

Advanced Lab Course 2.8A

Measuring the Lifetime of Positronium in Matter

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Task 1: Preparing for the lab course

The goal of this lab course is to measure the lifetime of positronium (Ps) in aluminium and polytetrafluoroethylene (PTFE / Teflon). For this purpose, the following points should be worked out in advance:

(Note: The following text provides only the most important information. It is therefore recommended to deal with the topics on the basis of the literature provided and further reading.)

1a) Decay scheme of ^{22}Na

^{22}Na decays to 89.9 % to ^{22}Ne via beta radiation. Thereby the beta particle has an energy of $E_\beta = 546.67 \text{ keV}$. The ^{22}Ne is in an excited state after the decay and reaches the ground state by emitting a gamma quantum with 1274.5 keV. The mean lifetime of the excited ^{22}Ne state is only 3.7 ps. [Bas15; FBC99]

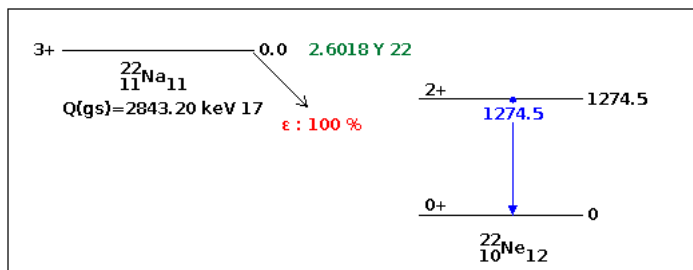


Figure 1: Decay scheme of ^{22}Na . [Bas15]

1b) Positronium formation and its properties in vacuum and matter

The positron is the antiparticle of the electron, which means that they will annihilate each other when interacting. Thereby two gamma rays with 511 keV emerge. However it is possible that they form a bounded state which is called positronium (Ps) before the annihilation which effectively extends the lifetime of the positron. The spin of the Ps can either be 1h or 0. For a spin of 1h the Ps is called orthopositronium (o-Ps) and otherwise its called parapositronium (p-Ps). Since there are three possible states for o-Ps and only one for p-Ps, the buildup ratio is 3:1 in favour of o-Ps. Due to conservation of angular momentum the 2γ -decay is not possible for o-Ps if no other particles are around. Therefore the lifetime of o-Ps in vacuum is 140 ns whereas for p-Ps its only 0.125 ns. In matter, the situation is different because the Ps interacts with the other electrons in its environment. Thereby the 2γ -decay of o-Ps is made possible due to pick-off processes. The o-Ps can also transform into p-Ps by exchanging the electron and vice versa (conversion processes). Thus, especially the lifetime of o-Ps depends on the electron density in its environment. [Hau79]

1c) Interaction of gamma radiation with matter

The three main interactions of gamma rays with matter are the photoelectric effect, the Compton effect, and pair production. In case of a photoelectric effect, the gamma ray transfers all of its energy to an electron, whereas in case of a Compton effect, the gamma ray only scatters with an electron so that only a fraction of its energy is transferred. If the energy of the gamma ray exceeds 1022 keV ($2m_e c^2$) pair production can occur. Thereby a positron-electron pair is generated in the field of an atomic nucleus. [Dem17]

1d) Gamma spectroscopy with scintillation counters

A scintillating material produces flashes of light when ionising radiation interacts with it. By combining a scintillating material with a photomultiplier tube (PMT) that converts the emitted light into a measurable electrical signal, one obtains a suitable detector for gamma spectroscopy since individual gamma rays can be detected and the amplitude of the output signal is proportional to the energy that has been deposited in the scintillator. In this lab course standard detector assemblies of the company Saint-Gobain Crystals with LaBr₃ scintillators are used. [Jen20; Cry19].

1e) Operation principle of the lab course setup

²²Na is especially well suited for measuring the lifetime of Ps. The reason for that is the small timescale (10^{-12} s) in which the positron ($E_\beta = 546.67$ keV) is slowed down to the eV-range as well as the short lifetime of the excited ²²Ne state. Therefore, in the scope of this lab course, the detection of a 1275 keV gamma ray can be considered as simultaneous with the creation of a positron. Furthermore, the detection of a 511 keV gamma ray indicates that a positron has annihilation. Measuring the correlation between those two events requires two detectors because their dead times are higher than the lifetime of the Ps. Also normal leading edge discriminators are not sufficient since the time walk caused by the slowly rising edge of the PMT, would distort the measurements. To compensate the time-walk effect, constant fraction discriminators (CFDs) by the company ORTEC are used. In these, the input signal is split up into two signals. Then one of them is attenuated and delayed before they are superimposed again. The zero crossing of the resulting signal is thus independent of the amplitude of the input signal and can be used for triggering. The CFDs also have upper and lower thresholds for the input signal. These can be used to ensure that they are only triggering when signals arrive that are in the desired range. The output signals of the CFDs are then processed by a time-amplitude converter (TAC) and finally passed to an analog-to-digital converter (ADC). To make sure that the stop signal is not reaching the TAC before the start signal and to enable a time calibration, an adjustable delay has to be inserted between the 511 keV CFD and the TAC. The TAC and the adjustable delay are also from the company ORTEC. The exact designations are: 583B Constant Fraction Differential Discriminator, 566 time-to-amplitude converter and 425A nanosecond delay. [Bas15; FBC99; ORT19; Cry19].

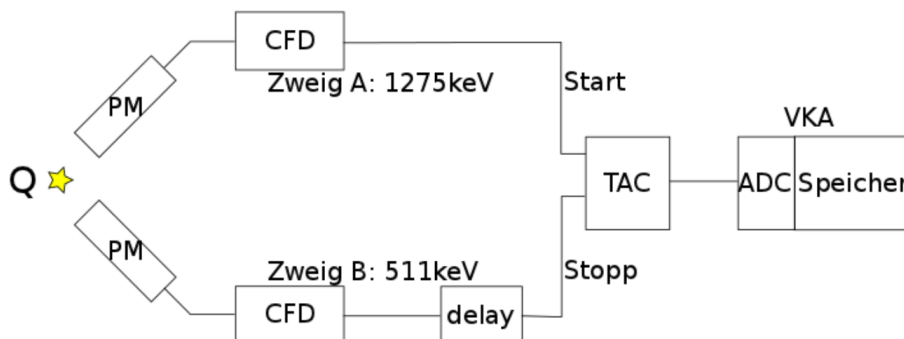


Figure 2: Schematic illustration of the setup for the lifetime measurements. A detailed description and the abbreviations are explained in the text above.

Task 2: Performing the lab course

2a) Commissioning of the detectors

Please do this step together with your tutor and don't touch the detectors after the high voltage (HV) is applied.

- Turn on the power supply of the rack with the nuclear instrumentation module (NIM) bins.
- Turn on the high voltage (HV) on the power supply for the scintillator detectors (both channels).
- Make sure the polarity of the power supply is negative (both channels).
- Provide both detectors with 1280 V.
- Check the output signals of the detectors resulting from the background radiation in the oscilloscope. (Note: The signals have negative voltages so the trigger level has to be under the baseline.)

2b) Measuring the background radiation and the gamma spectrum of ^{22}Na

- Measure the background radiation for 10 minutes.
- Then measure the gamma spectrum of one of the ^{22}Na sources for 2 minutes.
- After that the ^{22}Na source can be removed again for the time being.

(Note: The output signal of the detector has to be amplified to get into the acceptable range of the ADC.)

2c) Check the functionality of the electrical components by observing their input and output signals with the oscilloscope

- Put the output signal of one of the detectors in the CFD and check the output signal of the CFD in the oscilloscope.
- Check if the delay works properly by observing the two output signals (the two outputs of the CFD provide exactly the same signal) of one CFD in the oscilloscope and delaying one of them.
- Check if the TAC works properly by observing its output signal in the oscilloscope and using the two output signals of one CFD together with the delay as start and stop. (Note: The TAC signal has a positive voltage so in this case the trigger level has to be above the baseline. Also the TAC does not provide an output signal if the timespan between the start and the stop is out of its range.)

(Note: The velocity of signals in cables is approx. 5 ns per meter.)

2d) Performing the time calibration measurement

For the time calibration measurement, the setup used for checking the TAC can be kept. Just put the output signal of the TAC from the oscilloscope in the ADC and measure the amplitude for at least five different delays. The chosen delays have to be in the range of the ADC and as far apart from each other as possible. You will need this measurement to convert the channel difference to a time difference in the evaluation.

(Note: Don't amplify the output signal of the TAC. Instead, increase the delay in order to get to the acceptance range of the ADC.)

2e) Set the thresholds of the CFDs and start the lifetime measurements

To adjust the CFD thresholds a ^{22}Na source is required. The input (detector signal) and the output of the CFD have to be observed on the oscilloscope at the same time. Thereby the oscilloscope should be triggered by the output signal of the CFD. Now the thresholds has to be adjusted so that the CFD only provides an output signal for the desired range (one for input signals that are caused by gamma rays with about (511 ± 50) keV and the other one for input signals that are caused by gamma rays with about $(600 - 1325)$ keV). When both CFDs are set up properly everything has to be wired as illustrated in figure 2. Then the lifetime measurements can be started. The measurement has to done with two different ^{22}Na sources (one is encased by aluminium and the other by PTFE). They should both run as long as possible, but since your tutor will need to edit the sources, this should be discussed with him.

(Note: When setting up the thresholds of the CFDs, identifying the signal that belongs to the 511 keV photopeak can be hard. Start by increasing the lower limit just slightly till the low energetic part of the gamma spectrum is ignored. Then it should be the signal that occurs most frequently. After that, one has a good starting condition for identifying the signals that belong to the 1275 keV photopeaks.)

Task 3: Evaluating the measured data

3a) Calibration of the gamma spectrum

Use the 511 keV and 1275 keV photopeaks to calibrate the gamma spectrum. Then check if the Compton edges and the backscatter peaks are at the expected energies.

3b) Checking the background radiation for anomalies

The main question to answer here is if there were any other radiation sources in the surroundings of the experimental setup that could have distorted the measurements. Use the energy calibration from the previous task (3a) to make sure.

3c) Time calibration

Use the data from the time calibration measurement to determine which channel difference corresponds to a time difference of 1 ns.

3d) Events caused by random correlations

Determine the ratio between random correlations and real events and subtract the random correlations from the data if necessary. To determine the ratio, the sum of the counts caused by immediate annihilations is divided by all other counts.

3e) Time resolution of the life measurement setup

Fit a Gaussian distribution on the peak caused by immediate annihilations. Since there should also be counts caused by Ps annihilations on the right flank of the peak, the Gaussian distribution won't fit in this area. The time resolution of the setup corresponds to the full width at half maximum (FWHM) of the fitted Gaussian distribution.

3f) Lifetimes of p-Ps and o-Ps in aluminium and PTFE

Use the lifetime measurement data in logarithmic scale to find two areas on the right flank of the peak that are approximately straight so you can fit a linear regression on them to determine the lifetimes ($\tau = 1/m$).

3g) Ratio of p-Ps to o-Ps

Simply divide the sum of the counts in the areas you used for fitting the linear regressions.

3h) Writing the report

The report should contain the physical fundamentals that had been worked out in advance, the conduct of the experiment and the evaluation of the measured data. At the end of the report, there should also be a discussion on the differences between the lifetimes and the ratios between p-Ps and o-Ps for aluminium, PTFE and vacuum. Thereby attention should be paid to the temporal resolution of the setup.

References

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