POLARIZED GAMMA RAYS FROM SUPERNOVAE

C.Sivaram

Indian Institute of Astrophysics, Bangalore, India
Dept.of Physics, University of Bologna, Italy
World Laboratory, Lausanne, Switzerland

Abstract

It is generally believed that nuclear fusion processes, especially in a type-I supernova terminate with a production of a large quantity (about one $M_{\odot}$) of the isotope Ni-56 which beta decays to Fe-56. The decay sequence produces two high energy positrons for each decay and these positrons would be highly polarized with a 'right' helicity of almost one. The hot ambient medium into which the positrons are released is naturally electron rich, implying that the polarized positrons would also undergo annihilation in flight. The radiation from annihilation of highly polarized energetic positrons emitted from beta decay of unstable isotopes in the supernova material would be strongly (almost 100 per cent) right circularly polarized and in the Mev range. The right circularly polarized gamma radiation would also be accompanied by right circularly polarized hard X-ray bremmstrahlung radiation. Estimates are made of the flux of such radiation from supernovae at kpc and Mpc distances and discussion of their detectability from space-borne apparatus is made.

Introduction Gamma-ray line spectroscopy could provide basic information on important problems in astrophysics. Of special importance is the 0.511 Mev γ-ray line resulting from the annihilation of positrons. This line has been observed during solar flares, from the galactic centre and is also expected to occur in the interstellar medium, supernova remnants and pulsars [Ramaty 1981]. The positrons can be produced for instance by pair production by Mev gamma photons resulting from nuclear reactions on the stellar surface or by the beta decay (β^{+}) of certain nuclei which may also decay by electron capture. However in the stellar case, i.e.when positrons are emitted by beta decay, they will preferentially be in a 'right'-handed helicity state as a consequence of maximal parity non conservation in beta decay. This would mean that the positron spins will be aligned along their direction of flight. Electrons emitted in β-decay would be emitted with a net left handed spin. The "strength" of the polarization or helicity is defined as being $H = \alpha v/c$, where $\alpha = +1$ for positrons, $\alpha = -1$ for electrons and v is the velocity of the emitted particles [Wu 1966]. Massless particles like neutrinos have $v = c$, so that $H = +1$ for antineutrinos and -1 for neutrinos, i.e. they are fully polarized. Thus as a direct consequence of non conservation of parity and handedness of neutrinos [Wu 1966] e^{-} particles emitted in beta decay with velocity v have longitudinal polarization or helicity along their direction of motion of $\pm$ v/c. In terms of the kinetic energy T of the particles:

$$v/c = |H| = (2T/m_e c^2)^{1/2}(1 + T/2m_e c^2)^{1/2}.$$

Thus for a mean energy of ~ 50 kev (like decay of a typical isotope like C-14), this woul imply a polarization of ~ 41% for the beta particles. For Mev energies |H| is almost 100% as v/c → 1, i.e. for relativistic positrons or electrons.

Polarized beta decay and gamma rays from supernovae It is generally believed that nuclear fusion processes in a massive star terminate with a production of a large quantity (about one $M_\odot$) of the isotope Ni-56 at the peak of the binding energy curve. Ni-56 decays by positron emission to Fe-56. The decay sequence is Ni-56 → Co-56 (half life ≈ 6.1 days) and Co-56 → Fe-56 (78.8 days). Most of the energy released in a type-I supernova explosion (and a substantial fraction of the energy in type-II) is ascribed to this decay sequence [Clayton 1983] which produces two high energy positrons for each decay and these positrons (Mev energy) would be highly polarized with a 'right' helicity of almost one. The hot ambient medium resulting from the explosion into which the positrons are released is naturally electron rich implying that the polarized positrons would also undergo annihilation in flight. The energetic positron would strike the electron relatively at rest producing two photons: one along the flight direction of the positron and one in an opposite direction. The forward going annihilation photon which has most of the energy will preferentially have the same helicity as the initial positrons, i.e. the helicity of the positron would be transferred to this photon thus making it 'right' circularly polarized [Page 1957]. Thus the radiation from the annihilation of highly polarized energetic positrons emitted from beta decay of unstable isotopes in the supernova material would be strongly (almost hundred per cent) right circularly polarized and in the Mev range. Detection of these annihilation photons would be an independent confirmation of the presence of the unstable isotopes in supernovae.

Estimate of fluxes About $2\cdot10^{57}$ polarizsd positrons can be expected to be emitted in about 10^7s. As the internal energy is derived from Co-56 decay, luminosity goes as:

$$L(t) = L_o \exp(-t/\tau), \qquad \tau = 78 \text{ days}$$

Internal energy equation reads:

$$d(E_i R)/dt = L(t)R \quad \text{with a solution}$$

$$E_i = (\tau^2 L_o/t)\left[1 - (1 + t/\tau)\exp(-t/\tau)\right].$$

The driving pressure is $P_i \approx E_i/4\pi R^3$, R evolving as:

$R = (L/L_o)^{1/3} vt$ for $t \ll \tau$ (v is the velocity of expanding shell). The time t_s when the nuclear γ-rays become transparent to inner ejecta is:

$$t_s \approx \frac{L_o/10^{42}\text{erg/s}}{(L/10^{40})^{2/7} M^{3/7} (v/500 \text{ km/s})^{6/7}} \text{ yrs.}$$

Even for a type II supernova like SN 1987A, about 0.2 $M_\odot$ of Nickel was expected to be produced.If 0.2$M_\odot$ is produced, gamma ray luminosity is $\approx 10^{42}$ergs/s. About a tenth of this could be due to annihilation gamma rays with complete right circular polarization. The photons diffuse by scattering from electrons. The cross-section for electron scattering in Mev range is ~ $2 \cdot 10^{-25}$cm^2. For a column density $\approx$ 100 g/cm^2 this implies an optical depth $\approx$ 10. Again the positrons are emitted in a medium which is predominantly (Fe^{56}) especially for type I implying that they can slow down by emission of bremsstrahlung photons in the hard X-ray range, as probability of bremsstrahlung proportional to Z^2. Here $Z \approx 26$. The positron helicity would again be transferred to these photons making them right circularly polarized [Landau 1971]. Thus the right circularly polarized annihilation Mev gamma radiation would also be accompained by right circularly polarized hard X-ray bremsstrahlung radiation.

It would be most interesting to make special observations of extragalactic type I supernovae to search for such right circularly polarized photons. As a rough estimate of the expected number of photons, we can consider a supernova 10 Mpc away in which about a solar mass of Ni-56 is released. The peak flux would then be about 10^{-5} photons/m^2/s, the mean photon energy being about 1 Mev and a mean polarization greater than 50% A polarimeter 1 metre in diameter mounted on a space platform can pick up a few hundred such photons over a period of a month. For a supernova at the distance of the LMC about 10^5 such events would be detectable over the same period. Smaller fluxes can be expected from type II, (i.e. about an order of magnitude less). Again some of the radioactive nuclei could be trapped in grains condensing out of ejecta. These could give rise to narrow line Mossbauer type gamma emission whose intensity however would be rather small.

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