Positron-electron annihilation momentum transfer to trapped deuterons

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ABSTRACT
The probability of positron annihilation momentum transfer to a trapped deuteron is calculated based on neutron measurements from \(^2\)H(d,n)\(^3\)He reactions in deuterated palladium thin films. Deuterium gas loading in Pd thin films creates a high D/Pd fraction at point defects in the metal lattice. Unmoderated positrons from a Na-22 source thermalize and are trapped in the same point defects as deuterium in the Pd thin films. Similar to the Mössbauer effect, an interaction with the surrounding crystal lattice allows for conservation of momentum during electron-positron annihilation energy transfer to the trapped deuteron.

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I. INTRODUCTION
It has been postulated that positron-electron annihilation could induce fusion reactions in deuterated metals. In this process, originally described by Morioka, a positron and deuteron are co-located in a metal lattice vacancy, as shown in Fig. 1. Positrons and deuterons can both diffuse in the bulk of a crystal until being trapped at such a lattice vacancy.

This positron trapping mechanism can be related to defect size and electronic environment and is utilized in several positron-based defect analysis spectroscopy techniques. The “knock-on” mechanism described here has yet to be observed; however, a similar positron annihilation nuclear excitation process has been measured. In this process, annihilation energy can produce excited metastable states of surrounding nuclei (Fig. 2 left). Figure 2 (right) shows the Feynman diagram of the “knock-on” nuclear excitation process, whereby a virtual photon imparts up to 511 keV kinetic energy to a trapped deuteron.

Here, momentum is conserved via an interaction potential \(Q_{int}\) with associated momentum \(P\) transferred to the surrounding crystal. The form of this potential is borrowed from the Mössbauer effect,

\[
Q_{int} = -Ze\kappa e^{-P_{x}},
\]

where \(Z\) is the atomic number of the surrounding crystal, \(\kappa\) is the strength of the interaction, and \(x\) is the interacting particle coordinate.

In this way, Morioka calculates nonrelativistic solutions to the third order perturbed diagram in Fig. 2 (right) using the Feynman technique. Comparing the spin averaged differential cross section, \(\frac{d\sigma_3}{d\Omega}\), with the dominant 2-gamma annihilation process, \(\frac{d\sigma_2}{d\Omega}\), the momentum transfer probability, \(R\), is defined as

\[
R \equiv \frac{d\sigma_3}{d\sigma_2} = \frac{e^2}{2m^2} \sqrt{\frac{M_2}{m}} |I|^2,
\]

where \(I\) describes the nonrelativistic Hamiltonian S-matrix for the impulse interaction described above. \(M_2\) and \(m\) are the mass of the deuteron and positron, respectively. A square-well potential with binding energy in the ~electron-volt range is assumed, with Pd vacancy size between 1 and 2 Å. The momentum transfer probability depends strongly on the rigidity of the crystal. Here, the rigidity is described using a parameter \(h\) such that \(0 < h \leq 1\). The momentum transferred to the surrounding crystal is a fraction of final deuteron energy,

\[
P = hD_f.
\]
In a perfectly rigid metal where $h$ is unity, $R = 0.001$. The value for $R$ varies significantly with the rigidity parameter, as shown in Table I.

Typically, the fusion rate is defined by

$$\lambda_F = \sigma_D \nu_D,$$

where $\nu_D$ and $\sigma_D$ are the velocity and cross section of the deuteron-deuteron system. However, in the case where we include the momentum transfer probability, $R$, from the annihilating positron to the surrounding deuteron, the fusion rate becomes

$$\lambda_F^D = R \lambda_F.$$

### III. RESULTS

The neutron signal was determined throughout an approximately 1 month-long acquisition duration, consisting of 24 individual 6 h runs. Because the signal is near zero, the neutron rate is calculated using a Poisson distribution with confidence intervals calculated using the Agresti-Coull method for Poisson means. The lower and upper confidence intervals are $5.5 \mu\text{rem/h}$ and $6.2 \mu\text{rem/h}$ for the loaded runs. For the background runs, the lower and upper confidence intervals are $1.3 \mu\text{rem/h}$ and $1.7 \mu\text{rem/h}$.

We can now estimate the positron catalyzed momentum transfer probability per positron-electron annihilation. First, we must once this momentum transfer to the deuteron occurs, the fusion reaction probability is determined by the DD fusion cross section and surrounding deuterium number density. $^3\text{He}(d,n)^4\text{He}$ reactions will release energetic ($2.5 \text{ MeV}$) neutrons, which are a tell-tale sign of fusion reactions.

### II. EXPERIMENTAL

To measure the upper limit of the momentum transfer probability, a simple experiment, shown in Fig. 3, was set up to measure fusion neutrons from a low-activity ($6.7 \text{ mCi}$) positron source. This experiment used an uncooled Na-22 radioisotope source of positrons surrounded by 50 layers of $5 \mu\text{m}$ thick deuterium loaded Pd thin films. We assume that all of the emitted positrons thermalize inside of the Pd films as the thermalization length of unmoderated positrons from Na-22 is much less than the total Pd thickness ($250 \mu\text{m}$). The Pd thin films are loaded with deuterium by introducing pure D$_2$ gas at a pressure of 1 atm at room temperature for more than 6 h. In this case, the equilibrium gas loading of Pd thin films produces approximately $0.7 \text{ D/Pd}$ loading fraction over the entire Pd volume, giving a deuterium density ($n_D$) of approximately $10^{23} \text{ cm}^{-3}$. This assumption is based on the pressure-composition isotherms of the Pd-H system from Moon. In this case, every positron is likely to diffuse to a defect site containing one or more deuterium atoms (saturation trapping). By measuring the isotropic emission rate of neutrons, $\eta$, the nonrelativistic spin averaged differential cross section for the momentum transfer process is

$$R \approx \frac{2\eta A_B Y_D}{A_{Bq} \beta Y_D},$$

where $A_{Bq}$ is the Na-22 activity in Becquerels, $\beta$ is the positron branching ratio, and $Y_D$ is the fusion yield per deuteron created during the annihilation momentum transfer process. In addition to the neutron measurements, a gamma ray spectrum was taken during experimental runs with and without deuterium gas loading. A Kromek GR1A CdZTe scintillator and silicon photomultiplier were used to capture the spectra.

The background neutron rate depended on the physical location of the experimental apparatus and the amount of shielding surrounding the detectors. Therefore, background runs were taken in the same physical location, time period, and shielding environment as loaded runs, except with the Na-22 source removed. We found the neutron detectors to be insensitive to gamma radiation.

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estimate the $^2\text{H}(d,n)^3\text{He}$ reaction fusion yield per deuteron, $Y_D$. In this case,

$$Y_D = \phi \int_0^{D_0} \sigma(E) \frac{dE}{dx} \, dE,$$

where $\phi$ is the initial flux of energetic deuterons (cm$^{-2}$ s$^{-1}$), $\sigma(E)$ is the DD fusion cross section (cm$^2$), and $\frac{dE}{dx}$ is the stopping power in palladium. Using NIST reference data tables for DD fusion reaction cross section and stopping power, Eq. (7) is numerically integrated to obtain $Y_D = 10^{-4}$ DD fusion reactions per energetic deuteron. Similarly, commercially available beam target fusion neutron generators use a deuteron beam accelerated toward a deuterated metallic target at energies $<100$ keV. Fusion yields from beam target fusion neutron generator experiments indicate that Eq. (7) tends to overestimate $Y_D$ by at least an order of magnitude. Therefore, for the purposes of estimating the momentum transfer probability, we will assume $10^{-5} < Y_D < 10^{-4}$. For comparison, DD beam target fusion neutron generators typically have yields of approximately $10^{-7}$. Higher yields are expected from the 511 keV.

Deuterons are generated in the annihilation momentum transfer process as the DD fusion cross section increases monotonically up until 2.2 MeV; using the range of values for $Y_D$ calculated from Eq. (7), we find that momentum transfer probability is $7 \times 10^{-4} < R < 7 \times 10^{-2}$.

The gamma ray spectra in Fig. 4 show the 511 keV positron-electron annihilation photons as well as the coemitted 1.275 MeV peak from the main decay channel of Na-22. The spectra also show a significant difference in the low energy region compared to the background (Na-22 only) spectrum.

**IV. DISCUSSION**

We measure a statistically significant difference in the neutron rate for deuterium loaded samples with the Na-22 positron source when compared to background measurements. As most of the uncertainty in the measurement of $R$ comes from the uncertainty in yield, it may be beneficial to calibrate the D/Pd target using a deuteron accelerator at appropriate implant energy before introducing the positron source. Thermal Desorption Spectroscopy (TDS) can be used to determine D/Pd loading fraction, which may help further reduce the uncertainty in the measurement of $R$. In future work, higher activity sources will generate pulsed beams of monoenergetic positrons to measure time-of-flight and charge to mass ratios of ejected particles, which should give further clarity on the annihilation momentum transfer and DD fusion events.

An alternative explanation for the neutron rate measured is that a low energy nuclear reaction (LENR) is occurring within the sample, rather than the positron annihilation momentum transfer process described above. However, for the deuterium loading fraction and Pd mass used in these experiments, the neutron rate observed here is at least two orders of magnitude larger than predicted by LENR studies.

Morioka’s original theory did not consider more than a single deuterium atom in a lattice vacancy. As such, the local density and quantum state are likely to play a role in the annihilation momentum transfer probability. This may account for higher than expected values for $R$ although a more detailed study combining neutron

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**FIG. 3.** Experimental setup for long counter neutron detection of positron annihilation catalyzed fusion reactions.

**FIG. 4.** Gamma ray spectrum from the Na-22 source with (solid) and without (dashed) deuterium gas loaded palladium samples. The data are normalized to the 1.275 MeV peak, which is independent of any annihilation process.
measurements with superconducting quantum interference (SQUID), TDS, and TOF spectroscopy is required.

The differences in the gamma ray spectra and the peak around 80 keV are unexplained. This photon energy is too high to be due to x-ray fluorescence in Pd, yet too low energy to be due to nuclear fusion processes. We also cannot rule out bremsstrahlung radiation due to the slowing down of the energetic positrons and/or deuterons in the Pd metal. Pd activation via $^{197}$Pd(n,x) reactions is another possible source of gamma rays in this energy range; however, higher resolution (e.g., high purity Ge) detectors are required to investigate further.

Unfortunately, the CdZTe gamma ray detector used in this work did not have sufficient timing resolution to perform Positron Annihilation Lifetime Spectroscopy (PALS) nor the energy resolution to support Doppler Broadening Spectroscopy (DBS). These tools, or a combination thereof, could be used in future work to determine the annihilation site physical and chemical properties, which may provide insight into the annihilation momentum transfer process and the source of unexplained differences in the gamma ray spectra described above.

To conclude, we have measured a clear neutron signal in deuterated palladium metal thin films in the presence of a radioisotope positron source. Applying some simple assumptions regarding the deuterium density and DD fusion kinetics, these neutron measurements indicate that a positron-electron annihilation momentum transfer process is occurring in point defects in the Pd metal lattice. This result could aid in future advancements in a variety of fields, including inertial confinement fusion, antimatter-based spacecraft propulsion systems, or as the basis of a spectroscopy technique for materials analysis.

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