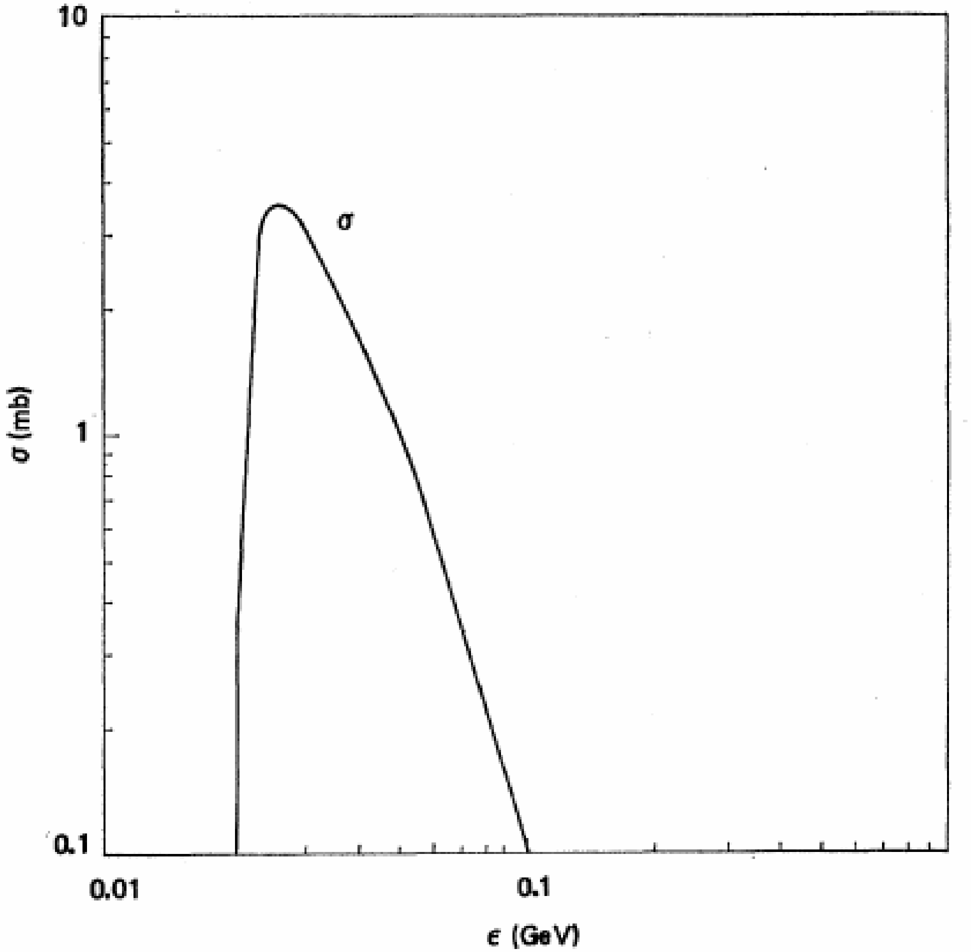


FIG. 1. Total cross section for the processes $He^4(\gamma,p)H^3$ and $He^4(\gamma,n)He^3$ as a function of γ-ray energy in the He rest system.

Scenario (1)

- Photo-disintegration of parent *A*
  - Giant Dipole Resonance (GDR)
    - At ε_γ^{GDR}~10-30 MeV (rest frame)
    - Ambient photon $\varepsilon = \varepsilon_\gamma^{GDR}/\Gamma_A$
    - Decays by emission of a single nucleon
- De-excitation of daugher (*A*-1)*
  - Emitting one or more photons
    - ε_γ^{dxn}~1-5 MeV (rest frame)
    - $\varepsilon_\gamma^{LAB} = \Gamma_A \, \varepsilon_\gamma^{dxn}$

http://www.kvi.nl/~annrep/ar1997/node5.html

An example of GDR

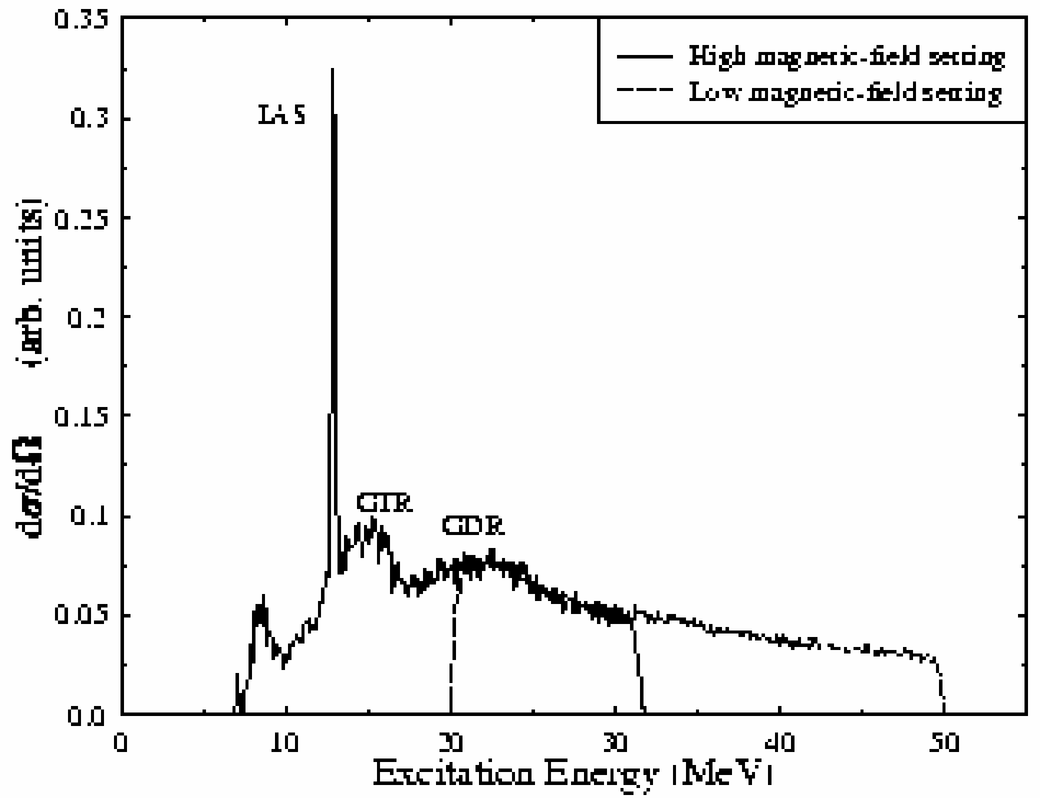


Figure: *Corrected neutron-coincident spectrum.*

The total neutron-coincident spectrum was obtained after correcting for multiplicity The Isobaric Analog State (IAS), Gamow-Teller resonance (GTR) and Giant Dipole Resonance (GDR) can clearly be seen.

Scenario (2)

- $\varepsilon\ \varepsilon_\gamma^{\mathrm{LAB}} \sim \varepsilon_\gamma^{\mathrm{GDR}}\,\varepsilon_\gamma^{\mathrm{dxn}}$ since $\varepsilon_\gamma^{\mathrm{GDR}}$, $\varepsilon_\gamma^{\mathrm{dxn}}$ are distributed (Lorentzian or Breit-Wigner)
- Thus, *A** process produces gamma-rays with energy

  $\varepsilon_\gamma^{\mathrm{LAB}} \sim \varepsilon_\gamma^{\mathrm{GDR}}\,\varepsilon_\gamma^{\mathrm{dxn}}/\varepsilon \sim 20$ TeV/(T/eV)

  if there exists and accelerated nuclear flux with boost

  $\Gamma_{\mathrm{A}} \sim \varepsilon_\gamma^{\mathrm{GDR}}/\varepsilon \sim 7\times10^6$(T/eV)

  or equivalent energy

  $E_{\mathrm{A}}^{\mathrm{LAB}} \sim 7$ PeV/(T/eV) per nucleon.

Ambient photon

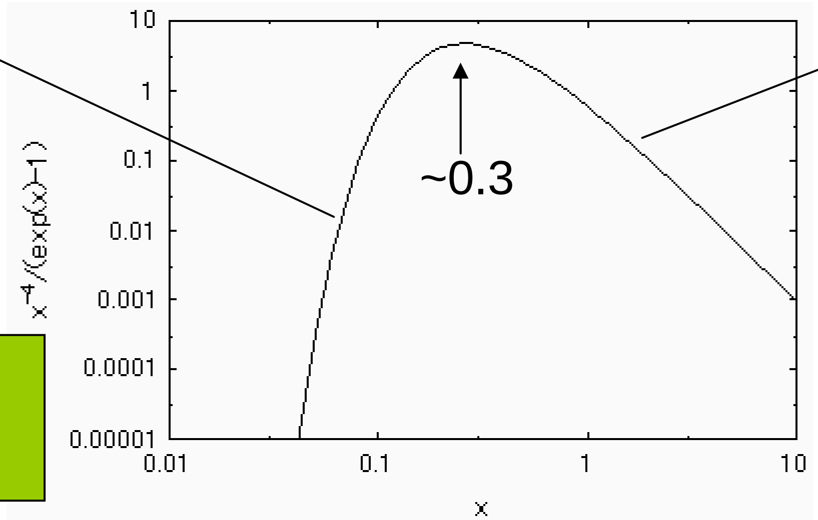
- Bose-Einstein distribution: $\varepsilon \sim 2.82T$
- *A** process may dominate in regions which contains far-UV photons.
  - Lyman-α emission of young, massive, hot stars such as O and B stars
    - T_*~40,000K (4.6eV) / 18,000K (2.1eV)
    - Shocks, giant winds, etc. may accelerate nuclei above PeV per nucleon
    - Starburst regions such as Cygnus OB associations

Gamma-ray spectrum

- Narrow width approximation for ε_γ^{GDR}, ε_γ^{dxn}
- Spectrum follows Bose-Einstein distribution for $\varepsilon = \varepsilon_\gamma^{GDR}\,\varepsilon_\gamma^{dxn}/\varepsilon_\gamma^{LAB}$

$$\frac{dn(\varepsilon_\gamma^{LAB})}{d\varepsilon_\gamma^{LAB}} \propto (\varepsilon_\gamma^{LAB})^{-4}[\exp(\varepsilon_\gamma^{GDR}\varepsilon_\gamma^{dxn}/\varepsilon_\gamma^{LAB}T)]^{-1}$$

Exponential suppression



Power -law

Lower limit below ε_γ^{LAB} ~ 20 TeV/(T/eV)

"Orphan" TeV sources??

A* rate (1)

- GDR cross section

$$\sigma_A(\varepsilon) \xrightarrow{NWA} \tfrac{\pi}{2}\sigma^{GDR}\Gamma^{GDR}\delta(\varepsilon_\gamma{}^{GDR} - \Gamma_A\varepsilon)$$

  where σ^{GDR}=1.45A$\times$10^{-27}cm^2, Γ^{GDR}=8 MeV, ε_γ^{GDR}=42.65$A^{-0.21}$(A>4) and 0.925$A^{2.433}$(A$\leq$4)

- Mean free path for a nucleus with energy $\Gamma_A m_A$

$$(\lambda_A)^{-1} \xrightarrow{NWA} \frac{\pi\sigma^{GDR}\varepsilon_\gamma{}^{GDR}\Gamma^{GDR}}{4\Gamma_A{}^2}\int_{\varepsilon_\gamma{}^{GDR}/2\Gamma_A}^{\infty}\frac{d\varepsilon}{\varepsilon^2}\frac{dn(\varepsilon)}{d\varepsilon}$$

  For thermal photons

$$(\lambda_A{}^{BE})^{-1} \approx \frac{\sigma^{GDR}\Gamma^{GDR}}{\varepsilon_\gamma{}^{GDR}}\left(\frac{T^3}{\pi}\right)w^2\left|\ln(1-e^{-w})\right|$$

  where $w \equiv \varepsilon_\gamma^{GDR}/ 2\Gamma_A T$.

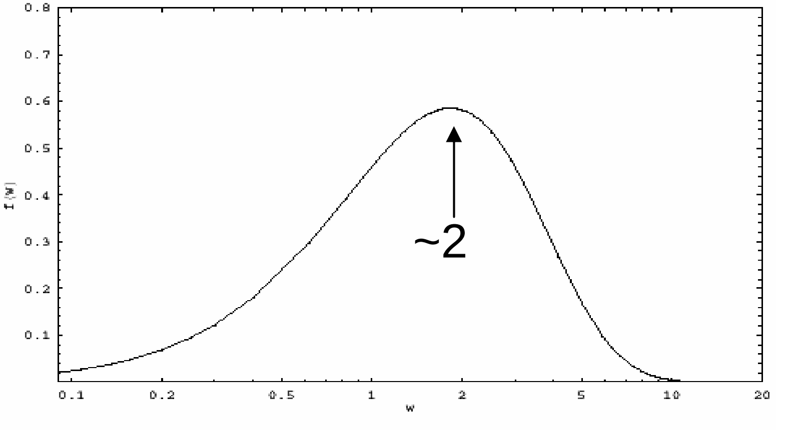


FIG. 1: The scaling function $f(w) = w^2\,|\ln(1-e^{-w})|$.

A* rate (2)

- Rough estimation:
  For $\Gamma_A \sim \varepsilon_\gamma^{GDR}/T$, $\Gamma^{GDR}/\varepsilon_\gamma^{GDR} \sim 3$,
  $$(\lambda_A^{BE})^{-1} \approx \sigma^{GDR} T^3 / \pi$$
  Using $n_\gamma^{BE} = 2\zeta(3) T^3 / \pi^2 \cong T^3 / 4$
  $$\lambda_A^{BE} \sim \frac{5\times 10^{13}\,\mathrm{cm}}{A(T/\mathrm{eV})^3} \sim \frac{3\mathrm{AU}}{A(T/\mathrm{eV})^3}$$
  for a nucleus with energy in the peak regime around $E_A \sim 10A$ (T/eV) PeV.
- Multiple steps?
  - Unlikely since $D/\lambda \ll 1$. (D: diffusion scale)

Starburst regions (1)

- Starlight photons: $\langle\varepsilon\rangle \sim 3T_*$
  - Density: $N_* \times 4\pi R_*^2 / 4\pi R_{SB}^2$
    (R_{SB}: loss surface of the starburst region)
  - $R_* \sim 10R_\odot$, $R_{SB} \sim 10$pc, $N_* \sim 2600 \rightarrow 10^{-12}$
  - $\lambda_A \sim (56/A)(2.1\text{eV}/T)^3 \times 10^{23}$cm
    - 95% are B type with $T_* \sim 2.1$eV
  - Cyg OB: diffusion time $\sim 10^4$yr$\sim 10^{22}$cm
    $\rightarrow$ A few percent of nuclei photo-disintegrate
- A GDR produce 0.5-2 gamma-rays
  - ~One photon per nuclear de-excitation

Starburst regions (2)

- Integral gamma-ray flux at Earth with ε_γ^{LAB} above a few TeV (eV/T):

$$F_\gamma = \frac{V_{A*}}{4\pi d^2}\frac{1}{\lambda_A^{BE}}F_A$$

- where $F_A(=cn_A)$ is an integral over peak: A(eV/T)PeV $<E_A<10A$(eV/T), V_{A*} is source region volume.
- Cyg OB2: R_{SB}=10pc, $\lambda_A=(56/A)\times10^{23}$cm, d=1.7kpc $\rightarrow$ $F_\gamma=2\times10^{-10}\mathrm{A}F_A$
  - Or f(cm^{-2}s^{-1}) in PeV at Cyg OB2 $\rightarrow$ $10Af\, F_{Crab}$ in TeV at Earth
  - $f_{56}=6\times10^{-10}$cm^{-2}s^{-1} to produce 3%Crab as HEGRA, which is ~1% of the kinetic energy budget of Cyg OB2

See accompanying paper: astro-ph/0611581

Accompanying paper: astro-ph/0611581

Cyg OB2

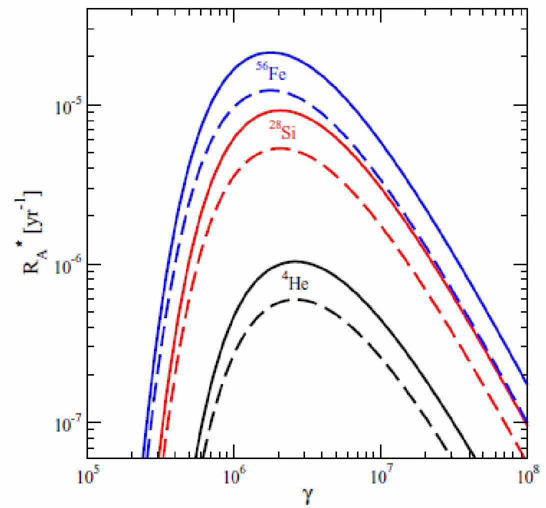


FIG. 3: Photo-disintegration rate of ^{56}Fe, ^{28}Si, and ^{4}He on the Cygnus OB2 starlight. Solid (dashed) lines represent the simplified (more elaborate) model as described in the text.

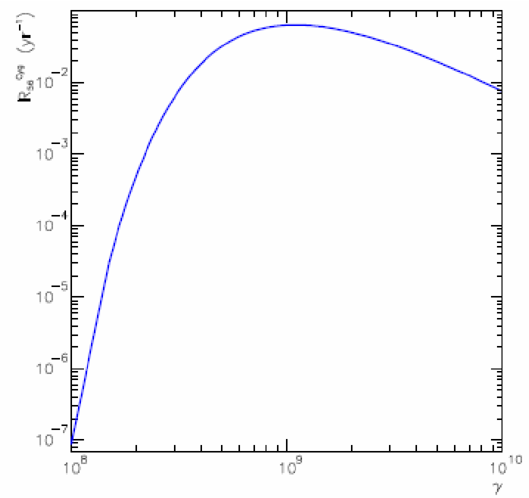


FIG. 4: Photo-disintegration rate of ^{56}Fe on the T = 50 K Cygnus OB2 blackbody radiation as given by Eq. (8).

Primary quanta	γ production mech.	ν production mech.	Number ratio	Energy ratio	comments
A	$A \to A^* \to \sim \overline{n_A}\,\gamma + A$ $[E_\gamma \sim \gamma_A\,\overline{E'_{\gamma A}}]$	$A \to n \to \overline{\nu}_e$ $[E_\nu \sim \gamma_A\,\epsilon_0]$	$\gamma:\nu \sim \overline{n_A} : 1/2$	$\frac{E_\gamma}{E_\nu} \sim \frac{\overline{E_A}}{\epsilon_0}$ $\sim 4-8$	observation of ν's at IceCube depends on ^{4}He abundance
p	$p \to \pi^0 \to 2\,\gamma$ $[E_\gamma \sim \frac{1}{10}\,E_p]$	$p \to \pi^\pm \to 3\,\nu$ $[E_\nu \sim \frac{1}{20}\,E_p]$	$\gamma:\nu \sim 1:3$	$\frac{E_\gamma}{E_\nu} \sim 2$	ν's ARE seen at IceCube
e-plasma	synchrotron inverse Compton	none			

TABLE I: Comparison of γ-ray and neutrino emission from A, p, and e primaries. Note that per γ-ray, an order of magnitude fewer neutrinos are expected from nuclei photodisentigration than from hadronic interactions followed by pion decays. Note also that the neutrino energy from the nuclei photo-disintegration is typically about one order of magnitude smaller than the γ-ray energy. When the primaries are electrons, only γ-rays are produced, but not neutrinos.

Energy spectrum

- In rest frame of nucleus, photon is emitted isotropically. In LAB frame:

$$\frac{dn_\gamma}{d\varepsilon_\gamma^{LAB}} \propto \int d\cos\theta\, \delta\left[\varepsilon_\gamma^{LAB} - \Gamma_A \varepsilon_\gamma^{dxn}(1+\cos\theta)\right] = \frac{1}{\Gamma_A \varepsilon_\gamma^{dxn}}$$

with $1+\cos\theta = \varepsilon_\gamma^{LAB} / \Gamma_A \varepsilon_\gamma^{dxn}$

which means ε_γ^{LAB} distributes in $[0, 2\Gamma_A\, \varepsilon_\gamma^{dxn}]$ evenly.

- Power spectrum $\propto \varepsilon_\gamma^{LAB}$, integrate power $\propto (\varepsilon_\gamma^{LAB})^2$
  - Peaking at $\varepsilon_\gamma^{LAB} \sim \varepsilon_\gamma^{GDR}\, \varepsilon_\gamma^{dxn}/4T \sim 10$ TeV/(T/eV)

Cosmogenic *A** process

- Photo-disintegration in propagation of UHE cosmic nuclei with CMB and CIRB
  - CMB: T=2.3$\times$10^{-4}eV$\rightarrow$ λ~A^{-1} Mpc for E_A ~4A $\times$ 10^{19}eV
  - CIRB: larger λ but ~10^{16}eV
- Cascading gamma-rays: bounded by EGRET <2$\times$10^{-6}eV/cm^3, but contributions from A* process is three orders of magnitude below the bound.