POSITRONIUM IN ASTROPHYSICAL CONDITION

V.V. BURDYUZHA[1], KAUTS V.L.[2], YUDIN N.P.[3]

[1]Astro-Space Center Lebedev Physical Institute
Profsoyuznaya 84/32, Moscow, USSR

[2]Institute of Nuclear Research, 60 October Str.,7a, Moscow, USSR

[3]Physical Department Moscow State University, Leninskie Gory, Moscow, USSR

From a physical point of view we analyzed the possibility of observation of the L_α-line of the positronium (Ps). In a broad range of temperatures the processes of recombination to states of Ps with different nl, collisions of Ps with electrons and protons of medium are examined.

1. INTRODUCTION

Observations of e^+e^- annihilation line (511 keV) have put forward the question on the formation of lepton atoms Ps and therefore the question on the observation of L_α-line of positronium. However in a previous paper (Burdyuzha et al., 1987) it was pointed out that the observed details in UV spectra of SN 1987A can't be interpreted as a Lyman series of Ps. The attempt to detect the radiorecombination lines of Ps in the direction of the center of the Galaxy used VLA and IRAM was also unsuccessful (Anantharamaiah et al., 1989). On the other hand the annihilation processes in nonthermal sources take place everywhere (radiopulsars, X and γ ray sources, solar flares and so on) and production of lightest atom is evident. Undoubtedly future missions with more sensitive γ -spectrometers will display new kinds of sources of annihilation line. We intend to discuss the formation of Ps in excited states (mainly in 2S, 2p states) and therefore the possibility of detecting the L_α-line of Ps ($\lambda \simeq 2431$Å). Note that this question was already considered in some degree in earlier literature (see for example, McClintock, 1984; Gould, 1989).

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2. ATOM OF POSITRONIUM

Positrons in medium come into the sufficiently complex processes, the final result of which is, of course, the annihilation. The annihilation of Ps takes place from S-states (the nonrelativistic limit). This is because the process demands that the e^+ and the e^- - have to be at small distances but the wave function of Ps in states with nonzero angular momentum ($l \neq 0$) at small distances will become very small. The states of Ps have a spin equal to zero (para - Ps) or to one (orto Ps). The orto - Ps decays to three photons, the para Ps decays to two-photons. (see Fig. 1).

Let's also give also some additional information on the Ps. The average lifetime of Ps from singlet (para) and triple (orto) states are:

$$\tau_{para} \simeq 1.25 \times 10^{-10}\, n^3 \text{ sec}; \tau_{orto} \simeq 1.33 \times 10^{-7}\, n^3 \text{ sec},$$

where: n is the main quantum number.
The energies E_n of Ps levels are given by the formula (in eV)

$$E_n = -6.8\, /n^2 \tag{1}$$

The probabilities A of radiative transitions in Ps are two times less than the probabilities of transitions between similar states of hydrogen $A_{Ps} = 1/2\, A_H$. The wave lengths of emitted photons in Ps are two times more than analogious wave lenghts of hydrogen $\lambda_{Ps} = 2\lambda_H$.

3. THE PROCESS OF RECOMBINATION

For radiative recombination of positron with electron the formulae are practically the same that for H with the trivial modification:

$$k = \sqrt{E_e + /E_1^{Ps}}, \quad E_1^{Ps} = 6.8 \text{ eV}, \sigma_{nl}^{Ps} = 4\sigma_{nl}^{H}$$

where E_e+ is $\mu v^2/2$, $\mu = \frac{1}{2} m_e$, v is relative velocity.
For $k \gg 1$ the cross section of radiation recombination is

$$\sigma_{nl} \approx \frac{1}{k}\, f_{nl} \tag{2}$$

where $f_{10} = 1/k^4$, $f_{20} = 1/8k^4$, $f_{21} = 3/32k^6$, $f_{30}=1/27k^4$, $f_{31} = 8/243k^6$, $f_{32} = 1/246k^8$.

From the asymptotic formulas it's seen that in the process of recombination only low levels are populated (the factor of suppression is $1/n^3$). It's also seen that for $k \gg 1$ mainly the states with $l = 0$ are populated. The populations of orto and para states are defined by their statistical spin weights.

4. THE ROLE OF COLLISIONS

For Ps in quasiclassical approximation cross section takes the form

$$\sigma_{para}(2^1S_0 \rightarrow 2^1P_1) = 72\pi\left(\frac{\hbar}{m/2\ v}\right)^2 \left[\ln\left(\frac{mv^2/2}{\Delta(2^1S_0 \rightarrow 2^1P_1)}\right) - 1.53\right]$$

$$\sigma_{orto}(2^3S_1 \rightarrow 2^3P_{0,1,2}) = 72\pi\left(\frac{\hbar}{m/2v}\right)^2 \left[\ln \frac{mv^2/2}{(\Delta_0^1\Delta_1^3\Delta_2^5)^{1/9}} - 1.53\right], \qquad (3)$$

where $\Delta_{0,1,2}$ is the corresponding differences of energy (see Fig.1). Simple arithmetic of Maxwell averaging over electroneutral plasma ensures the following formula for the probability of $2S \rightarrow 2P$ transition under collisions of Ps with e^- and p:

$$\overline{\sigma v} = 1.88\ 10^{-5}\ \frac{1}{T}\left\{2.73\ \ln\ \frac{T}{2B} - 4.66\right\} \qquad (4)$$

where T is the temperature in eV, $B = (\Delta_0^1\Delta_1^3\Delta_2^5)^{1/9}$ for the orto-Ps, $B = \Delta(2^1S_0 \rightarrow 2^1P_1)$ for the para-Ps.

Let's stress that the probability of intercombinational transitions for n = 2 is much less than the probability of basic processes.

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5. DISCUSSION

As shown by Gould (1989) at temperature $T > 7\ 10^5$ K the direct annihilation becomes dominant, i.e. this is the first limitation on production of Ps.

As seen from the results of our paper at small T ($T < 10$ eV) the recombination takes place, in general, to the 2P levels of Ps. The appearance in this case of the intensity of L_α-line is probable event with an effectiveness of 15% viewed from the annihilation line (in number photon), i.e. $L_{2431Å}/L_{511keV} \approx 1.5x10^{-6}$.

At temperature $T > 10$ eV the recombination takes place, generally, to the 2S levels of Ps. The main result of collisions is the existence of critical densities of electrons N_{cr} for which the probability of annihilation is equal to the probability of collisional transition 2S → 2P. If the density of electrons is more than the $N_{cr}^{(2)}$ then the emission of L_α-line positronium must take place.

More detail about observations of P_s you can read in our total paper in Astron. and Astrophys. (1991).

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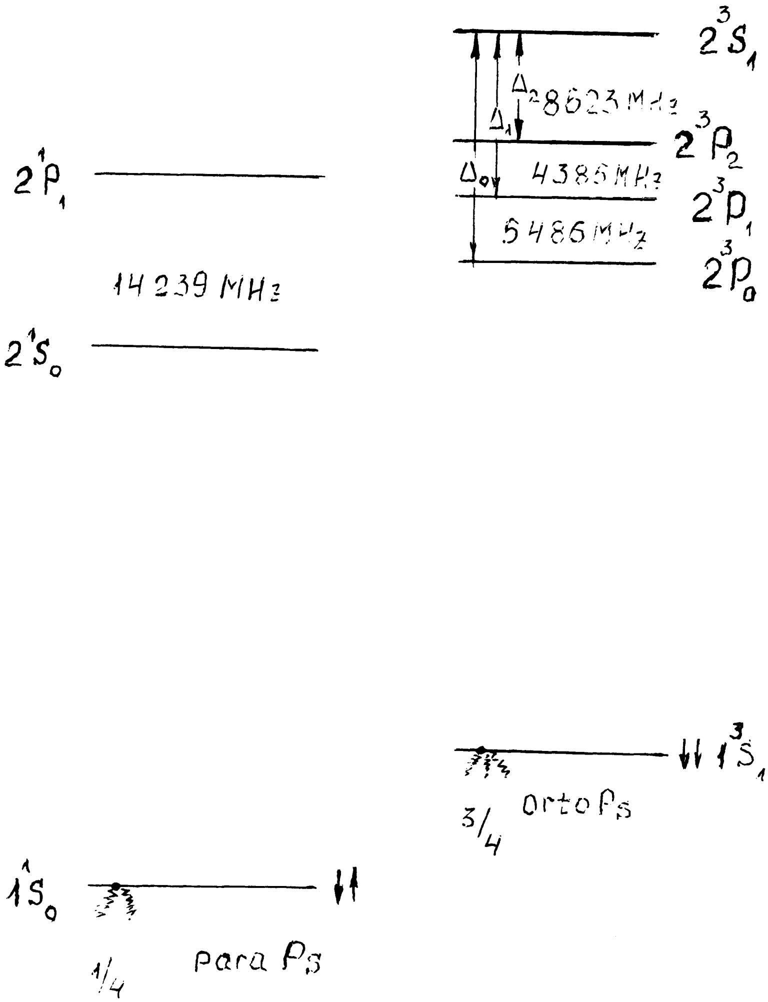

Fig.1 The low levels of Ps