GeV GAMMA-RAY ASTRONOMY TELESCOPES WITH HIGH ANGULAR RESOLUTION

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ABSTRACT

It is shown that a major improvement in angular resolution for the detection of gamma-rays in the GeV region can be obtained with a single crystal as converter. The electron produced by a gamma-ray incident at a small angle to a major crystal axis or plane is captured into channeling and radiates gamma rays. The channeling radiation and the electron-positron pair can be detected and yield point source locations with a precision of 5 arcseconds at 10 GeV. This is an improvement of three orders of magnitude on the angular precision of telescopes sensitive to gamma-rays above 50 MeV flown on satellites.

1. Introduction. During the past two decades observational gamma-ray astronomy been established as an important branch of astrophysical research. Gamma-ray telescopes flown from high altitude balloons provided the initial detection of the Crab Nebula pulsar. Similar but smaller telescopes were flown aboard the SAS-2 and COS-B satellites. These experiments (1,2) explored the galactic plane emission initially discovered by OSO-3 (3). The SAS-2 and COS-B experiments have detected 26 sources with COS-B making the major contribution (4,5). The identification of the gamma-ray sources with known objects at other frequencies has in all but four cases been unsuccessful. The poor angular resolution of the gamma-ray telescopes flown on satellites, with typical error boxes of a few square degrees, accounts for the failure to identify counterparts for the majority of the gamma-ray sources. The present observational situation emphasises an urgent requirement for telescopes with a major improvement in angular resolution.

2 Pair Production. The most probable opening angle of an electron or positron in pair production is $\theta = 0.8/E_\gamma$ where E_γ is the gamma-ray energy in MeV (6). The limitation results from the scattering in the pair production process due the unobserved momentum of the recoil nucleus. The most probable opening angle of an electron from a 2 GeV gamma-ray is 1.4 arcminutes assuming equipartion of energy between the electron-position pair. For a 100 GeV gamma-ray the opening angle of 1.6 arcseconds is comparable with the resolution of ground based optical telescopes. The cross-section for pair production by gamma-rays incident at small angles to crystal planes and axes has been predicted (7) and verified in experiments at accelerators (8). The cross-section depends on the polarisation of the gamma-rays. The variation of the cross-section above 1 GeV is large and may be used to measure the polarisation of the gamma-rays from cosmic sources.

A new pair creation process has been predicted (9) for high energy gamma-rays aligned with major crystal axes and planes. The crystal assisted cross-section along the <111> axes of heavy elements in equal to the Bethe-Heitler value at 10 GeV and exceeds it by an order of magnitude at 30 GeV. The directional pair creation process, if verified by experiment, predicts a higher efficiency for the detection of gamma-rays incident along major crystal axes and planes.

3 Channeling Radiation. Relativistic electrons and positrons, entering the crystal at a small angle to a major axis or plane and captured into channeling, radiate a characteristic spectrum of x-ray and gamma-rays. The theory of channeling radiation has been experimentally confirmed in experiments at accelerators using single crystals of diamond and silicon (10). The channeling radiation intensity from relativistic electrons is far greater than coherent bremsstrahlung and the bremsstrahlung from electrons travelling at random directions in the crystal. In gamma-ray pair production in a lead crystal the electron-positron pairs are produced near an atomic nucleus except for a small fraction that pair produce in the field of atomic electrons. In a model (11) for axial channeling in high Z materials, like lead, the atomic string is replaced by a tube of charge spread continuously with constant density inside a cylinder whose axis coincides with that of the atomic string. The radius R of the tube is determined by the amplitude of the thermal vibrations of the nucleii. The distance R in high Z materials is comparable with the electron screening radius and small in comparison with the distance d between neighbouring atoms in the string. Electrons with energy $E = \gamma mc^2$ will move inside the tube with angular frequency

$$\omega = \frac{e}{R}\left(\frac{2Z}{md\gamma}\right)^{\frac{1}{2}} \qquad (1)$$

where γ is the Lorentz factor. The positrons, unlike the electrons, will not be channeled as no significant bound states exist. The critical angle for electron capture into channeling is

$$\theta_A = \left(\frac{2Ze^2}{dE}\right)^{\frac{1}{2}} \qquad (2)$$

The values of θ_A, in arcminutes, for the <100>, <110> and <111> axes of lead are 2.4, 2.8 and 3.8 for 1 GeV electron. The electron will be channeled because the opening angle in pair production is smaller than the critical angle. At higher gamma-ray energies the electron will be channeled since θ and θ_A decrease as E^{-1} and $E^{-\frac{1}{2}}$ respectively. The electron may be dechanneled by a single Coulomb scattering through an angle greater than θ_A or by the accumulation of a large number of random scatterings. In lead the length ℓ in which half the electrons will be dechanneled is $\ell = 4\times10^{-7}\gamma$ cm.

In the model adopted for crystal planes, the planes are replaced with layers of positive charge of constant density and thickness 2R. The critical angle for electron capture into the layer is

$$\theta_p = \left(\frac{2\pi RZe^2}{Ed^2}\right)^{\frac{1}{2}} \qquad (3)$$

The angle θ_p refers only to the angle perpendicular to the plane since the angle in the plane can take any value. The angle θ_p is typically three times smaller for planes than axes resulting in a higher gamma-ray threshold for electron capture and channeling. The opening angle of an electron with half the gamma-ray energy and the capture angle into the (100) plane of lead are equal to 0.4 arcminutes for gamma-ray energies of 8 GeV.

The transverse oscillations of the channeled particles generate electromagnetic radiation which has been studies for electrons and positrons entering the crystal. The electron energy loss in lead is typically 10^{-1} γ^2 MeV cm^{-1} for the major axes and 10^{-3} γ^2 MeV cm^{-1} for the major planes (11). In the GeV energy range the channeling radiation is far greater than the bremsstrahlung radiation from electrons travelling at random directions in the crystal. The channeling radiation and bremsstrahlung have different spectral and angular properties providing additional discrimination against the bremsstrahlung background from nonchanneled electrons and positrons.

The maximum frequency of the channeling radiation is given by $\omega_m = \omega\,\gamma^2$ (12). The radiation from the channeled relativistic electrons is in the x-ray and gamma-ray regions and the maximum frequency increases as $\gamma^{3/2}$. For the <111> axis of lead the maximum energy of the radiated photons from 2 GeV electrons is about 100 MeV. For very high energy electrons the transverse motion of the electron is relativistic and the maximum frequency increases as $\gamma^{1/2}$. In channeling radiation the crystal governs the motion of the electron and therefore the halfwidth of the angular distribution is not due to multiple scattering but is determined by the radiation and beamed into an angle $1/\gamma$ where γ is the Lorentz factor of the radiating electron. The bremsstrahlung radiation is beamed into a much larger angle which is determined by the multiple scattering of the electron and positron in the crystal converter.

4 Gamma-Ray Telescopes. In almost all detectors sensitive to gamma-rays about 50 MeV flown on balloons and satellites, the direction of the gamma-ray was deduced from the directions of the electron-positron pair produced in a lead converter with an unspecified polycrystalline structure and recorded in a spark chamber (13,14,15,16). Two major changes in the traditional design of gamma-ray telescopes are required to utilise channeling radiation. [1] The converter should be replaced with a single crystal or a mosaic of aligned single crystals to cover the typical telescope areas of 0.1 to 1 m^2. [2] The drift or spark chambers for the detection of the electron-position pair require additional converters for the pair production and detection of the channeled radiation. In addition since this telescope can operate in both survey and pointed modes, the telescope requires a stabilised platform for pointed observations of selected sources.

A telescope of this type would have the following features: [1] As in conventional gamma-ray telescopes, operating in a survey mode with a large field of view, the directions of the electron and positron can be used to establish the incident direction of the gamma-ray to a precision of about 0.5°. [2] The requirement that the opening angle of the electron in pair production be equal to the capture angle into channeling determines the threshold energy of the detector. The gamma-ray threshold energy in lead for axial and planar channeling is about 2

GeV and 8 GeV. The channeled electron will typically radiate a burst of five or more gamma-rays into an angle of halfwidth $1/\gamma$. The number of bremsstrahlung photons radiated by an electron in a random direction in the crystal is

$$N = \frac{4x}{3t} \ln\left(\frac{\omega_2}{\omega_1}\right) \tag{4}$$

where x is the path length, t is the radiation length and ω_2 and ω_1 are the maximum and minimum frequencies of the detected photons. In a typical gamma-ray astronomy telescope, with x = 0.2 radiation lengths, N will be less than one for the electron and positron. [3] The capture angle of the electron into channeling determines the angular resolution of the telescope. The beamwidths of the axial and planar channels are different. The planar channel beamwidth is determined perpendicular to the crystal plane but in the crystal plane can take any value. The axial and planar channels may be used in point mode operation to map selected sources. The point source location precision will be about one-fifth of the beamwidth or 5 arcseconds at 10 GeV for planar channeling. [4] The gamma-rays from the channeled electron along with the electron-positron pair must be recorded in a spark or drift chamber which includes additional converters for the gamma-rays.

5 Conclusions. It has been shown that a major increase in the angular resolution of gamma-ray astronomy telescopes can be obtained with a crystalline converter. The characteristic signature of a gamma-ray incident at a small angle to a major crystal axis or plane arises from the radiation from the channeled electron that is beamed into an angle $1/\gamma$. The detection of the electron-positron pair and the gamma radiation from the channeled electron can yield point source locations with a precision of 5 arcseconds at 10 GeV.

6. References.

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