Development of a Positron-Electron Annihilation Spectrometer to Characterize Defects in Crystalline Materials at Union College

Jacob E. Feinstein, Colin M. Langton, Mia E. Villeneuve, Scott M. LaBrake, Michael F. Vineyard, and Heather C. Watson
Department of Physics and Astronomy
Union College, Schenectady, New York

Introduction

Electron-positron annihilation lifetime spectroscopy (or EPALS) is an analytical method for characterizing near surface defects on the atomic scale in crystalline samples of materials by measuring the lifetime of a positron, e^+ emitted from a nuclear decay. The method depends on the time it takes a e^+ to annihilate with an electron, e^-, when the e^+ travels through a material. The e^+ lifetime is inversely proportional to the number of defects in the material. Using EPALS we can characterize the vacancies in a material. This will allow us to further this research into the effects of radiation damage on crystalline materials which could help answer questions on the diffusion of radioactive elements into irradiated material. When a material is subject to radiation damage, defects are formed and it becomes easier for radioactive elements to penetrate the damaged material. This raises several concerns, one such concern is that of containment of radioactive waste. When a material contains radioactive waste, it will be subject to radiation damage and eventually become more susceptible to leaking radiation into our environment.

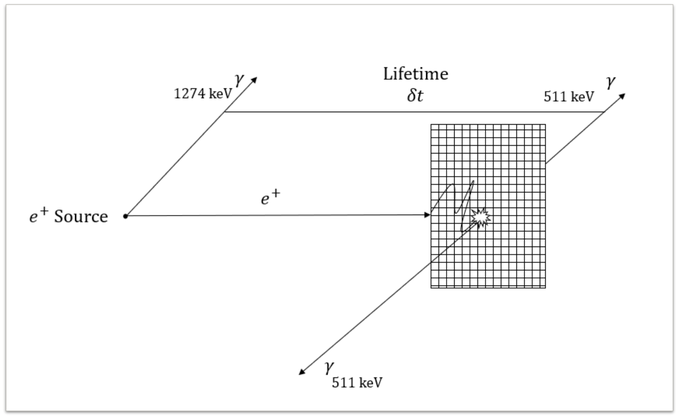

Fig. 1: Diagram depicting the lifetime of a positron in a material and associated gamma-rays.

Method

Sandwiching a sample of crystalline material around a thin ^{22}Na, e^+ emitting source near surface crystalline defects can be detected by measuring the lifetime of the emitted e^+, as shown in Fig. 1. In the radioactive decay of ^{22}Na, a e^+ is emitted producing an excited state of ^{22}Ne which decays by prompt gamma ray emission with an energy of 1247-keV into a stable state of ^{22}Ne, as can be seen in Fig. 2. The emitted e^+ will travel into the crystalline material and will eventually annihilate with an e^- in the material producing two counter-propagating 511-keV gamma-rays. The lifetime of the e^+ is the time from its emission from ^{22}Na nucleus to its subsequent annihilation. Crystalline defects in the material will produce lifetimes that are longer than those obtained from materials with fewer near-surface defects. The difference in time between the detection of the 1247-keV and the two coincident 511-keV gamma rays gives the lifetime of a e^+ (on average 0.4-2 nanoseconds). Thus from the lifetime of the e^+ we can glean some information on near surface defects in the material.

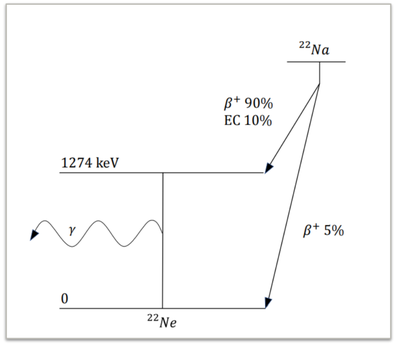

Fig. 2.: Energy Vs. Z diagram for the radioactive decay of ^{22}Na.

Current Work

We aligned the faces of 2.2-cm diameter sodium iodide (NaI) radiation detectors approximately 40-cm apart, as seen in Fig. 3. The detectors were calibrated using known gamma-ray emitters, ^{137}Cs (with energy 662-keV) and ^{133}Ba (with prominent energies at 80 & 356-keV). In Fig. 3, a sealed ^{22}Na source produces the e^+ in our experiment. The detectors are connected to an Ortec 418A coincidence module, operated in coincidence mode, to detect the characteristic 511-keV gamma rays emitted from the annihilation of the e^-/e^+. Thus when a 511-keV gamma ray is detected by one detector, within a small window of time a 511-keV gamma ray detected in the other detector, if this condition is satisfied then the detector will register this as one count. Measurements were made of the number of coincident gamma rays detected as a function of the angle between the aligned faces of the NaI detectors, taken as 0°. If we are actually detecting gamma rays from electron-positron annihilation, then as the angle between aligned faces of the NaI detectors varies about 0°, the number of coincident gamma rays detected should decrease. In Fig. 4. we plot the counts detected as a function of the angle between the faces of the NaI detectors. As expected, as the angle deviates about 0° the number of coincident gamma rays detected decreases. Thus, we are able to detect the coincident gamma rays produced and thus the annihilation of the e^+/e^-.

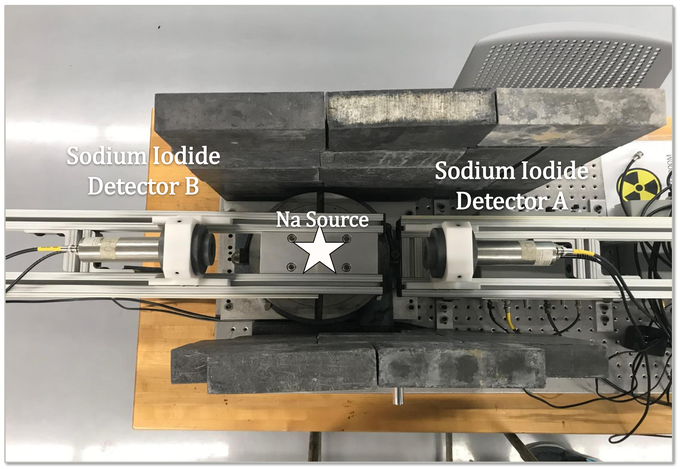

Fig. 3 Photograph of the current experimental setup for detecting coincident gamma rays from the decay of ^{22}Na.

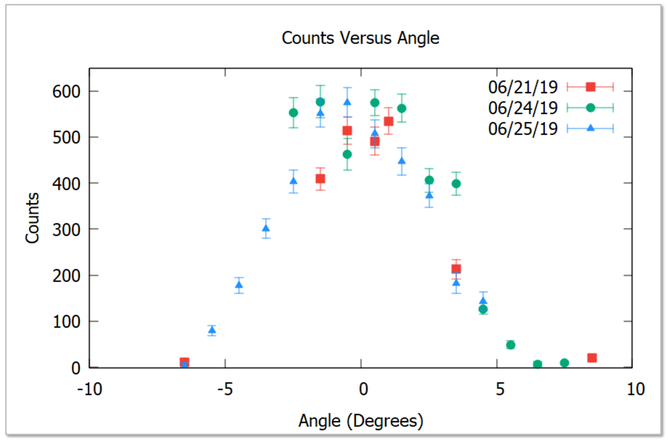

Fig. 4: A plot of the number of coincident gamma rays detected versus angle between the two NaI detectors from e^+/e^- annihilation.

Future Work

Measurements of the lifetime of the e^+ will necessitate modifications to our current set-up. Modifications will include changes in the activity of the radioactive source being used as well as the need for faster timing electronics. At present, the sealed ^{22}Na source we have been using is several millimeters thick and most of the e^-/e^+ annihilations occur with in the plastic case surrounding the source. To have the positrons annihilate in the sample of crystalline material and not in the source casing we require a substantially thinner sealed radioactive ^{22}Na source. In addition, our current ^{22}Na source has an activity of 0.037μCi. We have purchased a 10μCi ^{22}Na and this will allow for more e^+ emissions into our sample material. To determine the lifetime of the e^+ we will be using fast plastic scintillators. Currently, our detectors do not possess the timing resolution necessary to accurately measure the lifetime of a positron, which is around 100-400 picoseconds. However, these scintillators will have a resolution on the scale of picoseconds making them the perfect candidates for our experiment and a necessary tool. Additionally, a germanium detector will allow us to employ coincidence doppler broadening as another method of defect detection.

Acknowledgements

We would like to thank the donors of the Davenport Fellowship Grant, the Union College Department of Physics and Astronomy, and Union College's Summer Research Administration for their financial support.

References

[1] R.W. Siegel, 1980, Positron Annihilation Spectroscopy, Ann. Rev. Mater. Sci. 1980. 10: 393-425
[2] C. N. Taylor et al. 2013, Development of Positron Annihilation Spectroscopy for Characterizing Neutron Irradiated Tungsten. PFMC-14, May 2013.
[3] Zhenyu Shen et al., Investigation Of Helium Behavior in RAFM Steel by Positron Annihilation DOppler Broadening and Thermal Desorption Spectroscopy, Materials 2018, 11, 1523; doi:10.3390/ma11091523
[4] Xunxiang Hu et al, Positron Annihliation Spectroscopy investigation of vacancy defects in neutron-irradiated 3C-SiC, Physics Rev. B 95, 104103 (2017)