POSSIBLE EFFECTS OF POSITRONIUM NEGATIVE ION ON 0.511 MeV γ-RAY LINE IN ASTROPHYSICAL SOURCES

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Abstract. The astrophysical importance of the negative positronium ion, detected recently in the laboratory, has been pointed out. It is found that the presence of Ps^- ions will contribute additionally to the width of 0.511 γ-ray line formed by pair annihilation. The formation of Ps^- ion from an aggregate of electrons, positrons and positronium results in a variable positron population in the 0.511 MeV γ-ray line source.

1. Introduction

It is being increasingly recognized that γ-ray line spectroscopy could provide basic information on important problems in astrophysics. Of particular importance is the 0.511 MeV γ-ray line which 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 and Lingenfelter, 1981). The γ-ray line at 0.511 MeV is believed to be excited in the regions containing high densities of electrons and positrons which can be produced by cosmic ray interactions in the interstellar medium, radioactive decay in supernova remnants, pair production in the strong magnetic fields in pulsars, electromagnetic and nuclear processes in the vicinity of massive black holes, in galactic nuclei, and the evaporation of primordial black holes.

A single type-I supernova is believed to be a source of positron production by explosive nucleosynthesis via the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$. Observations would require some of the sources to have a variable positron production. In short it appears that the role of the 0.511 MeV line emission in γ-ray astronomy may prove to be of importance comparable to that of the 21 cm-line emission in radio astronomy. As such the high intensity, time variability and width of this γ-ray line deserves to be studied from various microscopic aspects. For instance, it has been recognized that in most astrophysical cases positronium formation may occur (Chupp, 1980). The bulk of the positrons slow down to energies comparable with those of the ambient electrons where annihilation takes place directly or via positronium (Wang and Ramaty, 1975, Crannel *et al.*, 1976). Positronium is formed by radiative recombination with free electrons and by charge exchange with neutral hydrogen, 25% of the positronium (Ps) is in the singlet state, 75% in the triplet state. Singlet Ps annihilation also produces a line at 0.511 MeV, while triplet Ps annihilation produces three photons forming a continuum below 0.511 MeV. These phenomena are seen for example in γ-ray emission from solar flares. The width of the 0.511 MeV line depends on whether the annihilation takes place in the cool photosphere or in the hot flare plasma. In what

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follows we propose a possible astrophysical significance for the very recently discovered (in laboratory experiments) negative positronium ions (designated as Ps^- ion) in the electron-positron rich sites in astrophysical objects and its possible effects on the characteristics of the 0.511 MeV γ-ray line. This would be analogous to the very important role now known to be played by the H^- ion in astrophysics (Gibson, 1972).

2. The Ps^- Ion and Its Discovery

The stability of the positronium negative (Ps^-) ion which is a bound system of two electrons and one positron was first theoretically demonstrated by Wheeler (1946). Recently the first experimental observation of the positronium negative ion was made by Mills (1981). In the experiment a beam of 400-eV positrons form radioactive ^{58}Co was transmitted through a 40-Å C-film in vacuum. The emerging beam could be accelerated by applying electric fields. By measuring the γ-ray energy spectrum with a down stream Ge (Li) detector a new γ-ray peak was observed, the energy of which can be changed by applying a voltage to the grid behind the film. The new peak was attributed to a Doppler-shifted annihilation γ-ray, implying a mass-to-charge ratio 3.01 m/e, signalling the presence of the $e^- e^+ e^-$ Ps^- ion. During the passage through the carbon film the positrons combine with the electrons to form neutral positronium (Ps) and the negatively charged Ps^- ions. The ratio of the density of Ps^- to Ps (i.e., the Ps^- conversion efficiency) was found to be 3×10^{-4}. The binding energy of Ps^- against break-up into (Ps) and a free electron is 0.3267 eV (Frost *et al.*, 1964), a little less than half the binding energy of the H^- ion. The 2γ-annihilation rate of Ps^- is found to be $\Gamma = (0.502\ \mathrm{ns})^{-1}$ (Ferranto, 1968), while the branching ratio for 3γ-rate is 3×10^{-3}. One can also have higher order processes, such as annihilation into a single photon of energy $\frac{4}{3} m_e c^2$ and an energetic electron of energy $\frac{2}{3} m_e c^2$. The probability of which is $\sim \alpha^4 \sim 5 \times 10^{-9}$. An auto-ionizing excited s state of Ps^- is also predicted with picosecond life time (Ho, 1979).

The unambiguous signature of Ps^- is a blue-shifted annihilation line the energy of which is determined by the accelerating voltage V. The Doppler shift of the line emitted at angle θ from the direction of Ps^- velocity is given (Møller, 1962) by

$$(\Delta E/m_e C^2) = [\lambda + (2\lambda + \lambda^2)^{1/2} \cos\theta], \tag{1}$$

where

$$\lambda = \mathrm{eV}/3\, m_e C^2 \tag{2}$$

the $3m_e$ in the denominator being the mass of the Ps^- ion. The width is maximum for line emitted in the direction of the flight, i.e. $\theta = 0°$. For a voltage of about 1000 V, the width is 20 keV, which is easily observable in a large background of unshifted γ-ray lines. The same effect would also be seen in magnetic fields, the electric intensity being replaced by $(\mathbf{V} \times \mathbf{B})/C$.

3. Astrophysical Sites for Production of Ps^-

As remarked earlier, most astrophysical sources of the 0.511 MeV γ-ray line favour formation of positronium (Chupp, 1980). As pointed out in Section 2, the Ps^- ion, can form provided one has a source of positrons (say a radioactive source); a medium of free electrons (plasma) and a matrix of solid grain particles (graphite, silica, ice, etc.). Of course the ambient temperature has to be less than the breakup energy of Ps^- which as seen above corresponds to a temperature of 0.32 eV or about 3000 K. Now it has been pointed out (Clayton, 1979) that in both nova and supernova, grains precipitate in gas densities of $\sim 10^{12}$ particles cc^{-1} a few months after the explosion with many radioactive isotopes trapped in the refractory grains forming near 1800 K. He has given several examples of positrons-emitting radio-active isotopes (like ^{22}Na, half life 2.6 yr) trapped within grains of graphite, Al_2O_2, SiO_2, etc. Graphite grains especially may form in novae. Again silicate grain formation can occur in outflow from cool giant stars (Draine, 1979) and also in the extensive atmospheres surrounding proto stars. The grains also have an effective electric potential and moreover a weak magnetic field may be present in all these cases. As remarked before positronium is known to form during solar flare γ-ray bursts. However, the temperature at the burst sites is well above the dissociation temperature of Ps^-, therefore, the formation of Ps^- is not favoured. The cooler red stars (especially the red-dwarf flare stars) might be the ideal site for the formation of Ps^-. The electric and magnetic field in the stars may accelerate the Ps^- and lead to an observable line width in the 0.511 MeV γ-ray line. The cool red giant stars with circumstellar envelopes rich in grains and condensates would also be a favourable site for Ps^-.

4. Consequences of Ps^- for the 0.511 MeV γ-ray Line

The chief difference between Ps and Ps^- lies in the fact that the former is neutral and would be unaffected by electric and magnetic fields whereas Ps^- is charged and could be accelerated or decelerated. Equations (1) and (2), show that even moderate fields can cause substantial changes in the linewidth of the 0.511 MeV line. The OSO-7 observations have only set an upper limit ($\sim$40 keV) on the line width but higher resolution observations are in the offing. It would, therefore, be worthwhile to look for such characteristic Doppler shifted line widths in the 0.511 MeV line corresponding to the presence of the Ps^- ion. That is, over and above the unshifted 0.511 MeV peak, we will see low intensity peaks fluctuating in energy as the acceleration (analogously the accelerating fields) changes. The line will not be monoenergetic.

Apart from fluctuations in the line width due to acceleration, Ps^- can cause intensity fluctuations too. That is some of the positrons can be temporarily bound up with the electrons to form Ps^- and give additional contribution to the γ-ray emission. As remarked in the introduction, some of the sources producing the 0.511 MeV line seem to require a variable positron production. This may be partly explained by some of the positrons forming Ps^- which lasts for a nanosecond and then breaks up again releasing the positrons. This may lead to intensity fluctuations at time scales of the order of nanoseconds. Of course the lifetime of the Ps^- is too small to contribute to the line width. The latter as pointed out above occurs because of the acceleration of the ion. In short the presence of Ps^- should give a lot of structure to the line.

5. Conclusions

The recent discovery of Ps^- ion in the laboratory has led us to explore its possible role in the astrophysical situations, where the electrons, positrons and positronium atoms are known to prevail. It is found that a small fraction of Ps^- ion population can give an additional width of the order of a few KeV to the γ-ray line at 0.511 MeV because of it being a charged particle. The recombination of some of the positronium atoms with electrons resulting in Ps^- ion can lead to a variable positron population, which in turn results into intensity fluctuations of the γ-ray line over time scales of the order of a few nanoseconds. The Ps^- ion is an analogue of the H^- ion which is the main ingredient affecting opacity in the solar atmosphere in the visible wavelength region. The comparable role of Ps^- ion is in the γ-ray region.

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