Muon-catalyzed fusion in deuterium at 3 K

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Muon-catalyzed fusion in deuterium has traditionally been studied in gaseous and liquid targets. The TRIUMF solid hydrogen layer target system has been used to study the fusion reaction rates in the solid phase at a target temperature of 3 K. Both branches of the cycle were observed; neutrons by a liquid organic scintillator, and protons by a silicon detector located inside the target system. The effective molecular formation rate from the upper hyperfine state and the spin exchange rate have been measured, and information on the branching ratio parameters has been extracted.

Keywords: muon-catalyzed fusion; deuterium; solid

1. Introduction

During the commissioning of the TRIUMF layered solid hydrogen target system, data were taken on \( \mu \text{CF} \) in solid deuterium. The preliminary values for the kinetics parameters were in sharp disagreement with theory and have initiated further investigations of the reactions in solid [1,2].

2. Experimental setup

The target system used in this measurement has been presented elsewhere [3,4].

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Layers of solid deuterium, each 10.54(53) mg cm\(^{-2}\) thick and \(\sim 40\) cm\(^2\) in area, were frozen onto 50.4 \(\mu\)m thick gold foils maintained at 3 K. Because a palladium filter at 600 K was used to purify the D\(_2\) gas immediately prior to freezing, the ratio of even to odd molecular spins was expected to be statistical (nD\(_2\)) [5].

Muons entered the target by passing through the thin gold layer, which acted as a degrader, and stopped either in the first or second solid hydrogen layer. Muon-catalyzed fusion of d\(_2d\) molecules then occurred. The higher energy fusion products, neutrons at 2.45 MeV and protons at 3.02 MeV, were detected.

The arrangement of detectors has been given in ref. [3] with the modification that two neutron detectors were used. Each neutron detector was a 12.5 cm diameter by 10 cm deep cylinder of NE–213 liquid scintillator viewed by a photomultiplier. Pulse shape discrimination (PSD) was used to differentiate between photon and neutron events. An event veto based on anticoincidence with charged-particle detectors ensured that only events from neutral particles were gated to the PSD units. These veto scintillators were also used as electron detectors to record the electron following muon decay.

A silicon detector of 600 mm\(^2\) active area was mounted inside the vacuum system and viewed the solid deuterium layer directly. Its 150 \(\mu\)m active thickness was sufficient to measure protons of up to 4.5 MeV, and was well suited for detecting the fusion protons at 3.02 MeV.

The timing of all events was taken with respect to the time of the incident muon as measured by a beam entrance scintillator.

Measurements with pure solid layers of D\(_2\) and H\(_2\) were made at TRIUMF in August of 1992. The thick D\(_2\) layers received an integrated muon flux of \(220 \times 10^6\mu\) with \((57.6 \pm 1.3)\%\) stopped in the solid layers, while the study of the background in H\(_2\) was done with \(130 \times 10^6\mu\), with stopping fractions varying from 30 to 60\% depending on the layer thickness used.

3. Reaction kinetics

The kinetics of the muon-catalyzed reactions in pure deuterium have been discussed in refs. [6, 7]. The differential equation representing the kinetics was solved analytically and the solution used for the analysis.

The reduced rate of formation of d\(_2d\) molecules from a \(\mu d\) atom in the hyperfine state \(F, \tilde{\lambda}_F\), is composed via the formula

\[
\tilde{\lambda}_F = \lambda_{nr} + \sum S \lambda_{FS} \frac{\tilde{\lambda}_f}{\tilde{\lambda}_f + \sum F' \Gamma_{SF'}}.
\]

It represents molecular formation that leads to fusion and is composed of the non-resonant formation rate and the fraction of resonantly formed molecules which successfully fuse via \(\tilde{\lambda}_f\) rather than resonantly scatter as characterized by \(\Gamma_{SF'}\).