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 $^2H(d,n)^3He$ 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,[1] 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.[2] The "knock-on" mechanism described here has yet to be observed; however, a similar positron annihilation nuclear excitation process has been measured.[3–5] 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,

$$Q_{int} = -Ze\kappa e^{iPx}, \tag{1}$$

where Z is the atomic number of the surrounding crystal, κ 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, $\frac{d\sigma_R}{d\Omega}$, with the dominant 2-gamma annihilation process, $\frac{d\sigma_{2\gamma}}{d\Omega}$, the momentum transfer probability, R, is defined as

$$R \equiv \frac{d\sigma_R}{d\sigma_{2\gamma}} = \frac{e^2}{2m^2}\sqrt{\frac{M_D}{m}}\left|I^2\right|, \tag{2}$$

where I describes the nonrelativistic Hamiltonian S-matrix for the impulse interaction described above. M_D 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,

$$P = hD_f. \tag{3}$$

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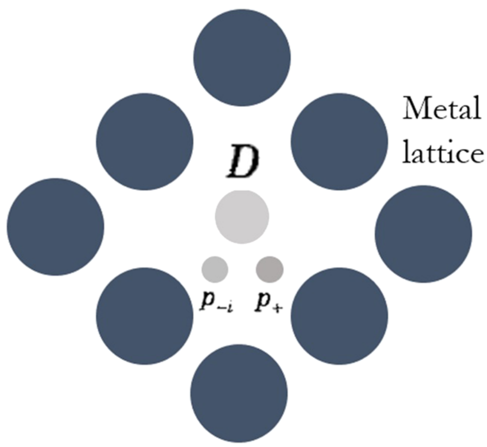

FIG. 1. Showing a trapped deuteron, D, inside a metal lattice vacancy defect, co-located with a positron, p+, and an electron, p−.

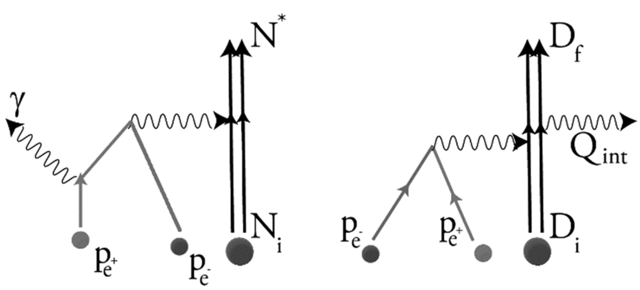

FIG. 2. Feynman diagrams for inelastic nuclear excitation process (left) and the Morioka process (right). Q_{int} describes the sudden momentum transfer interaction with the surrounding crystal (analogous to the Mössbauer effect).

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

$$\lambda_F = \sigma_D v_D, \tag{4}$$

where v_D and σ_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

$$\lambda_F^D = R\lambda_F. \tag{5}$$

TABLE I. Crystal rigidity effects on the momentum transfer probability. Data reproduced from Ref. 1 using 1.5 Å trap width and 12.08 eV trap potential.

Rigidity parameter (h)	R
0.9999	1.5×10^{-4}
0.999	3×10^{-7}
0.99	8.1×10^{-14}

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.[6] ^{2}H(d,n)^{3}He reactions will release energetic (2.5 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 mCi) positron source. This experiment used a uncooled Na-22 radioisotope source of positrons surrounded by 50 layers of 5 μm 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 μm). 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 D/Pd loading fraction over the entire Pd volume,[7,8] giving a deuteron density (n_D) of approximately 10^{23} cm^{-3}. This assumption is based on the pressure-composition isotherms of the Pd-H system from Moon.[8] In this case, every positron is likely to diffuse to a defect site containing one or more deuterium atoms (saturation trapping).[2] By measuring the isotropic emission rate of neutrons, η, the nonrelativistic spin averaged differential cross section for the momentum transfer process is

$$R \approx \frac{2\eta}{A_{Bq}\beta Y_D}, \tag{6}$$

where A_{Bq} is the Na-22 activity in Becquerels, β 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.[9]

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.[10] The lower and upper confidence intervals are 5.5 μrem/h and 6.2 μrem/h for the loaded runs. For the background runs, the lower and upper confidence intervals are 1.3 μrem/h and 1.7 μrem/h.

We can now estimate the positron catalyzed momentum transfer probability per positron-electron annihilation. First, we must

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