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**Measurements of Neutron Emission Induced by Muons  
Stopped in Metal Deuteride Targets**

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## Abstract

An 80 MeV/c negative muon beam from the Alternating Gradient Synchrotron at Brookhaven National Laboratory was used to investigate the stopping of muons inside Pd, Ti and Y targets saturated with deuterium. Neutron emission from the targets was measured with an array of  $^3\text{He}$  detectors, and in some runs, the temperature of the target was monitored as a function of time, with and without a flux of muons on the target. The neutron rates were also measured for Pd cathodes in an active electrochemical cell similar in design to those used in so-called "cold fusion" experiments, and the electrolyte solution was analyzed for excess tritium. No evidence was found for muon catalyzed fusion at rates consistent with those claimed in "cold fusion" experiments. Neutron production from catalyzed fusion due to the presence of deuterium in palladium deuteride,  $\text{PdD}_{0.7}$ , exposed to muons was determined to be  $0.0 \pm 0.03$  (stat.)  $\pm 0.25$  (syst.) neutrons per stopped muon.

## Key Words

Cold Fusion

Muon

Muon Catalyzed Fusion

Metal Deuteride

## Introduction

Recently, three papers have reported<sup>1-3</sup> observation of D-D fusion in metal deuterides. These claims have been examined in many experimental,<sup>4,5</sup> computational<sup>6,7</sup> and theoretical<sup>8,9</sup> studies. A possible mechanism explaining cold fusion that has been presented is the catalysis of D-D fusion by naturally occurring negative muons from cosmic rays.<sup>9</sup> In this theory it was suggested that in fully saturated metal hydrides, muons might be shielded from capture by heavy element nuclei because of the band structure of this solid. The largest muon catalyzed fusion turnover rate observed has been 150 fusion reactions per muon in a liquefied mixture of D<sub>2</sub> and T<sub>2</sub>.<sup>10</sup> However, the result of exposing metal hydrides to muons is not documented. To investigate the possibility of muon catalyzed fusion in metal hydride targets, we conducted an experiment with deuterated Pd, Ti and Y on a muon beam line at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. Presented here is a preliminary report summarizing the apparatus, targets used and analysis of a representative experimental run.

## Experimental Apparatus

A diagram of the the AGS muon facility is shown in Figure 1. Approximately  $1.5 \times 10^{13}$  protons are accelerated to 30 GeV every 2.5 s and then slowly extracted out of the AGS to the experimental target stations for 1.0-1.25 s. A fraction of the AGS protons (typically  $5 \times 10^{11}$ ) are split off to the muon beam experimental

area where they are focused onto a 10 cm long Pt target. The secondary particles produced are then captured in the muon beam line. A portion of the pions produced in the collision enter the beam line, where they are first momentum selected by a dipole magnet and then allowed to decay into muons in a quadrupole channel. The muons are momentum selected to 80 MeV/c by a dipole magnet and focused by quadrupole magnets directly before entering the concrete, steel and lead shielding structure of the experimental target area.

A diagram of the target area is shown in Figure 2. The 2 x 2 cm collimated muon beam is defined by a fast coincidence plastic scintillator hodoscope. An incident muon event is defined by a coincidence of the S1, S2, and S3 scintillators within a gate width of 10 ns. The defined beam size at the target is approximately 4 cm<sup>2</sup>. A "muon stop" is counted if the muon is not subsequently detected at the veto counter, S4, situated behind the target. The thin plastic scintillators have efficiencies near unity for both fast muons and electrons. The difference in the range of photomultiplier pulse heights between the electrons and the muons permitted discrimination between the two. From this measurement, we conclude that the electron contamination in the beam was less than 25%. A degrader (0.5 cm of Pb) was placed between the S2 and S3 scintillators to slow down the muons in the beam in order to maximize the number of muons that stop in the target.

The target and the veto counter, S4, were located in a tube along the axis of a drum containing 2 coaxial rings of <sup>3</sup>He

detectors. A cross section of the array of  $^3\text{He}$  detectors is shown in Figure 3. The detector array was constructed of 20 high pressure (4 atm fill pressure) 2.5 x 38 cm  $^3\text{He}$  tubes inserted in a cylindrical block of polyethylene moderator which was wrapped with a layer of Cd. The polyethylene block was situated in a steel drum, the void space inside was filled with polyethylene beads, and the drum was wrapped with more Cd sheets. The neutron counting efficiency obtained was high because, in addition to the large neutron absorption cross-section of  $^3\text{He}$ , the detector had a nearly  $4\pi$  steradian geometry. Background neutrons were further minimized by the concrete and polyethylene built into the structural shielding surrounding the target area.

Since the neutron background from the AGS during a beam pulse was about 1000 cts/s, an electronic gate of typically 50  $\mu\text{s}$  was opened for neutron counting immediately after a muon stop was registered. The background count rate between beam pulses was much lower ( $<1$  cts/s) than during a pulse. Even with this synchronous detection scheme, the random background neutron rate was large enough to cause an overestimate in the ratio of neutrons to stopped muons. To correct for this, the random neutron coincidence rate was measured by opening a second gate of the same width after a 180  $\mu\text{s}$  delay beyond the muon stop.<sup>11</sup> The real neutron count was then determined by the difference between the prompt, and delayed, gated neutron counts. The neutron detector signals were also pulse height and time delay analyzed by a microcomputer controlled CAMAC system.

Calibration of the Detector. A  $^{252}\text{Cf}$  source was used to determine the counting efficiency and the response time of the  $^3\text{He}$  detector array. The setup used to calibrate the neutron detector is shown in Figure 3.  $^{252}\text{Cf}$  has a half life of 2.65 y and a branching ratio of 96.9% for alpha decay to  $^{248}\text{Cm}$ , which has a half life of  $4.7 \times 10^5$  y and thus does not produce any significant neutrons or gammas. The other 3.1% branch undergoes spontaneous fission, which on the average simultaneously produces 2.5 neutrons per event. The absolute neutron emission rate is  $2000 \pm 50$  n/s. In addition, prompt gammas with a total energy of about 7 MeV are emitted for each fission event.

The absolute neutron counting efficiency was determined by counting the number of neutrons from the  $^{252}\text{Cf}$  at different positions in the detector. The maximum efficiency observed was 20%, with the source located at the center of the  $^3\text{He}$  detector. At the spot where the target was positioned, the efficiency was  $14 \pm 1\%$ . This location was chosen to reduce the systematic error due to positioning of the target and the S3 and S4 scintillation counters.

The time response of the  $^3\text{He}$  detector was measured using the time difference between the signal of the prompt gammas recorded by a NaI(Tl) detector, and the signal of the moderated neutrons in the  $^3\text{He}$  detector. The time delay between the NaI(Tl) gamma pulse and the  $^3\text{He}$  pulse is plotted in Figure 4. A fit to the form  $e^{-t/\tau}$  determines  $\tau = 53 \mu\text{s}$ . These measurements are consistent with rough calculations that assume that the neutrons are moderated in the

polyethylene just before reaching the detector, and only a very few random walk collisions occur.

Pulse height analysis of the  $^3\text{He}$  signal for three conditions, (a) with prompt, gated neutrons, (b) with the  $^{252}\text{Cf}$  source, and (c) with self-triggered neutrons, is shown in Figure 5. The self-triggered neutrons represent all neutrons, synchronized or not, with stopped muons. The shape of all three spectra are similar and agree with the detector specifications.<sup>12</sup> These data provide strong evidence that neutrons, and not gammas or other particles, were being counted.

Target Preparation. A variety of targets were prepared and tested:

- 1) Palladium (annealed and cold worked)
- 2) Palladium pressure-loaded with deuterium to  $\text{PdD}_{0.7}$
- 3) Palladium electrolytically-loaded with deuterium to  $\text{PdD}_{0.7}$
- 4) Palladium in an active  $\text{D}_2\text{O}$  electrolysis cell
- 5) Titanium shavings
- 6) Titanium shavings pressure-loaded with deuterium to  $\text{TiD}_2$
- 7) Yttrium pressure-loaded with deuterium to  $\text{YD}_3$
- 8) Empty plastic or glass sample containers

In general, the pressure-loaded metal deuterides were prepared at elevated temperatures and pressures using standard procedures.<sup>13</sup> The deuterium content was calculated by the increase in mass of the samples. The electrolytically-loaded palladium targets were prepared in 0.1 M  $\text{LiOD}/\text{D}_2\text{O}$ . The loading process of the 6.4 mm rod was monitored for evidence of cold fusion.<sup>4</sup> Some

palladium targets were annealed under vacuum just below the melting point. A detailed description of the target preparation will be described in a later publication.

### Experimental Results

In this preliminary report, for brevity, only a representative set of experimental data will be discussed. A typical result is found in runs comparing palladium and palladium deuteride targets. The deuterated target was a 1 cm thick stack of four pressure-loaded  $\text{PdD}_{0.7}$  sheets, prepared from Pd samples that were annealed near its melting point, producing millimeter-sized crystals. Data were acquired over 13 min. The plastic scintillator counts were:

Total  $\mu^-$  in the beam

$$S1 \cdot S2 \cdot S3 = 43,669$$

Total  $\mu^-$  stopped in target

$$S1 \cdot S2 \cdot S3 \cdot \overline{S4} = 18,693$$

Since the single rates in S1, S2, S3 and S4 are low,  $\sim 100/\text{s}$ , and the coincidence gate width is small, 10 ns, the random coincidence rate in either measurement is negligible. The fact that the stopped muons,  $S1 \cdot S2 \cdot S3 \cdot \overline{S4}$ , are 43% of the spatially defined muon beam,  $S1 \cdot S2 \cdot S3$ , indicates the beam is sufficiently degraded.

The ungated neutron count was 319,648. The 50  $\mu\text{s}$  gated count was 3,804 and the 180  $\mu\text{s}$  delayed gated count was 1237. The real neutron count is thus the difference of these two numbers, or 2,567. Since the neutron detector efficiency was  $14 \pm 1\%$  (syst.),



and approximately 39% of the neutrons fall outside the 50  $\mu$ s gate, (see Figure 4) the absolute neutron count was 30058. The ratio of real neutrons to stopped muons was  $1.61 \pm 0.02$  (stat.).

Similarly, data taken with a palladium target without deuterium shows that the ratio of the real neutrons to stopped muons was  $1.65 \pm 0.02$  (stat.). Systematic errors in both ratios (target with and without deuterium), due to mechanical alignment,  $^3\text{He}$  detection efficiency, effects due to gate width, and subtraction of the random neutron counts, are estimated to be 30%, but are similar for the different targets. The resultant systematic error on the the difference of the two ratios is estimated to be 15%, since many systematic errors cancel out. The neutron count per stopped muon due to deuterium being present in the metal is thus  $0.0 \pm 0.03$  (stat.) with a systematic error of  $\pm 0.25$  absolute.

Experimental runs were made in which the temperature of a pressure-loaded palladium target was monitored with a linear thermistor fixed directly to the metal. No detectable temperature difference,  $26 \pm 0.5$   $^{\circ}\text{C}$ , was measured over the time the target was exposed to the muon beam, and after the beam had been shut off.

The electrolyte solution from the electrolysis cell target was analyzed for excess tritium, a product of D-D fusion, by liquid scintillation counting.<sup>14</sup> The minimum detectable level was 35 dpm, and no change above the background level of  $100 \pm 14$  dpm was observed.

Similar neutron measurements made with Ti and Y deuterated targets yielded results within the above absolute error bar,  $1.5 \pm$

0.5 (absolute) neutrons per stopped muon. An account of all the experimental runs, together with a description of target preparation will appear in a later publication.

### Conclusion

From the difference in the measured number of neutrons yielded per stopped muon in deuterated and non-deuterated palladium targets, we conclude that muon catalyzed fusion occurs at a rate of  $0.0 \pm 0.03$  (stat.)  $\pm 0.25$  (syst.) neutrons per stopped muon. The observed ratio is consistent with the capture of muons by the heavy element nuclei,<sup>15</sup> within experimental error. Together with the temperature and tritium measurements, these data do not support the notion of cosmic ray induced muon catalyzed fusion in palladium deuteride, PdD<sub>0.7</sub>.

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### Figure Captions

Figure 1 Simplified diagram of the BNL AGS muon facility.

Figure 2 Simplified diagram of the muon target area and the electronic diagnostics.

Figure 3 Cross section of the  $^3\text{He}$  neutron detector with the calibration source,  $^{252}\text{Cf}$ , and the  $\text{NaI(Tl)}$  gamma detector.

Figure 4  $^3\text{He}$  neutron detector response time to a  $^{252}\text{Cf}$  source. The response time was fitted to an exponential decay; the time constant was found to be 53  $\mu\text{s}$ . The characteristics of the fission reaction are discussed in the text.

Figure 5  $^3\text{He}$  pulse height spectra for: (a) prompt, gated neutrons, (b) the neutron calibration source,  $^{252}\text{Cf}$ , and (c) self-triggered neutrons.

# Alternating Gradient Synchrotron

$15 \times 10^{12}$  Protons











