Radiation Physics and Chemistry 119 (2016) 85–89

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Positron lifetimes in crystalline solids exposed to γ rays with energies above the electron–positron pair formation threshold and a weak magnetic field

Gerald. A. Smith [a,b,*]

[a] Professor of Physics Emeritus, Pennsylvania State University, University Park, PA USA
[b] Positronics Research LLC, 13631 E. Windrose Dr., Scottsdale, AZ 85259, USA

H I G H L I G H T S

- A positron lifetime of 233 ± 40 min is measured in KCl at 12 gauss magnetic field.
- Lifetimes in KCl, KBr and KI at 95 gauss are 4.1 ± 0.4, 8.5 ± 1.3 and 10.0 ± 1.0 min.
- Lifetimes are due to electric dipole radiation of positronium bound to a halide anion.
- Lifetimes vary as the inverse magnetic field squared and anion electron density.
- A positron lifetime of 9.8 ± 2.0 min has been measured in naphthalene ($C_{10}H_8$).

A R T I C L E I N F O

Article history:
Received 17 June 2015
Received in revised form
18 September 2015
Accepted 20 September 2015
Available online 5 October 2015

Keywords:
Positrons
γ-Rays
Magnetic fields
Alkali halides
Polycyclic hydrocarbons

A B S T R A C T

Theory predicts that positrons in crossed motional electric and magnetic fields form long-lived positronium in vacuum. It follows that binding of the electron to anions of dielectric solids may prevent fast annihilation by forming electric positron–electron dipole oscillators with lifetimes of hundreds of minutes. To test this hypothesis, lifetime distributions of time-coincident, 180° γ-rays from crystalline alkali halides and a polycyclic hydrocarbon were measured in 12 and 95 G magnetic fields. Gamma-ray sources with energies above the electron–positron pair formation threshold were used to make positrons.

1. Introduction

For a long time after the discovery of the positron it was axiomatic that its lifetime against annihilation was $\approx 10^{-10}$ s and depended only on atomic electron density and square of the positron wave function (Dirac, 1930). Later it was found that lifetimes of the spin singlet and triplet bound electron–positron state, positronium (Ps), differed by one thousand (Deutsch, 1951) and could be altered by strong external magnetic fields (Halpern, 1955). Much later, with the advent of pseudo-momentum that allowed separation of Ps collective and internal motions, crossed motional electric and magnetic fields were shown theoretically to create Ps lifetimes of order one year in vacuum (Ackermann et al., 1997; Shertzer et al., 1998; Schmelcher et al., 1998; Ackermann, 1998). This was followed by a proposal that 'metastable Ps', as we call it, may exist in extra-galactic jets (Giblin Jr. and Shertzer, 2012).

We planned an experimental search for metastable Ps that involved several strategic issues. First, to avoid self-annihilation the positron and electron must be separated by a large distance. According to theory (Shertzer et al., 1998), a Ps pseudo-momentum just above one (au) avoids unstable coulomb states and gives large separations in small magnetic fields. Calculations showed that practical laboratory magnetic fields of 10–100 Gauss (G) gave lifetimes up to hundreds of minutes. Second, to enable long lifetimes theoretical (Wheeler, 1946; Simons, 1953) and experimental (Stewart and Pope, 1960; Bisi et al., 1963; Bertolaccini et al., 1971; Hautojarvi and Nieminen, 1973) studies showed that the positron binds to the anion in alkali halides and behaves like a free particle not localized to any one anion. We also considered that similar

* Corresponding author at: Positronics Research LLC.
E-mail address: gerry@pr-llc.com

http://dx.doi.org/10.1016/j.radphyschem.2015.09.011
0969-806X/

results might be expected for crystalline hydrocarbons such as C_8H_{10} (naphthalene) (Bisi et al., 1987; Consolati and Quasso, 1994) where hydrogen anions host metastable Ps.

Third, by bombarding samples with γ rays above the external pair formation threshold (Oppenheimer and Plesset, 1933), positrons are formed near the nucleus and repelled outward with a greater probability of binding with anion electrons than positrons from radioactive sources that do not penetrate far into the electron cloud. Obvious sources of γ-rays above the 1020 keV pair threshold are natural ^{40}K (1.25 billion year half-life) in potassium halides and synthetic ^{152}Eu (13.5 year half-life). A common feature is the presence of high energy γ rays at 1461 keV and 1408 keV, respectively. This is important as the pair cross section increases one hundred fold between 1077 and 1407 keV (Yamazaki and Hollander, 1965). Fourth, the electric dipole structure of metastable Ps (Shertzer et. al., 1998) provides a unique time profile of so-called 'double-helix' annihilation of electron–positron entanglement in the magnetic field (Chiueh, 1997).

Finally, two options for counting were considered. First, Geiger counters were used in early low rate experiments, notably enrichment of cosmic ray positrons by coincidence counting (Blackett and Occhialini, 1932). Apropos to the present experiment, back-to-back Geiger counters were successfully used to identify coincident annihilation γ rays from $^{11}C \rightarrow \beta^+$ decay (Klemperer, 1934), as well as measure angular correlations (Beringer and Montgomery, 1942). The efficiency of early Geiger counters has increased 20-fold with the introduction of pancake counters. At $\approx$100 cpm singles rates it is shown later in this paper that their 50–100 μs dead time creates manageable 13% accidental background.

Second, fast scintillation counters were considered. They were initially used with delayed coincidence circuits that led to the discovery of Ps (Deutsch, 1951) with 10^{-7}–10^{-10} s lifetimes and later magnetic quenching studies of alkali halides (Bisi et al., 1971; Herlach and Heinrich, 1972; Bisi et al., 1973; Smedskjaer and Dannefaer, 1975). However, the delayed coincidence method requires a prompt start γ ray pulse that does not exist in pair formation. Alternatively, in-time coincidence counting with energy gates was considered. To illustrate, we cite an experiment with two 4″ diameter × 2″ thick NaI(Tl) counters that viewed an enriched ^{40}KCl source mounted on a plastic β^- veto counter with energy discriminators in each arm (Leutz et al., 1965).

The coincident energy distribution exhibited a pair formed annihilation peak at 463 keV with a FWHM width of 200 keV and background of 25%. The nominal resolution of the NaI(Tl) crystal should be $\approx$20%, including a factor of two for γ rays that cut the NaI(Tl) edges. In our opinion the excessive width and large background were due to accidental coincidences of 1461 keV γ rays with Compton scattered electrons in the NaI(Tl). As the efficiency for detecting low energy electrons is $\approx$100%, coincidence counting with 1461 keV γ rays (60% efficiency) produces large accidental rates. The smaller efficiencies of pancake Geiger counters for electrons (65% at 200 keV) and γ rays (22% at 1461 keV) should reduce the accidental rate by roughly four, or 13% as shown later in this paper. For these reasons and previous successes reviewed above we selected the less expensive, reliable Geiger counters.

2. Theory

We now briefly review the theory of long-lived Ps (Shertzer et al., 1998). In an electric field created by Ps moving on the y axis in a magnetic field B on the z axis, the potential (au) is $V(x, 0, 0) = B^2x^2/4 + BKx/2 + K^2/4 - 1/[\mathrm{abs}(x)]$, where K is the Ps pseudo-momentum. For $B/K << 1$ an outer well exists at $x_0 = -K/B$. Large positron–electron separation requires small B with K being just above unity to avoid unstable coulomb states. To illustrate, Fig. 1 shows $V(x, 0, 0)$ for $B = 7$ gauss ($2.9787234 \cdot 10^{-9}$ au) and $K = 1.01$ au. The well created by the coulomb-diamagnetic potential is centered at $x_o = -3.39 \cdot 10^8$ au (electron–positron separation = 18 mm), with a depth $V_0 = -B/K = -2.95 \cdot 10^{-9}$ au ($-8.0 \cdot 10^{-8}$ eV). Only the ground state at $1.48 \cdot 10^{-9}$ au ($4.0 \cdot 10^{-8}$ eV) is below the ionization level at $I = B = 2.98 \cdot 10^{-9}$ au ($8.1 \cdot 10^{-8}$ eV).

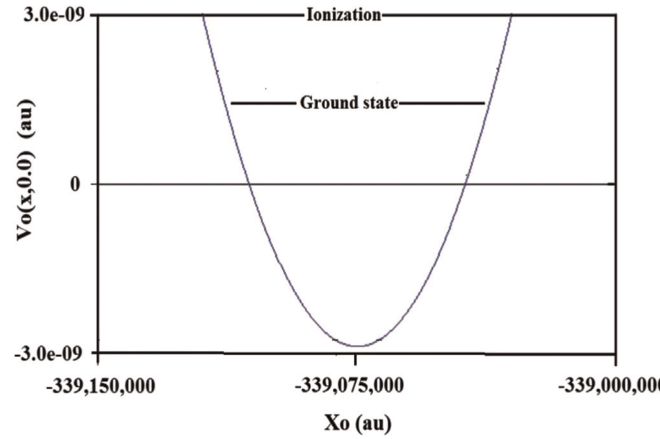

Fig. 1. Effective potential: $B = 2.98 \cdot 10^{-9}$ au (7 gauss), $K = 1.01$ au.

3. Experiment

Two Aware Electronics RM-80 pancake type Geiger counters viewed 210 g of salt-substitute KCl ($\rho = 1.52$ g/cm^3) (Fig.2). The counters had 45 mm diameter thin mica windows, with measured efficiency and dead time of 22% for 511 keV γ-rays and 50–100 μs, respectively. They were at 180° to detect annihilation γ ray pairs in coincidence (C-box). Each counter was 150 mm from the center of a 117 mm long × 38 mm diameter cylinder of KCl wrapped in 1 mm thick pasteboard. To test the system the KCl was replaced with a ^{22}Na positron source with 20 mm thick, 9 mm diameter lead cylindrical holes in front of each counter. The coincidence/singles ratio was $(8.3 \pm 1.7) \cdot 10^{-4}$, compared with $(10 \pm 1) \cdot 10^{-4}$ from a similar experiment with a ^{64}Cu positron source (Beringer and Montgomery, 1942).

A magnetic field was created by a Helmholtz pair of 17 mm diameter × 3 mm thick NdFeB disc magnets with 12,300 G residual field. Each was centered 30 mm from the ends of the inside surface

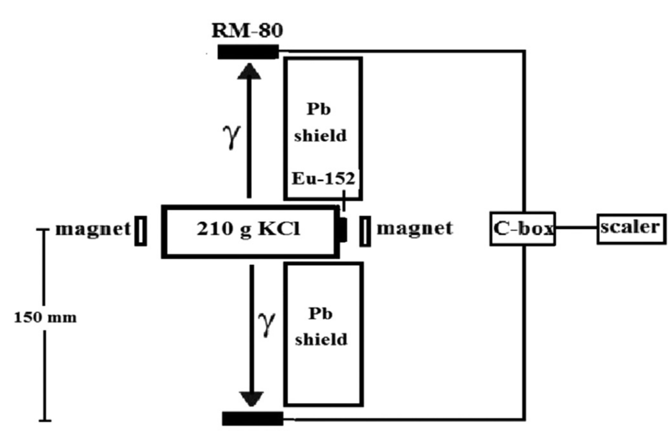

Fig. 2. Experimental setup: plan view; 210 g KCl cylinder with 2 NdFeB disc magnets, 12 G central field at 150 mm disc separation, two RM-80 Geiger counters, lead shields, coincidence circuit (C-box), scaler.