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Producing μ^-d and μ^-t in Vacuum

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Abstract

After the feasibility of vacuum isolated μ^-d production was demonstrated at TRIUMF in 1989,

development was begun on a target system that would take advantage of the process to aid in the understanding of the muon catalyzed fusion cycle. Minimal neutron backgrounds, the ability to use silicon detectors, and compatibility with tritium were considered important for a very versatile target system. The advantages which the target gives in isolating μCF process will be outlined.

Muon catalyzed fusion research has traditionally been carried out in gaseous or liquid hydrogen where a multiplicity of interactions obscures energy dependence measurements. A target system has been developed at TRIUMF to permit the production of a low-energy "beam" of muonic atoms in vacuum. The emitted atoms can be observed in flight and subsequent reactions can be measured on an individual basis. The target allows observation of charged fusion fragments as well as neutrons.

Figure 1 illustrates the target frames which support thin gold foils and their relation to the gas deposition mechanism. Two 1.6 mm Cu frames support Au foils of diameter 65 mm and thickness 51 μm. The frames are attached to a cryostat by a clamp which allows the spacing between the foils to be adjusted easily. When operating the foils are cooled to 2.5 K.

A two-sided gas diffusion mechanism consists partly of two thin stainless steel foils, perforated by many tiny holes, mounted on a support which can be inserted between the target frames. Hydrogen gas enters the diffuser system and is released through the diffuser perforations either towards one cold foil or the other where it sticks and solidifies. After target deposition, the diffuser is removed and sufficient room is available to allow the attachment of a detector or collimator to the top of the diffuser mechanism.

The gas target will remain on the foil provided it is maintained at a temperature such that the vapour pressure of the gas is small compared to the residual gas pressure in the vacuum system. For a vacuum of 10^{-11} bar, a temperature less than 3 K is required. Multiple layers can be deposited, with each layer being pure or a mixture of several isotopes. Hydrogen can be deposited at a rate up to 2 μg/cm^{2}s so a typical target deposition takes $\sim$ 30 minutes. Depositions on one foil do not contaminate the second foil to a limit $\leq 5 \times 10^{-3}$. Targets have been maintained for a period of 25 hours with no significant evidence of deterioration.

A typical fusion event begins in the target when a μ^- enters a scintillator on the beam axis and starts the timing clocks. The negative muons of interest stop in the hydrogen and are captured by a proton. Since μ^-p has a large scattering cross-section with H_2 the μ^-p will remain in the target and eventually the μ^- transfers to a deuteron or triton yielding a μ^-x (x is d or t) with $\sim$ 48 eV. The μ^-x interacts with the target hydrogen until it reaches an energy $\sim$ 1 eV and the Ramsauer-Townsend scattering effect increases the mean free path of the particle to a dimension as large as the hydrogen layer thickness. The μ^-x is emitted into the vacuum with a speed of a few mm/μs which allows the atom to travel a few centimeters before decaying. Variable target spacing allows us to select the range of μ^-x energies incident on the reaction foil, which is of interest when discussing resonant [(dμx)dee] formation.

Experimental information is obtained from a large number of different types of detectors. Figure 2 shows their positions with respect to the hydrogen target. Below we discuss the detectors and the information they reveal about the processes under study.

Three multi-wire proportional chambers give tracking information sufficient to find the position of the decayed μ^- to within $\pm$3 mm. Time cuts allow the viewing of prompt gold events ($t < 0.5$ μs after the incident μ^-) or the delayed events ($t > 0.5$ μs) originating from decays in hydrogen and from μ^-x in flight (Fig. 3). Combining the timing and position information gives a measure of the energy spectrum of emitted μ^-x atoms (see the contribution from G.M. Marshall *et al.* this proceedings).

The uniformity of the deposited hydrogen layer can be found by comparing the stopping distribution of muons in the hydrogen with that in a uniform foil, as measured by the position of the decay electrons. The muon stopping distribution in the Au target support foil include beam profile irregularities and solid-angle effects and thus defines the appearance of a uniform foil to the imaging system (Fig. 4). Seeing the same shape from μ^- decays in the hydrogen film implies a uniform deposition (here taken from a target thickness of 3.0 mg/cm^2).

A silicon detector (active area 600 mm^2, dead layer 50 nm) was used to measure the spectra in Fig. 5. The background represents the energy spectrum for a 3.0 mg/cm^2 protium target with a deuterium concentration $c_d = 10^{-3}$. With the addition of 140 μg/cm^2 of D_2 to the surface, fusion protons appear as a clean 3 MeV peak, evidence that the μ^-d atoms emitted from the first layer were stopping in the D_2 and undergoing fusion.

Although dd fusion also produces tritons and ^{3}He, the lower energy (~1 MeV) makes them much harder to distinguish from the background resulting from muons scattered into the detector.

When making timing measurements on the fusion processes using neutrons, it is important that the other neutron production processes time correlated with the incident muons occur in an understood way. From recent data taken with the target, the neutron lifetime from background was measured at 86 ns, a lifetime characteristic of muon capture in high Z nuclei. Given the target geometry and construction, no shorter lifetimes are possible.

The study of the transfer of μ^- from the μ^-x to higher Z materials via the subsequent muonic x-rays is intrinsically interesting (see R. Jacot-Guillarmod *et al.* this proceedings) but represents a significant loss for the fusion channel. Observing those x-rays gives an indication of the target impurities. Figure 6 show spectra taken from two different 3.0 mg/cm^2 H_2 targets with c_d of 10^{-3} and an added layer of 140 μg/cm^2 D_2. Nitrogen contamination is evident in both curves, with the upper showing the most. The more contaminated target exhibited only 53% of the fusions observed from the clean target, evidence that μ^-d were being lost to transfer.

The target system, with its μ^-x beam in vacuum, variable spacing between production and reaction foils, and tritium compatibility will be a useful tool for mapping the resonances in the dμ^-t system (see the contribution from G.M. Marshall *et al.* this proceedings). The operation of silicon detectors in the vacuum environment gives important data for branching ratio measurements in dμ^-d fusion. The versility of the solid gas layer target is not limited to fusion research only, since other muonic hydrogen processes, such as transfer, can benefit from the multi-layer target approach.

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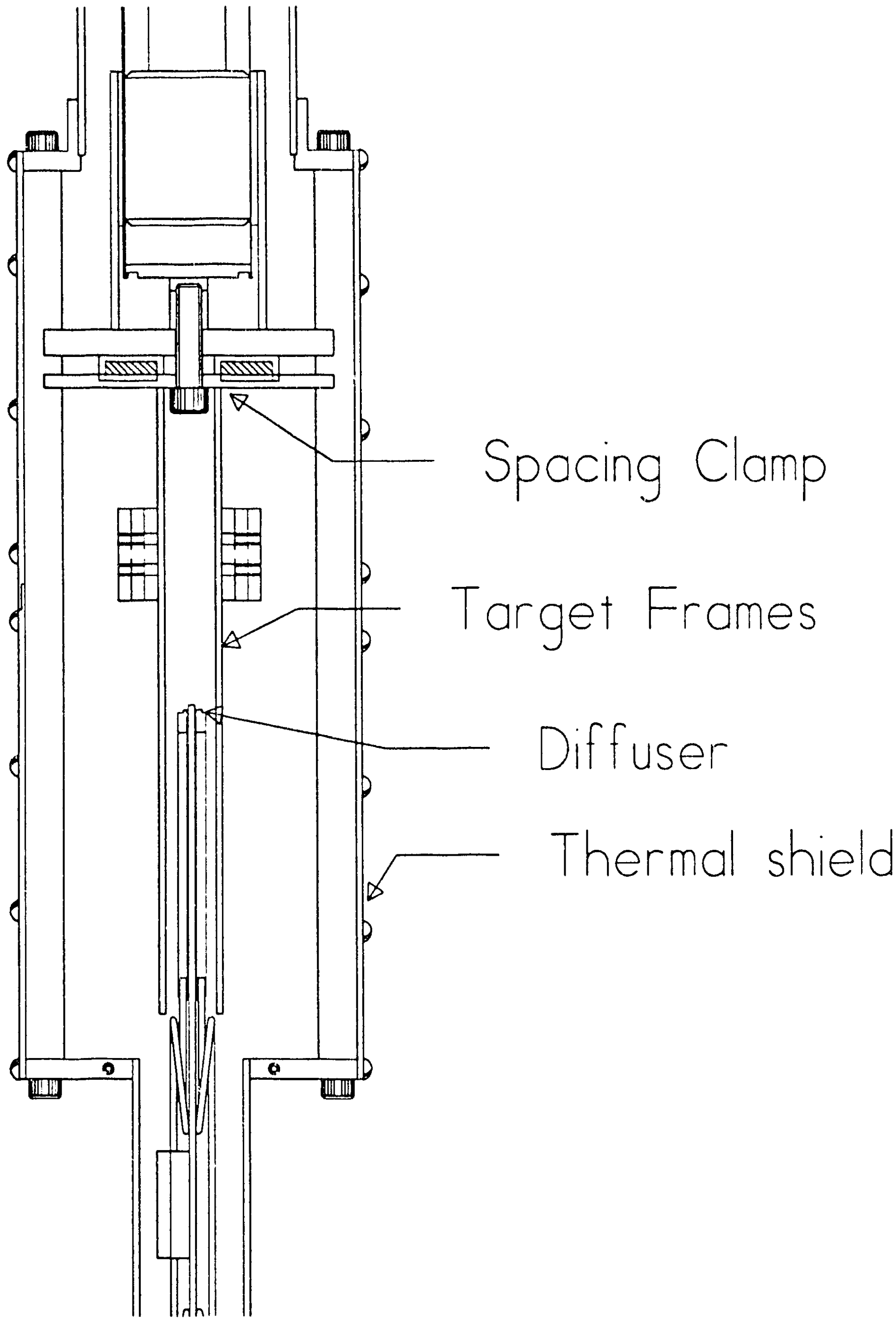

Figure 1: Schematic view of the target assembly showing the diffuser inserted between the target frames.

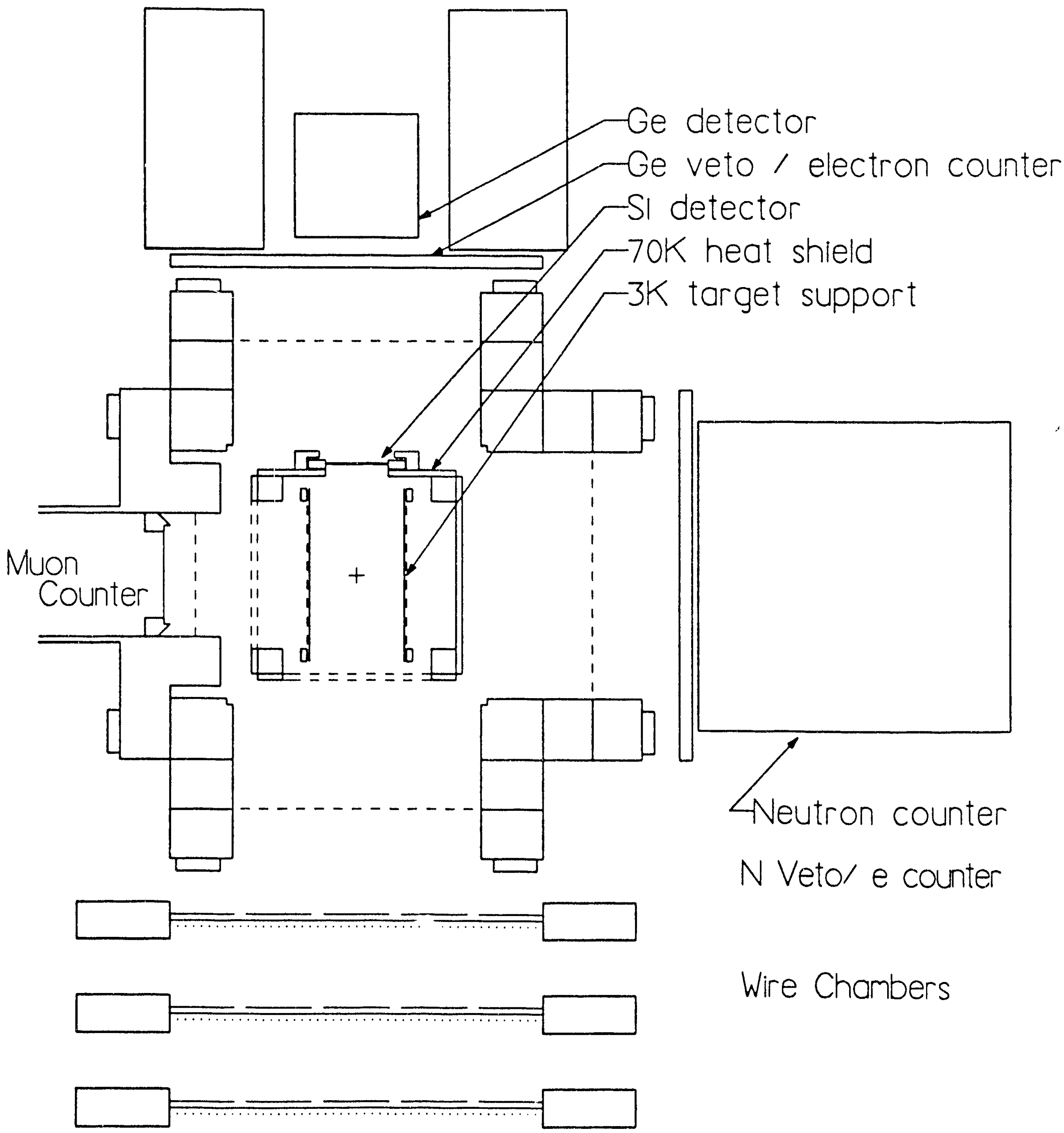

Figure 2: The array of detectors and their relative positions with respect to the target foils.

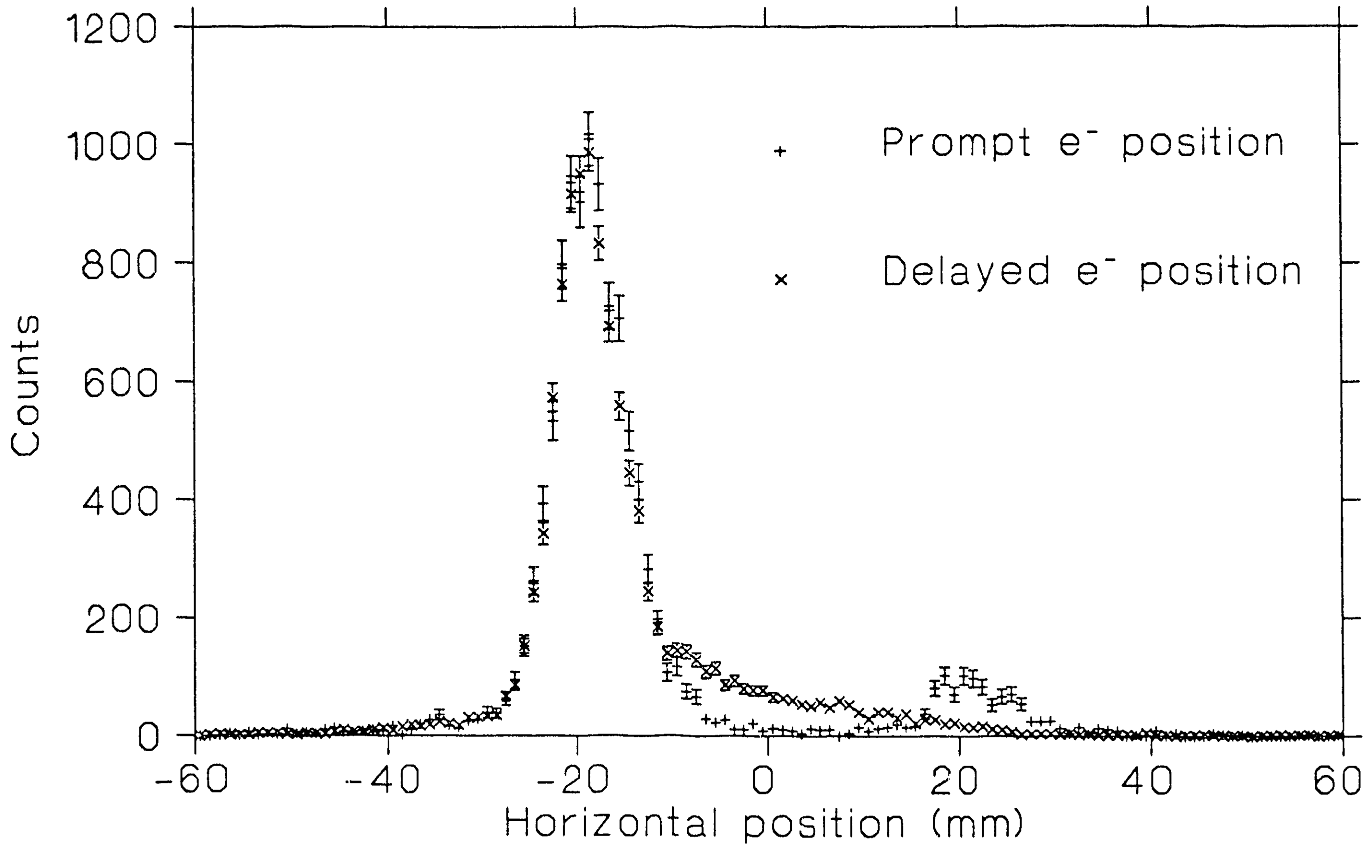

Figure 3: MWPC data revealing the positions of muon decay. Visible in the -10 to $+10$ region are μ^{-}d decay events.

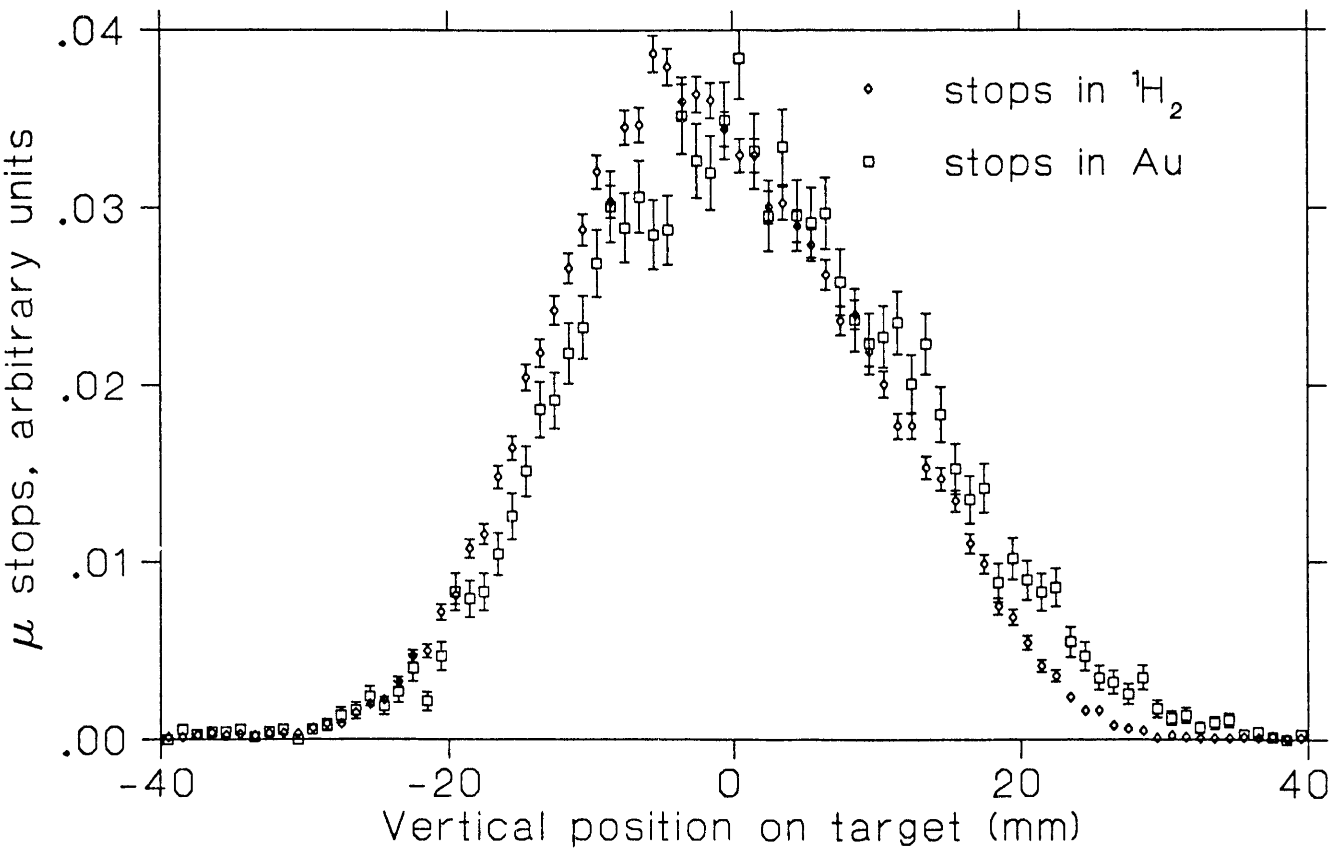

Figure 4: A vertical profile of the decay electron image shows the uniformity of deposited targets as measured with respect to bare targets.

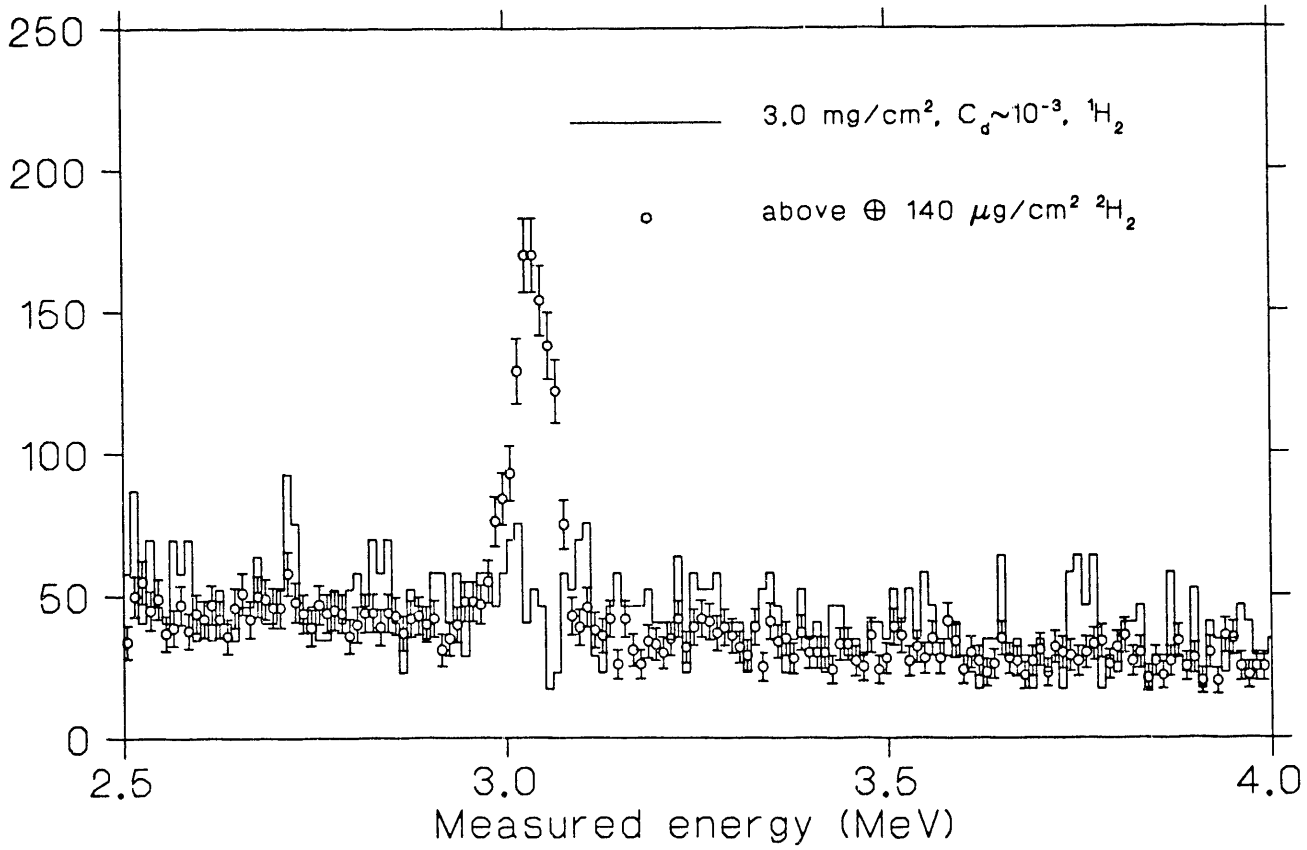

Figure 5: The addition of a layer of D_2 to the surface of a μ^-d emitting target produces a clean proton signal from dd fusion

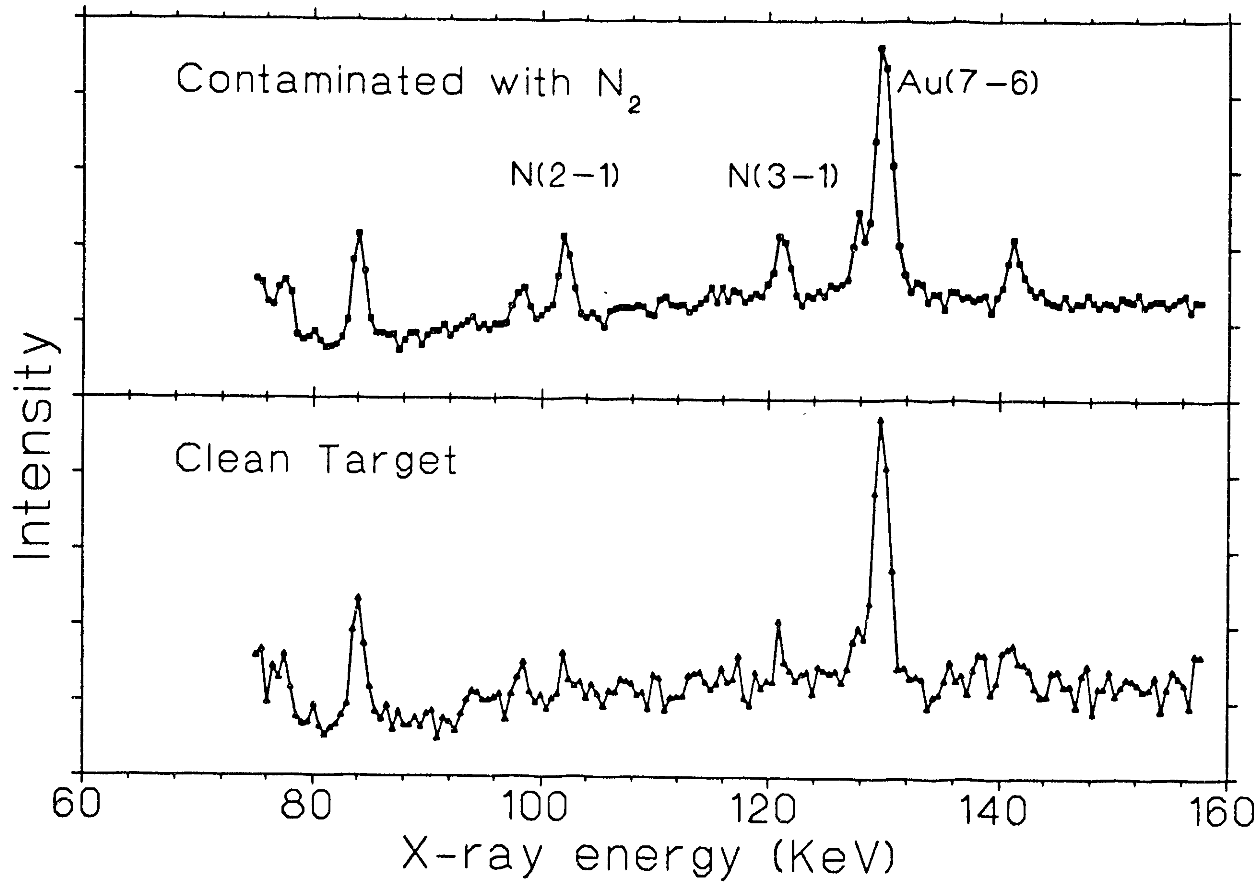

Figure 6: Germanium spectrum indicating nitrogen contamination in a hydrogen target compared to a cleaner target.

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