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Software implementation and modernization of positron annihilation spectroscopy experiments

Positron annihilation spectroscopy is a non-destructive method used to study materials, especially semiconductors, and is used to probe vacancy-type defects inside the material. In the formation of semiconductors, impurities and defects can be introduced to obtain certain desired effects, however, this can create unwanted defects, which can be on the atomic scale, throughout the material, affecting the optical and electronic properties.

The main interaction we are interested in is the electron-positron annihilation that usually happens in regions of reduced electron density, usually found in the vacancies and voids of the material. Through this process, we can measure the lifetime of the positron, i.e., the time between positron emission and annihilation. This interaction produces two equally energetic gamma photons, each with an energy of 511 keV (corresponding to the rest mass of an electron), in opposite directions. The lifetime is inversely proportional to the local electron density, providing information about the concentration and types of vacancy defects present in the material.

The method of detection for this experiment makes use of coincidence detection, since we must determine both when the positron (β^+) is emitted from the radiation source, and when the positron annihilates. Usually, we use a β^+ emitter that also emits a gamma, and, in our experiments, we use a ^{22}Na source. This is due to the fact that when the positron decays, there is a prompt gamma emission accompanying the β^+ decay, and since they differ in energy, they can be identified through energy-based triggering techniques.

To be specific, the ^{22}Na emits a 1.27 MeV photon almost immediately after the positron, so we take that signal as the start of our measurement. After that, we wait for the 511 keV photon resulting from the annihilation, which is our stop signal. There are other considerations, like cable delay, dead time in the detector, geometry of the setup that are traditionally taken care of by the electronics of the experiment. In the past, this was done in complex and expensive specialized electronics, but nowadays, with more affordable and efficient computational resources, we can make use of a digital oscilloscope along with a general-purpose computer to achieve comparable performance to the specialized electronic setup.

In my thesis, I tackle how to design and program such an experiment, in order to run on standard computing hardware with a specialized digital oscilloscope. The main challenges arise from the fact that the lifetime measurements require sub-nanosecond accuracy, since the average lifetime of a positron in a semiconductor is around 150-200 ps. Longer lifetimes indicate reduced local electron density, typically associated with vacancy-type defects.

Before using a full setup for positron annihilation spectroscopy, due to the constraints of radiation safety and convenience, we only started with one NaI scintillator with a low activity source (radium clock), which can be used safely outside of controlled radioactive environments. Because most of the work is software programming of the digitizer and software analysis, this ensured easier bug fixing and optimization.

The main programming languages used for this project are C# and C++. Both were used because the previous setup already made use of C++ for the data analysis, allowing highly optimized data analysis and efficient execution. C# was used for hardware control and user interface development, providing a flexible platform for hardware control and data visualization tasks. This resulted in a self-contained hardware control system with integrated data analysis and multiple visualization tools.