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POSSIBLE FORMATION OF ANTIHYDROGEN ATOMS FROM METASTABLE ANTIPROTONIC HELIUM ATOMS AND POSITRONS/POSITRONIUMS

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The possible formation of antihydrogen atoms via the collision of metastable antiprotonic helium atoms with positrons and positroniums is discussed based on the known behavior of positrons in helium media.

1 INTRODUCTION

Antihydrogen, the bound state of antiproton and positron, $\bar{\mathrm{H}} = \bar{\mathrm{p}}\mathrm{e}^+$, is the most basic building block of antimatter. Although its basic property is of great fundamental importance, its synthesis has not yet been realized. Recently one of the present authors [1] has proposed a new possible way to form antihydrogen atoms from metastable antiprotonic helium atoms with an over-all lifetime of about 3 μsec, which have been discovered to be formed abundantly in helium media [2, 3]. The metastable antiprotonic helium atom is an ensemble of bound states of $[\bar{\mathrm{p}}\mathrm{He}^+]_{NL}$ with large principal quantum numbers N (≈ 38) and large angular momenta L (≥ 35). These metastable states are formed in helium media with 3 % branching ratio.

The proposed reaction processes for antihydrogen atoms are

$$[\bar{\mathrm{p}}\mathrm{He}^+]_{NL} + \mathrm{e}^+ \rightarrow \bar{\mathrm{p}}\mathrm{e}^+ + \mathrm{He}^+ \; - \; 11 \text{ eV} \tag{1}$$

and

$$[\bar{\mathrm{p}}\mathrm{He}^+]_{NL} + \mathrm{Ps} \rightarrow \bar{\mathrm{p}}\mathrm{e}^+ + \mathrm{He}^0 \; + \; 6.8 \text{ eV} \tag{2}$$

The process (1) is endothermic and thus less likely. In addition, there are competing processes

$$[\bar{\mathrm{p}}\mathrm{He}^+]_{NL} + \mathrm{e}^+ \rightarrow \mathrm{Ps} + [\bar{\mathrm{p}}\mathrm{He}^{++}]_{nl} - \; 10.4 \text{ eV} \tag{3}$$

and

$$[\bar{\mathrm{p}}\mathrm{He}^+]_{NL} + \mathrm{e}^+ \rightarrow 2\gamma + [\bar{\mathrm{p}}\mathrm{He}^{++}]_{nl}, \tag{4}$$

where the $\bar{\mathrm{p}}$ annihilates immediately through the ionized $\bar{\mathrm{p}}\mathrm{He}^{++}$. Thus, the formation process with Ps, eq. (2), is more likely.

The cross sections for these processes are not yet calculated, but can be assumed to be a typical atomic cross section, namely, $\sigma = 10^{-16}$ cm^2. In the following we discuss how to collide metastable antiprotonic atoms with positrons and positroniums and estimate the event rate for antihydrogen formation.

To synthesize antihydrogen atoms from reactions between e^+ or Ps and $[\bar{\mathrm{p}}\mathrm{He}^+]_{NL}$ it is necessary to implant both the positron and the antiproton beams in the same spatial region of a helium target as well as in the same time range. To this end we need a pulsed positron beam synchronized with a pulsed $\bar{\mathrm{p}}$ beam; with a continuous beam as usually employed for experiments the encounter probability should be extremely small. Since the lifetime of metastable $\bar{\mathrm{p}}\mathrm{He}^+$ atoms is 3 μsec, long enough compared with the positron lifetime, the positron beam can be injected after the arrival of the $\bar{\mathrm{p}}$ beam, but with no stringent timing condition. The spatial confinement of metastable $\bar{\mathrm{p}}\mathrm{He}^+$ atoms requires thoughtful consideration to achieve, as discussed in section 2.

How many times can positrons encounter helium atoms (how long can positrons survive and traverse in helium media) is an essential clue in the present problem. Fortunately, the mobility of positrons is very high and thus they can collide with a number of helium atoms within their survival time so that they may encounter one of the metastable $\bar{\mathrm{p}}\mathrm{He}^+$ atoms produced in the same medium. The formation probability of antihydrogen atoms depends on the behavior of positrons and positroniums

in helium media. We will discuss this aspect in section 3. Finally, in section 4, we will estimate the formation rate and propose some experimental procedures.

2 PRODUCTION AND BEHAVIOR OF METASTABLE ANTIPROTONIC HELIUM ATOMS

For a high-rate production of antihydrogen, it is necessary to achieve high densities of antiprotonic He atoms in a small stopping volume even in a low density gas target. For this purpose we need a low energy, monoenergetic $\bar{p}$ beam with maximum $\bar{p}$ rate. This can presently be found only at the Low Energy Antiproton Ring (LEAR) of CERN, Geneva. The lowest possible momentum is 65 MeV/c ($E_{\rm kin}$ = 2.25 MeV). In the future, it can be expected that a total number of 10^9 antiprotons will be extracted in one bunch with a length of about 1 μs [4].

To estimate the range distribution of $\bar{p}$ under this condition we made a Monte Carlo simulation. The program used Ziegler's parametrization for the *proton* stopping power [5] to calculate the energy loss at low energies. However, since it was recently found that the energy loss of antiprotons differs from that of protons at very low energies [6], the calculations have some uncertainty. The results of the simulations are listed in Table 1 together with the parameters of the positron beam. The range straggling is in the order of 500 μm in high pressure gas and 30 μm in liquid He, whereas the beam diameter is about 4 mm FWHM.

To increase the $\bar{p}$ stopping density, a confinement in an electromagnetic trap like the anticyclotron trap used in P118T at LEAR might be suitable [7]. The $\bar{p}$ can be stopped in about the same volume (several cm^3). How positrons could be produced and stopped in these conditions is not straightforward and is currently being investigated. However, the low density of the surrounding medium might be an advantage for the survival of $\bar{\rm H}$ as discussed in section 4.

In order to calculate the encounter rate of positrons and metastable $\bar{p}{\rm He}^+$ atoms, it is necessary to know their mobility. At the formation stage, the $\bar{p}$ brings in an energy up to 25 eV, which is transferred to the metastable $\bar{p}{\rm He}^+$ atom, but further collisions should thermalize the $\bar{p}{\rm He}^+$ atoms in a short time. Therefore, in our estimation we used a thermal velocity for the metastable atoms.

3 POSITRON AND POSITRONIUM IN He MEDIA

A) Positron Beam and Implantation Profile of Slow Positrons

Monoenergetic slow positrons ($E_{\rm kin} \approx 5$ keV) can be produced with an intensity of $\sim 10^8$/s by using high-energy electron linacs [8]. There are also several competing projects of producing intense (10^{10} e$^+$/s) slow positron beams, but here we will make a plausible assumption of the positron beam. The implantation profile $p(x, E)$ of positrons in a substance is described by a Makhovian profile [9]

$$\begin{aligned} p(x,E) &= \frac{\rm d}{{\rm d}x}[\exp(-x/x_0)^\beta] \\ x_0 &= x_{\rm mean} \,/\, \Gamma(1+1/\beta) \\ x_{\rm mean} &= \frac{40}{\rho}E^{1.6} \end{aligned} \tag{5}$$

where E is the positron energy (keV), x is the length (nm), and ρ is the density of the substance. Γ denotes the gamma-function. For the parameter β, 1.9 is known to give the best result. The third term of eq. (5) gives the mean penetration depth of the positrons. Table 1 gives values for the case of high pressure He gas and liquid He.

B) Positron and Positronium in He

Energetic positrons traversing He media are slowed down due to ionization and excitation losses. Below the kinetic energy of about 25 eV, they can form positronium (Ps) by electron abstraction reaction [10]

$$\mathrm{e}^+ + \mathrm{M} \rightarrow \mathrm{Ps}^* + \mathrm{M}^+ \tag{6}$$

The appropriate energy region of the incident e$^+$ for the Ps formation is called the Ore gap and is

$$E_{\rm th} \leq E(\mathrm{e}^+) \leq I\,, \tag{7}$$

where I (= 24.58 eV for He) is the ionization potential of the gas molecule and $E_{\rm th} = I - 6.8$ eV (= 17.78 eV for He) is the threshold energy of reaction (6), which

is endothermic. Ps will emerge with energies corresponding to the width of the Ore gap, i.e. its maximum energy will be 6.8 eV. It is known that about 23% of the e^+ form Ps in He.

Positrons that failed to form Ps, i.e. 77% of the incident e^+, continue to slow down. This stage begins from the energy corresponding to the bottom of the Ore gap, E_{th}. Since this energy is smaller than the first electronic excitation energy (= 19.82 eV for He), inelastic collisions do not take place any longer and the slowing down of the positrons is governed by elastic collisions.

C) Non-equlibrium Stage

Thus after passing the Ore gap, positrons emerge either as epithermal Ps (with energies up to about 6.8 eV) or as epithermal e^+ (with initial energy of about 18 eV). The slowing down of these epithermal states by elastic collisions is slow because of the smallness of the e^+ and Ps masses. This slowing-down process is reflected in a positron annihilation time spectrum as a "non-equilibrium" component (see Fig. 1). This non-equilibrium component is typical of pure rare gases, and is characterized by the product of the time duration of the non-equilibrium component (the shoulder), τ_s, and the gas density, n_M,

$$\tau_s \times n_M = \text{constant}. \tag{8}$$

The observed values are shown in Table 2.

The number ν of elastic collisions required to slow down e^+/Ps from E_i to E_f can be estimated, according to the procedure of neutron thermalization theory, as

$$\nu = \frac{\ln\frac{E_i}{E_f}}{1 + \frac{\alpha}{1-\alpha}\ln\alpha} \tag{9}$$

where

$$\alpha = \left[\frac{\frac{M_{He}}{m} - 1}{\frac{M_{He}}{m} + 1}\right]^2 . \tag{10}$$

For e^+ ($E_i = 17.78$ eV and $m = m_e$) it is calculated to be

room temperature gas:	$T = 273$ K,	$E_f = 2.3 \cdot 10^{-2}$ eV,	$\nu_{e^+} = 2.4 \times 10^4$
liquid helium:	$T = 4.2$ K,	$E_f = 3.54 \cdot 10^{-4}$ eV,	$\nu_{e^+} = 3.7 \times 10^4$,

and for Ps ($E_i = 6.8$ eV and $m = 2m_e$)

room temperature gas:	$\nu_{Ps} = 1.0 \times 10^4$
liquid helium:	$\nu_{Ps} = 1.8 \times 10^4$,

For e^+, this corresponds to the slowing down time (non-equilibrium lifetime) of 2.3 nsec in liquid helium and 43 nsec in 37-atm He gas (see Table 2). This may be compared to the electron thermalization time in liquids which are well studied in radiation chemistry (Table 3). Although there is no data for electron thermalization time in liquid He it should be smaller than that in liquid Ar.

In this non-equilibrium stage the probability for any e^+/Ps to encounter one of the metastable antiprotonic helium atoms is

$$P = \nu \cdot n(\bar{p}He^+) \,/\, n_M \tag{11}$$

and thus, the formation rate of antihydrogen atoms per burst in the slowing-down process is given by

$$R^{s.d.} = N(e^+/Ps) \cdot \nu \cdot n(\bar{p}He^+) \,/\, n_M \tag{12}$$

where n_M and $n(\bar{p}He^+)$ are the densities of He atoms and the metastable $\bar{p}He^+$ atoms per burst per cm^3, and $N(e^+/Ps)$ is the total number of e^+/Ps which stop in the same spatial region as the antiprotons, respectively. Here, we have assumed that an antihydrogen atom be formed at *every* encounter of e^+ with $\bar{p}He^+$.

D) Equilibrium Stage

The non-equilibrium component is followed by an "equilibrium" positron stage which shows an exponential lifetime component. The lifetime, τ_f, of the equilibrium positron state is the inverse of λ_f,

$$\lambda_f = \pi r_0^2 \, c \, n_M \, Z_{eff} \tag{13}$$

where r_0 is the classical radius of electron, $\pi r_0^2 c = 7.48 \times 10^{-15}$ $cm^3 s^{-1}$, n_M is the density of molecules, and Z_{eff} is the effective number of electrons per one molecule

available for positron annihilation. $Z_{\rm eff}$ is a function of the positron energy and is about 1.8 before thermalization and 3.0 at thermal equilibrium.

For Ps, there exist two different spin states: $S = 0$ (para-Ps) and $S = 1$ (ortho-Ps). Para-Ps annihilates with the intrinsic mean lifetime of 125 ps and therefore does not contribute significantly to the antihydrogen formation. The ortho-Ps is observed as a long-lived component whose lifetime is determined by the vacuum lifetime $\lambda_T^{-1} = 141.8$ ns and the "pick-off" rate

$$\lambda_p = \lambda_T + 4\pi r_0^2 \, c \, n_M \, {}_1Z_{\rm eff}. \tag{14}$$

${}_1Z_{\rm eff}$, similar to $Z_{\rm eff}$, is the effective electron number per molecule available for annihilation with the positron in o-Ps state. The positronium formation probability, F, is 4/3 times the intensity of the o-Ps component. Some data are shown in Table 2.

Equations (13) and (14) apply for a wide range of gas density. At high density and low temperature, however, the e^+ and Ps lifetimes deviate from these linear relationships: the e^+ lifetime becomes shorter due to "cluster" formation around e^+, and the o-Ps lifetime becomes longer due to "Ps bubble" formation [13] (see Table 4).

The e^+ cluster and the Ps bubble are localized states in dense gases, and their mobility is supposed to be approximately the same as the localized electron (e^- bubble) in liquid, because their mobility is governed by the diffusion process. The dynamics of the localization of positron and positronium is not well known, but it is known that the clusterization is a critical phenomenon which takes place at some critical conditions of gas density and temperature.

Since the mobility of e^+ and Ps is very much reduced in these states, it would be preferable to avoid those regions for antihydrogen production. This is possible in choosing He gas either at higher temperature ($T \geq 8$ K) or higher densitities ($n \geq 2 \times 10^{22}$ cm^{-3}), or by using an electric field. It was found that the cluster formation in liquid He was delayed when an external electric field was applied [15]. This is due to the "heating" of e^+ energy by the electric field, in which the effective thermalization energy of e^+ is shifted to,

$$(k_B T)_{\rm eff} = k_B T + {\rm e}\, \varepsilon\, \ell \sqrt{M/8{\rm m}} \tag{15}$$

where ε is the electric field strength and ℓ is the mean free path of e^+. The energetic criterion for the e^+ localization was estimated to be $E_c = 15 \pm 3$ meV.

In any case, the mobility of e^+ or ortho-Ps in the equilibrium state is dominated by a diffusion process. The encounter probability K for one e^+/Ps with the $\bar{p}He^+$ atoms can then be estimated by

$$K = 4\pi \cdot D \cdot r \cdot n(\bar{p}{\rm He}^+) \cdot \tau \tag{16}$$

with D being the diffusion constant of e^+/Ps [cm^2/s], r the reaction radius (it was roughly taken to be $r \approx 0.2$ nm), $n(\bar{p}He^+)$ the density of $\bar{p}He^+$ per cm^3 and τ the mean lifetime of e^+/Ps. The e^+ and Ps diffusion constant in He is not known but can be estimated from the known mobility of electrons (see Table 5). To obtain the antihydrogen yield per bunch, K has to be multiplied by the total number $N_{e^+/Ps}$ of e^+/Ps

$$R^{\rm thermal}_{e^+/Ps} = N_{e^+/Ps} \cdot K. \tag{17}$$

Since the stopping distribution of positrons is narrower than that of antiprotons, this gives the total antihydrogen yield per bunch.

4 ENCOUNTER RATE OF e^+/Ps WITH A METASTABLE $\bar{p}H^+$ ATOM

With the information described in the previous two sections, we can now estimate the encounter rate between e^+/Ps and the metastable $\bar{p}He^+$ atoms. The results are shown in Table 6.

Because the energy is low, the local density of stopped antiprotons and stopped positrons can be made as large as 10^{10} to 10^{12} cm^{-3}. This is one of the advantages of the present method. We assume that both antiproton and positron beams can be injected into helium medium so that the peak positions of their stopping profiles can meet in the same spatial region.

During the slowing down process, about 10 antihydrogen atoms might be produced per bunch in encounters with positrons in both 37 atm He gas and liquid helium, whereas for positronium the number is one order of magnitude smaller. In

the region of thermal mobility, the situation is different: in liquid He the production rate is much smaller ($\sim 10^{-3}$ $\overline{\mathrm{H}}$ per bunch) due to the small e^+/Ps diffusion constant. On the other hand, for 37 atm He gas, the estimation yields a production of 10^3 to 10^4 $\overline{\mathrm{H}}$ per bunch, a number which would be big enough to study the antihydrogen atoms.

The question arises, how to detect the formation of $\overline{\mathrm{H}}$ in this experimental situation. The table shows that about 0.1 % of $\overline{\mathrm{p}}\mathrm{He}^+$ (37 atm He gas) can encounter positrons. Thus, if in an experiment of lifetime measurements of antiprotons, we irradiate a bunch of slow positrons at a time suitably delayed from the antiproton arrival, we shall be able to observe a small change in the shape of the lifetime spectrum. The nature of this change depends on the fate of the $\overline{\mathrm{H}}$ atoms in the dense gas medium. Most probably, antihydrogen atoms will be destroyed in atomic collisions with other He atoms. Both processes should take place within a few nanoseconds or a few tens of ns. In this case, immediately after the implantation of the positron beam, the $\overline{\mathrm{p}}$ annihilation time spectrum will show a spike from increased $\overline{\mathrm{p}}$ annihilation, followed by a slight (unobservable) decrease of the delayed component after this spike. Such a spike, however, only indicates that the $\overline{\mathrm{p}}\mathrm{He}^+$ atoms have reacted with e^+ and/or Ps. The next step will be to confirm the formation of antihydrogen by some way. The only unique way to identify $\overline{\mathrm{H}}$ is to ionize it by laser excitation and to observe the associated $\overline{\mathrm{p}}$ annihilation. For this purpose the produced antihydrogen atoms should survive for some time around 10 ns and thus we have to use a very dilute gas medium.

5 CONCLUSIONS

We have discussed the possible formation of antihydrogens in encounters between metastable antiprotonic helium atoms and e^+/Ps by implanting positrons and antiprotons simultaneously into helium medium. It appears probable that 10^3 to 10^4 antihydrogen atoms are formed in high pressure He gas in one bunch of $\overline{\mathrm{p}}$ and e^+ beams. The parameters shown are by no means the best optimization. There are also many technical problems such as window construction of the positron beam. We emphasize the importance to study theoretically the cross sections for the collision processes of the metastable $\overline{\mathrm{p}}\mathrm{He}^+$ atoms with e^+/Ps.

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Figure Captions

Fig. 1:
Schematic lifetime spectrum of e^+ in He gas at 5.5 K (solid line) and 7.5 K (dotted line) obtained from ref. [11]. The spectrum at 5.5 K shows a slightly nonexponential shoulder (time constant τ_s) followed by the exponential free decay of e^+ (time constant τ_f) and the decay of ortho-Ps (time constant τ_p). At 7.5 K, a small bump appears after the shoulder, which is due to e^+ cluster formation. The lifetime of the e^+ cluster is much smaller than the free e^+ lifetime τ_f.

Table 1: Parameter of the antiproton and positron beam

	antiprotons	positrons
energy	2.25 MeV	5 keV
intensity per 1 μs bunch	10^9 $\bar{p}$	10^8 e^+
beam diameter [cm]	0.4	0.4
range straggling in 37 atm He gas (FWHM) [cm]	0.05	0.0075
range straggling in liquid He (FWHM) [cm]	0.003	0.0004

Table 2: Positron parameters in some gases. ${}_1Z_{\rm eff}$ and $Z_{\rm eff}$ are effective nuclear charges for ortho-Ps and e^+ annihilation. F is the positronium formation probability.

molecule	Z/atom	${}_1Z_{\rm eff}$	$Z_{\rm eff}$	F	$\tau_s \times n_M$ (ns·amagat)
He	2	0.35	3.0	0.23	1600
Ne	10	0.23	6.0	0.26	1700
Ar	18	0.35	18-27	0.33	360
Kr	36	0.45	40-67	0.11	290
Xe	54	1.03	320	0.03	200
H_2	2	0.19	12-13		
N_2	14	0.26	19-31		
O_2	16	14-86	19-26		
CO_2	22	0.48	50-120		

Table 3: Electron thermalization time in some liquids [12]

liquid	T [K]	$\tau_{\rm th}$ [ns] (estimated)	$\tau_{\rm th}$ [ns] (measured)
Xe	161	5.5	6.5
Kr	121	2.6	4.4
Ar	87	1.0	0.9
CH_4	111	0.022	—

Table 4: Positron and positronium states in liquid and solid He [14]

Liq. He (4.2K, 1 atm)	e^+ cluster	τ = 1.90 ns ($\sim$ 75%)
	Ps bubble	τ = 88 $\pm$ 8 ns (15-18%)
		bubble radius $\sim$ 1.9 nm
Solid He (1.7K, 1 atm)	Ps bubble	τ = 51 ns
		bubble radius $\sim$ 1.5 nm

Table 5: Electron mobility in He and Ar [16]

material	μ_e [$cm^2V^{-1}s^{-1}$]	D_e [cm^2s^{-1}] ($\mu_e = D_e/kT$)
He 4.2K	0.020	1.7×10^{-6}
He 77K	430	0.037
He 293K, 37 atm	7.8×10^6	5.17
Ar 126 K	321 (minimum)	

Table 6: Electron and antiproton stopping distributions and estimated $\overline{\mathrm{H}}$ production rates for 37 atm He gas and liquid He.

parameter of stopping medium		
	37 atm He gas	liquid He
Helium density n_M [cm^{-3}]	$9.9 \cdot 10^{20}$	$2.0 \cdot 10^{22}$
Range straggling (FWHM) $\overline{\mathrm{p}}$ [cm]	0.05	0.003
number of $\overline{\mathrm{p}}\mathrm{He}^+$	$3 \cdot 10^7$	
$n(\overline{\mathrm{p}}\mathrm{He}^+)$ [cm^{-3}]	$5 \cdot 10^9$	$8 \cdot 10^{10}$
Range straggling (FWHM) e^+ [cm]	0.0075	0.0004
number of e^+ (1-F=0.77)	$7.7 \cdot 10^7$	
$n(e^+)$ [cm^{-3}]	$8 \cdot 10^{10}$	$1.5 \cdot 10^{12}$
number of ortho-Ps	$1.7 \cdot 10^7$	
n(Ps) [cm^{-3}]	$1.8 \cdot 10^{10}$	$3.4 \cdot 10^{11}$
D [cm^{2}s^{-1}]	5.17	$1.7 \cdot 10^{-6}$
τ_{e^+} [ns]	45	1.9
τ_{Ps} [ns]	56	5.6
slowing down region		
No. of encounters for e^+	$2.4 \cdot 10^4$	$3.7 \cdot 10^4$
encounter probability P_{e^+}	$1.2 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$
total No. of $\overline{\mathrm{H}}$ / bunch $R_{e^+}^{\mathrm{s.d.}}$	9.3	11.4
No. of encounters for Ps	$1.0 \cdot 10^4$	$1.8 \cdot 10^4$
encounter probability P_{Ps}	$5.0 \cdot 10^{-8}$	$7.2 \cdot 10^{-8}$
total No. of $\overline{\mathrm{H}}$ / bunch $R_{\mathrm{Ps}}^{\mathrm{s.d.}}$	0.82	1.2
thermal equilibrium		
encounter probability K_{e^+}	$2.8 \cdot 10^{-4}$	$6.4 \cdot 10^{-11}$
total No. of $\overline{\mathrm{H}}$ / bunch $R_{e^+}^{\mathrm{thermal}}$	$2.2 \cdot 10^4$	$5.0 \cdot 10^{-3}$
encounter probability K_{Ps}	$3.5 \cdot 10^{-4}$	$1.9 \cdot 10^{-10}$
total No. of $\overline{\mathrm{H}}$ / bunch $R_{\mathrm{Ps}}^{\mathrm{thermal}}$	$6.0 \cdot 10^3$	$3.2 \cdot 10^{-3}$

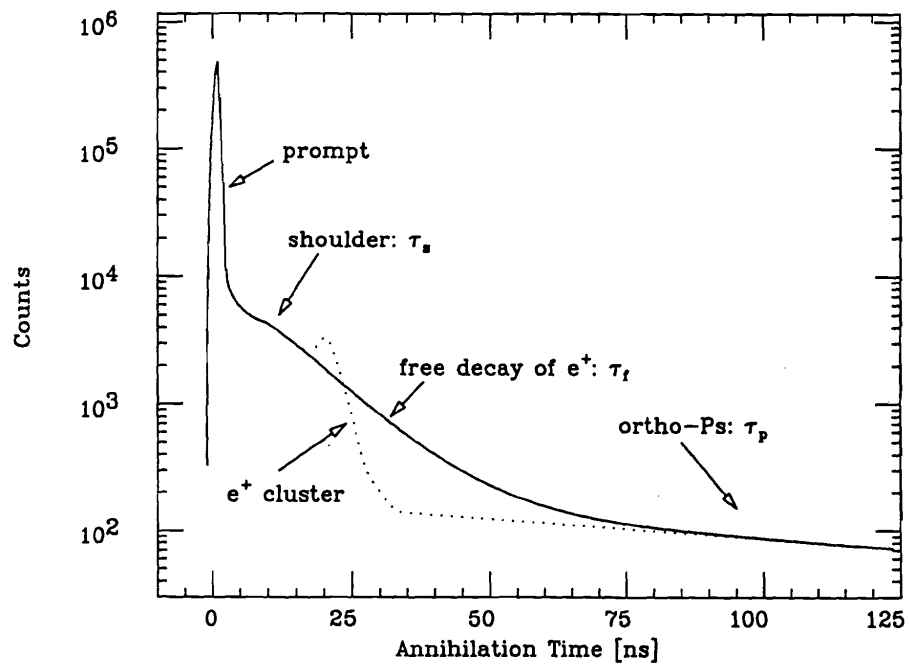

Fig. 1