Measurement of the Half-Life of Orthopositronium

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1. Abstract

Until recently, measurements of the orthopositronium decay rate disagreed with the value predicted by quantum electrodynamics. This poster describes a novel attempt to measure this decay rate. Positrons from the decay of ^{22}Na were slowed in a vacuum chamber containing a sample of aerogel. The release of a positron by the ^{22}Na source was signaled by the detection of a 1.27 MeV gamma ray by a plastic scintillation detector. Orthopositronium typically decays into three gamma rays, which were detected by three NaI detectors. By detecting the annihilation gamma rays in coincidence and using energy information from the events, systematic effects due to contamination by parapositronium decay, which plagued previous measurements, may be reduced. Preliminary analysis of data taken over 200 hours has yielded a value for the decay rate of 7.83±0.5 μs^{-1}. Currently, problems with Compton scattering are preventing the use of the energy information in analysis.

2. Introduction

Until very recently, the decay rate of orthopositronium predicted by QED disagreed with the measured value. This led to new experiments and techniques to measure the decay constant as well as more careful theoretical calculations of the decay constant. The earliest experiments were done at the University of Michigan where positronium was allowed to form in a gas, and the vacuum decay rate was determined by extrapolating the results to zero pressure. The results of these experiments differed from the theoretical prediction by around 6.2 standard deviations. This led to performing other experiments in which the positronium was formed in powders, porous surfaces, and aerogel.

Recently, however, groups at Michigan and Japan have performed measurements which found the value of the decay constant to be in good agreement with QED. The group in Japan used SiO_2 for positronium formation, while the Michigan group used a porous silica film. Both these techniques allowed the positronium to be formed at near-thermal energies. The groups also used energy information to eliminate the events where orthopositronium was converted to parapositronium through interaction with the environment. It is now thought that these two effects were responsible for systematic errors in previous experiments. In our measurement we will attempt to more accurately eliminate the effects of parapositronium contaminated by looking for all three gamma rays from orthopositronium decay.

2.Theory

Positronium formation maybe understood qualitatively using the “ore Gap” theory. Positrons which enter a gas are slowed by collisions with the gas molecules until their energy is lower than the energy required to disassociate positronium, around 6.8 eV. At this energy the positrons can form positronium by capturing atomic electrons. Generally between 25% and 50% of positrons entering a gas will form positronium. If the positron and electron have their spins aligned, the resulting exotic atom is call orthopositronium; if they are anti-aligned, it is called parapositronium. Parapositronium decays into two back to back gamma rays of equal energy, while orthopositronium, decays into three gamma rays of varying energies, due to the charge-conjugation selection rule,

$$(-1)^{\ell+s} = (-1)^{n}$$

Where ℓ is the orbital angular momentum, s is the total spin, and n is the number of gamma rays emitted. Since decay into a single gamma ray is forbidden by momentum conservation, the smallest number into which orthopositronium may decay is 3 gamma rays. Parapositronium has a much shorter half-life than orthopositronium, with a decay rate of approximately 140 ns^{-1}. Orthopositronium has a decay rate of approximately 7.4 μs^{-1}.

Once the positronium has formed, it will decay according to the exponential decay law,

$$R = Ae^{-\lambda t} + B.$$

In this formula λ is the decay rate. The decay rate as a gas is always higher than the decay rate in the vacuum, however, because the positron may annihilate with a nearby, bound electron. In the past it has been usual to measure the decay rate at several pressures and then extrapolate to zero pressure. Another problem which can result (especially in oxygen rich gas such as air) is called spin-exchange. Since molecular oxygen has two unpaired spins, it can convert orthopositronium into parapositronium, further distorting the measurement of the decay constant. The recent experiments in Japan and Michigan have used silicon-based powders and films in order to reduce the effects of environment interaction. In these substances there are “vacuum pockets” inside the substance in which the positronium can move and decay after formation.

3. Experiment

As shown in Figs. 3, 4, and 5, our experiment was performed using a plastic scintillator to detect when a positron is released from a ^{22}Na source, and three NaI scintillator detectors to detect the annihilation gamma rays. When ^{22}Na emits a 1.27MeV gamma ray, it simultaneously emits a positron (see Fig. 1). The emitted positrons slowed down as they traveled through the walls of the aerogel cells, and eventually captured and electron to form positronium. The plastic scintillation detector was placed beneath the ^{22}Na, to select events for which the ^{22}Na source emitted a positron. The three NaI detectors were used to detect the gamma rays from the decay of the orthopositronium.

The signals from the detectors were processed by the circuit in Fig. 2. The circuit was designed to only trigger when a gamma was detected in the plastic scintillator and at least one of the NaI detectors. Later only those events where the plastic detector has a 1.7 MeV gamma, corresponding to a positron emission, were selected.

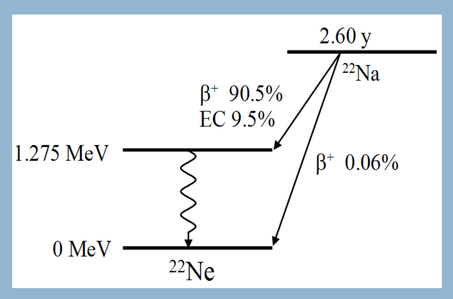


Figure 1. The decay scheme for ^{22}Na. About 90.5% of these decays involve the release of a positron and a 1.275 MeV gamma ray.

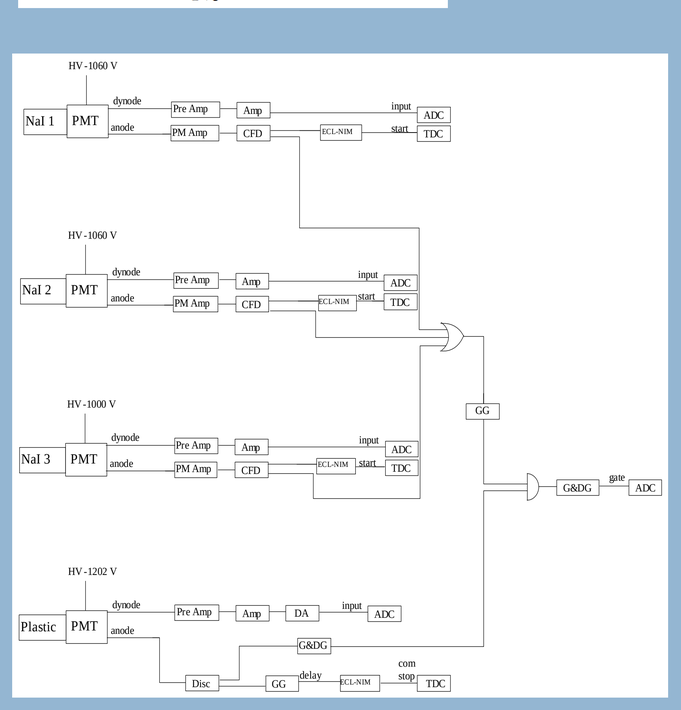
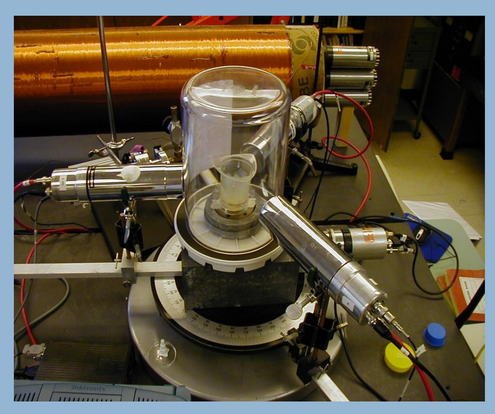
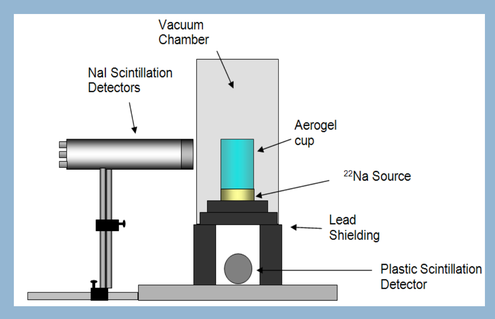
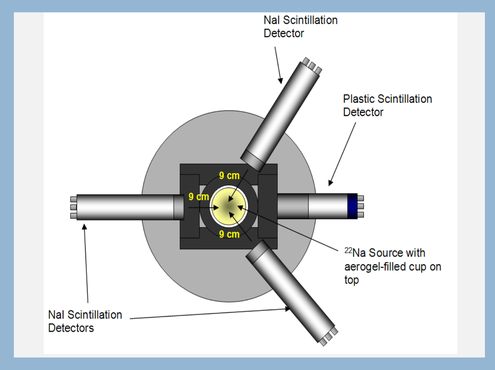


Figure 2. The scintillators are connected to photomultiplier tubes, which have dynode and anode outputs. The dynode output goes through preamplifiers and amplifiers into an Amplitude-to-Digital Converter (ADC), which measures the energy of the event. The anode outputs are used to generate triggers for the ADC. The outputs from the NaI detectors are OR gated together and AND gated with the output of the plastic detector to generate the triggers. The anode outputs are also used as inputs on the Time-to-Digital Converter (TDC). The TDC runs in “common stop” mode: the signals from three NaI detectors go into separate “start” inputs, and the plastic detector runs into the “common stop.” When the TDC receives such a stop signal, it sets the “Look At Me” (LAM) flag, which tells the computer that the data is ready. The computer then reads out the data and stores it for later use.







Figures 3,4, and 5. Side and top views of the experimental setup. Positronium was formed in the aerogel and the annihilation gamma rays detected by the surrounding NaI scintillation detectors, which were placed with an angle of 120 degrees between them. The 1.27 MeV gamma rays released by the ^{22}Na were detected by the plastic scintillator underneath the vacuum chamber.

4. Results and Conclusions

The analysis of data from the first NaI detector (shown in Figure 8) required a simultaneous 1.27 MeV pulse in the plastic scintillator and a NaI pulse with less than 511 keV. The decay time is plotted backwards because of the common-stop electronics. A lifetime of 122±11 ns was found. Since the decay rate is the inverse of the lifetime, the decay rate from detector one was therefore 8.2±0.74 μs^{-1}. Taking a weighted average of the results from all three detectors gave a decay rate of 7.83±0.5 μs^{-1}. This is a slightly higher decay rate than predicted by QED or measured in previous experiments. This is a larger uncertainty than other modern measurements, in part due to the short time over which the data were collected.

One problem with this measurement was Compton scattering of the gamma rays (see Fig. 7). If this occurs then only part of the gamma ray energy will be detected. There are two cases: Compton scattering in the detector being used to make the prediction, and Compton scattering in the detector whose energy is predicted. Either way, the predicted energy will be higher if there is Compton scattering in either detector.

This means that using the current setup, it will be very difficult to use energy information from coincidence events to check whether the events are from orthopositronium. If this technique is to be implemented, a new system will be needed.

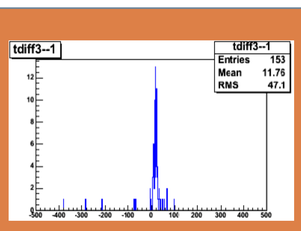


Figure 6. The time difference between signals produced by NaI 1 and 3, for events in both detectors satisfying the requirements to be an orthopositronium event. Notice that there are a fairly small number of coincident events. Also notice that most events come within approximately 50 ns of each other. This shows that most coincidences are coming from positronium decay events.

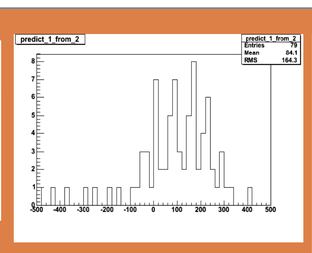


Figure 7. Histogram of the difference between the predicted energy and the measured energy for the NaI 1 scintillator. The peak would be expected to be around zero. Its shift may, however, be explained by Compton scattering.

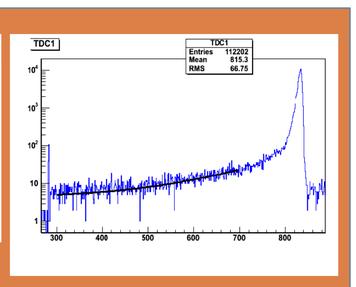


Figure 8. Decay curve from detector 1. The peak around 800 ns is the fast decay curve from the parapositronium. The black curve is the fit. The decay rate was found to be 8.2±74 μs^{-1}. Points used were those between channels 300 and 700, which correspond to orthopositronium decay.