Radioactive Muonic Atom Studies with Intense Muon Beams

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RIKEN

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Introduction

- **Physics Motivation**

X-RAY SPECTROSCOPY of **MUONIC ATOMS !**

- Powerful tool to probe the **NUCLEAR CHARGE DISTRIBUTION**.
- Usefully complement the knowledge obtained from electron scattering and laser spectroscopy.
- Successfully used since more than 30 years to study **STABLE ISOTOPES** in condensed or gaseous states !

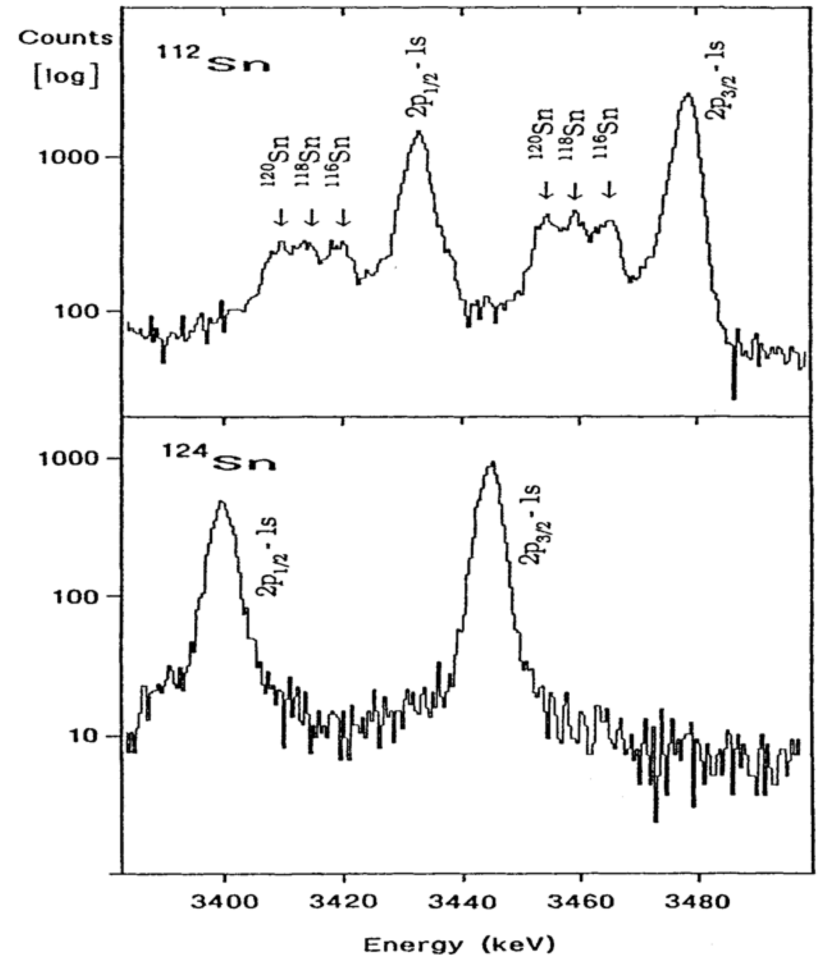

Fig. 3. Prompt muonic x-ray spectra showing the $2p_{1/2} - 1s$ and $2p_{3/2} - 1s$ transitions in the two tin isotopes at the extreme ends of stability, ^{112}Sn and ^{124}Sn (ref.2). The isotopic purity of ^{112}Sn was 68%, which explains the appearance of further tin isotopes in the upper half of this figure.

Nuclear Charge Radii of Tin Isotopes from Muonic Atoms

C. Piller et al., Phys. Rev. C **42** (1990) 182,
L.A. Schaller Z. Phys. C **56** (1992) S48.

Towards Radioactive Muonic Atoms ?

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- **Towards Radioactive Muonic Atom Formation**

  RI BEAM PROJECTS are being planned or already coming into operation at facilities where negative muon beams are also available:

  - **ISAC Project** at **TRIUMF**,
  - **E-Arena** in the **J-PARC Project** (3^{rd} phase),
  - **RI BEAM Factory Project** at **RIKEN** (if intense μ^- beams can be produced there),
  - and maybe at a **NEUTRINO FACTORY PROJECT**

- **In the near Future**

  - **MUON BEAM** of significant higher flux,
  - **NEXT GENERATION** of RNB facility,
  - **SYNERGY** effects if at one place, e.g., **CERN**, **RAL** , **J-PARC** , ...

Why Radioactive Muonic Atoms ?

- **Probing Nuclear Charge Distribution**

  Matter distribution deduced from measured interaction cross sections. Charge distribution needed to get information on proton and neutron distributions in nuclei.

  ➡ **X-RAY SPECTROSCOPY** of **RADIOACTIVE MUONIC ATOMS !**

- **Deformation Properties**

  Quadrupole hyperfine spitting of muonic X-rays yield precise and reliable absolute quadrupole moment values. Measure the deformation properties of nuclei.

  ➡ **IMPORTANT ROLE** in **ESTABLISHING** and **REFINING NUCLEAR STRUCTURE MODELS !**

- **Muon Capture**

  Tools to explore changes in collective excitation modes of neutron-rich nuclei.

  Kolbe, Langanke & Riisager, Eur. Phys. J A **11** (2001) 39

  ➡ **IMPORTANT ASTROPHYSICAL IMPLICATIONS !**

- **Novel nuclear structure effects may exist far off the valley of stability ?**

RAMA Workshop

EXPERIMENTAL METHODS

- **Radioactive Muonic Atoms**
  - Merging Beams Scenario
    (M. Lindros, CERN)
  - Combined Cyclotron Trap & Penning Trap
  - **SOLID HYDROGEN & MUON TRANSFER**
- **Unstable Nuclei**

  PRESENT:
  - Optical Laser Spectroscopy
    (ISOLDE, RIKEN, …)

  FUTURE:
  - Electron Scattering using electron & RI collider Rings
    (MUSES at RIKEN, GSI, …)

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

Institutional Member of the European Science Foundation Associated Committee NuPECC

Landscape of Valle di Cembra, near Trento ("Wehlsch pirg"), watercolour, painted by A. Dürer on one of his trips to Venice (1495?) - (1505?). Courtesy of the Ashmolean Museum, University of Oxford.

RADIOACTIVE MUONIC AND ANTIPROTONIC ATOMS

May 22-26, 2001

MAIN TOPICS:

- Survey of nuclear and general physics background and motivation
- Review of previous muonic and antiprotonic atom research
- Discussion of novel ideas to produce radioactive antiprotonic and muonic atoms
- Comparison with alternate experimental methods
- Identification of key experiments
- Exploration of the possibilities for technical realization
- Impulses to form new international collaborations

SPEAKERS INCLUDE:

N.Auerbach (*Tel Aviv*), J.Deutsch (*Louvain la Neuve*), R.Engfer (*Zürich*), M.Hasinoff (*Vancouver*), J.Jastrzebski (*Warsaw*), A.S.A. Jokinen (*Geneva*), E.Kolbe (*Oak Ridge*), K.Langanke (*Aarhus*), M.Lindroos (*Geneva*), W.Nazarewicz (*Oak Ridge*), T.Nilsson (*Geneva*), H.L.Ravn (*Geneva*), P.-G.Reinhard (*Erlangen*), K.Riisager (*Aarhus*), J.Suhonen (*Jyväskylä*), A.Vacchi (*Trieste*), M.C.Volpe (*Orsay*), D.Vretenar (*Zagreb*), T.Yamazaki (*Tokyo*)

ORGANIZERS OF THE WORKSHOP:

Juha Aysto, CERN and University of Jyväskylä, co-ordinator (juha.aysto@cern.ch)
Klaus Jungmann, KVI Groningen, organizer and group-leader (jungman@kvi.nl)

Director of the ECT*: Prof. Wolfram Weise (Trento)
Scientific Secretary: Prof. Renzo Leonardi (Trento)

The ECT* is sponsored by the "Istituto Trentino di Cultura" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and with the support of the Department of Physics of the University of Trento.

Participation in the ECT* scientific projects led by researchers of the EU Member and Associated States is partially financed by the EU - Human Potential Program to provide access to Major Research Infrastructures (STATE project); see http://ect.it/NEWS/5pq.html Postdoctoral researchers are encouraged to apply to individual EU fellowships; see http://www.cordis.lu/improving/src/hp_mcf.htm

μA* Technical Feasibility

- **How to produce such very exotic μA* atoms ?**

We propose:

- **SOLID HYDROGEN FILM** used to stop both simultaneously μ^- and A* beams.
- ***μA* ATOMS*** formed through **MUON TRANSFER REACTION** to higher Z nuclei, i.e.,

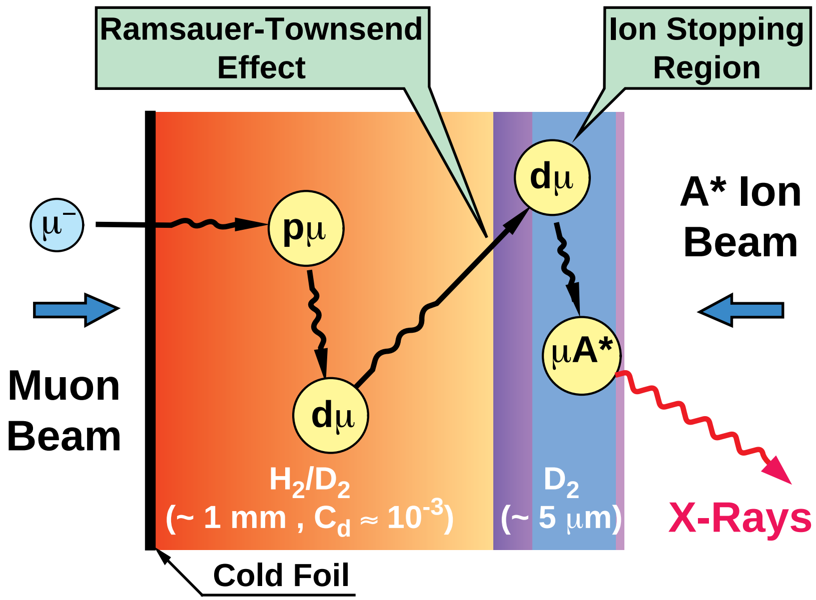
$$\mu H + A_z^* \rightarrow \mu A_z^* + H$$ with

TRANSFER RATE: $\lambda_z \approx C_z\, Z\, 10^{10}\ s^{-1}$

HIGH TRANSFER RATE & HIGH EFFICIENCY

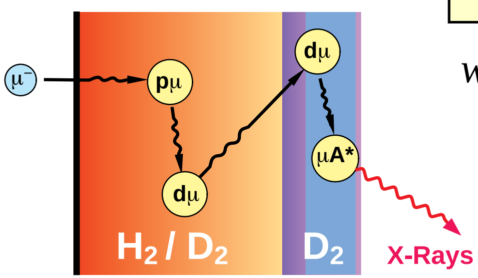
e.g., $Z = 50$ and
$C_z = 1$ ppm (5×10^{16} nuclei/cm^3)
⇒ $\lambda_z \approx 5 \times 10^5\ s^{-1}$

Basic Concept (Two-Layer Arrangement)



Preliminary Transfer Yield Estimation

◆ **Transfer Yield Estimation**
(Two-Layer Arrangement)

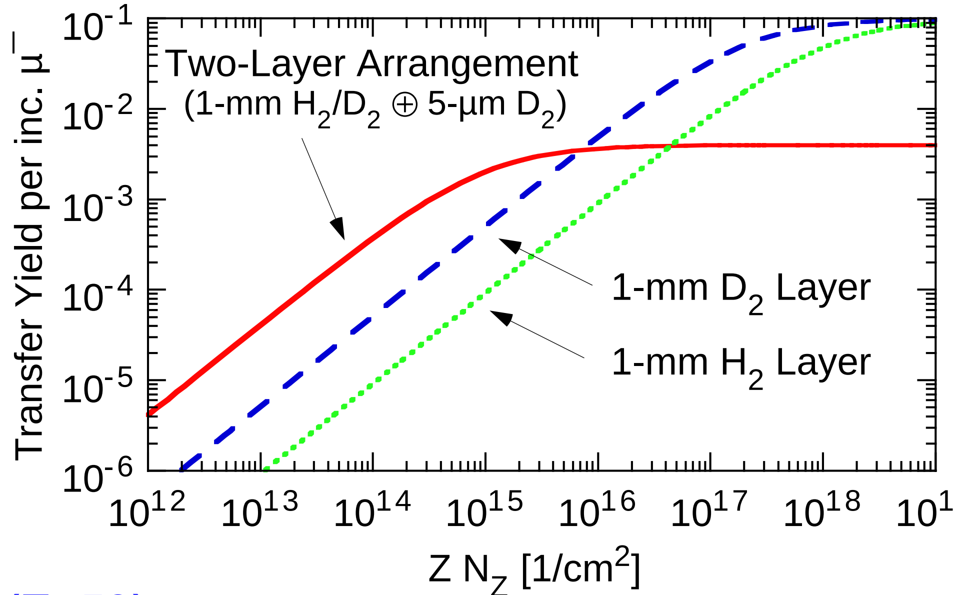


$$Y_X = \frac{\phi \lambda_Z}{\lambda_0 + \phi \lambda_Z} Y_{\mu^-} Y_{d\mu}$$

$$\textit{with} \;\; \lambda_Z \approx C_Z Z \times 10^{10} s^{-1},$$

$$C_Z = N_Z / N_D,$$

$$Y_{\mu^-} \cong 0.1, \;\; Y_{d\mu} \cong 0.04$$



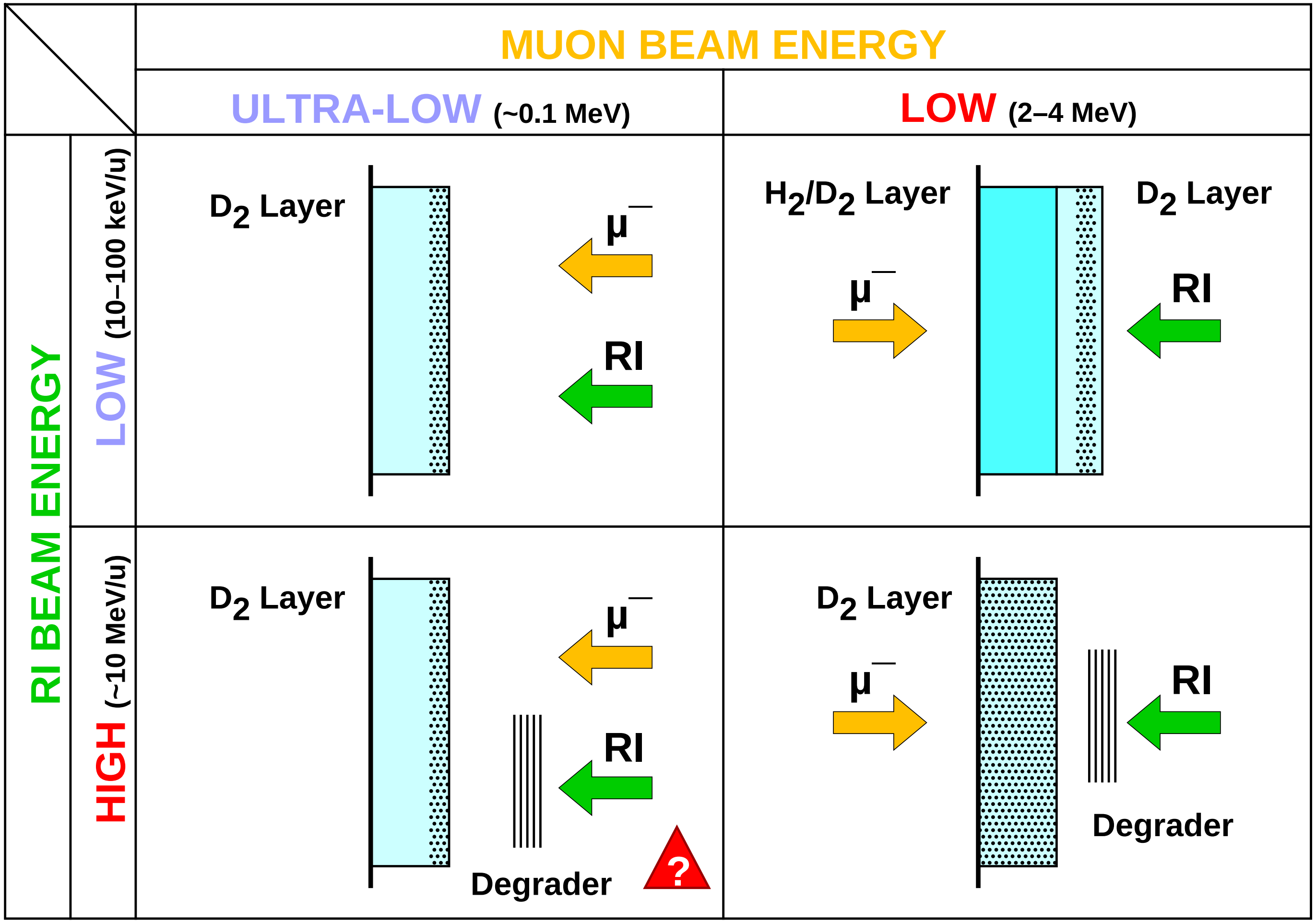
◆ **Preliminary Yield Estimation for Tin (Z=50):**

- **Muon Intensity** (1 cm^2, 30 MeV/c): **1×10^8 [s^{-1}]** SHC confinement, 21st Century Muon Beam
- **Implanted Sn Ions (1 cm^2):** **1×10^{12}** Uniform Implantation in 5 μm thickness
- **Transfer Yield per incident μ^-:** **2×10^{-4}**
- **Muonic Tin Atoms Formed:** **20’000 [s^{-1}]**
- **Total X-Ray Number Detected:** **500 [hr^{-1}]**

Assuming for μSn 2p→1s X-ray detection (~3.4 MeV) : b.r. ~ 0.7, ε ~ 0.005 and ΔΩ ~ 0.002.

μA* Formation Scheme

- Comparison between different μA* formation schemes:



Practical Considerations

- **SIMULTANEOUS** implantation of unstable nuclei and measurement with μ^-.

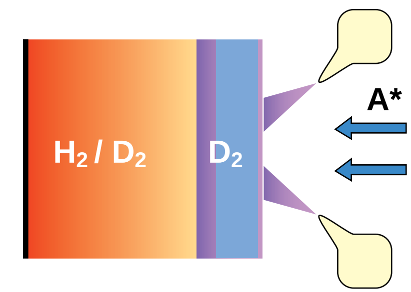
- Ion beam **ENERGY** and **SPREAD** determine the implantation **DEPTH** and **THICKNESS**.

  Ion range in solid hydrogen: 1 mm ➪ ~ 10 MeV/u
  5 μm ➪ ~ 30 keV/u
  ➡ **SWEEPING** Beam Energy

- **CONTINUOUS SPUTTERING** of solid hydrogen films.

  If proven important,

  ➡ **SIMULTANEOUS** Hydrogen Deposition & Ion Implantation



- RI beam **COMPLETELY** stopped in the target!
  - **ACCUMULATION** of **DAUGHTER NUCLEI**
    - ➡ **LIMITATION** (static target): $T_{1/2}$ > 10 min.
  - **ACTIVITY HIGH RADIATION BACKGROUND**
    - ➡ Pulsed Muon Beam
    - ➡ Active BG suppression, Detector segmentation, ...

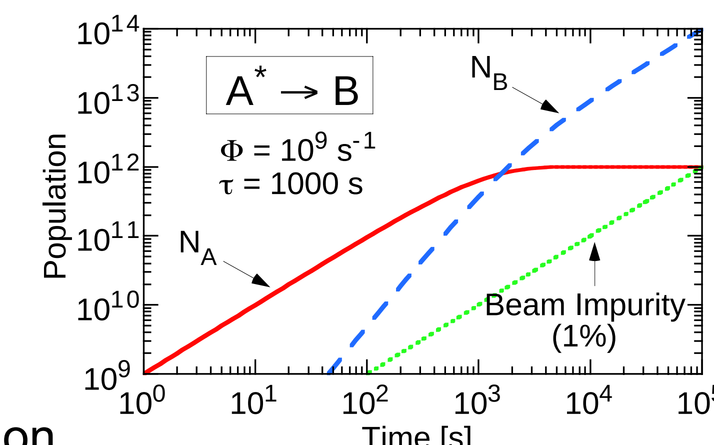
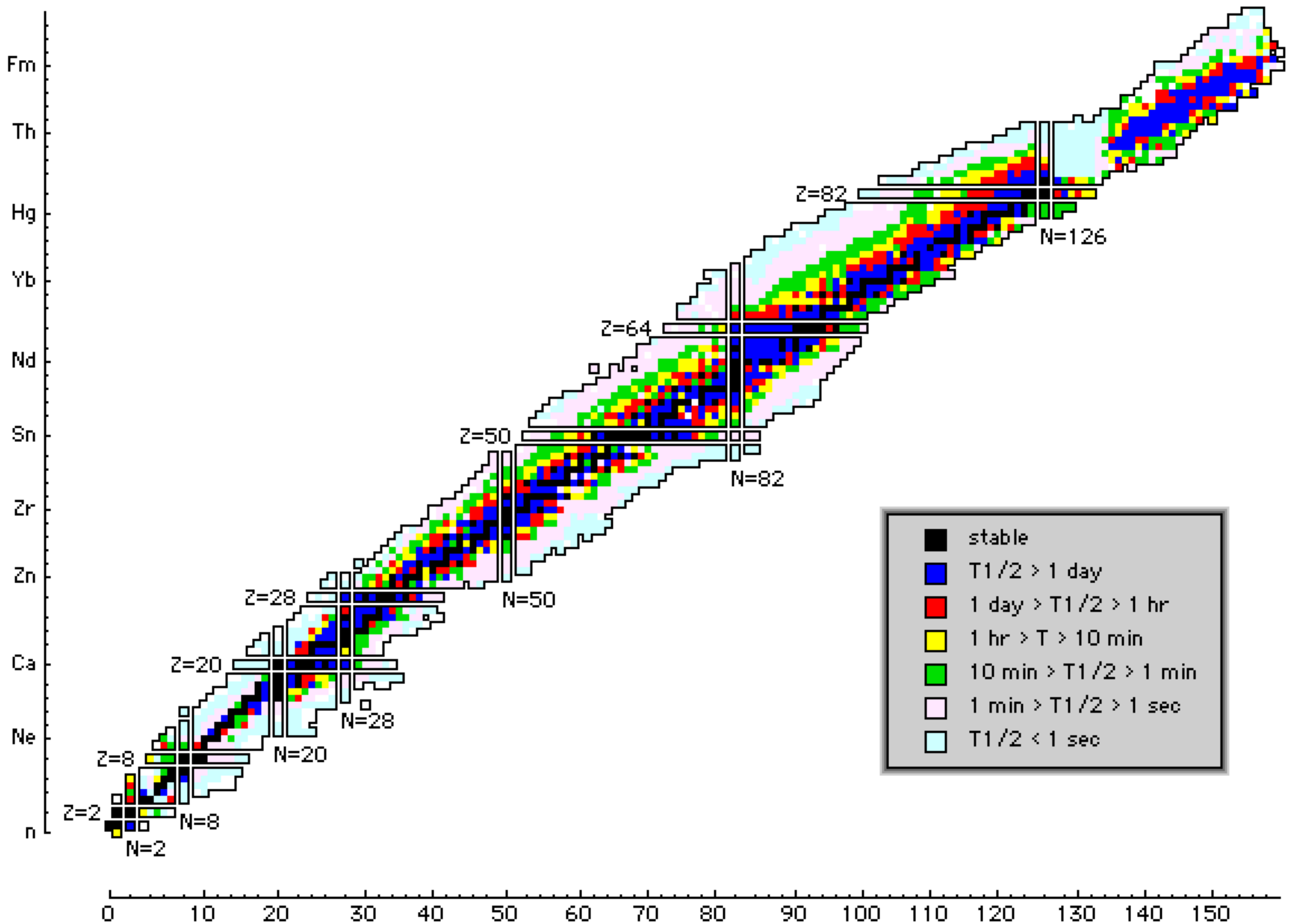


Chart of Isotopes (half-lives)



Using Solid Hydrogen Films

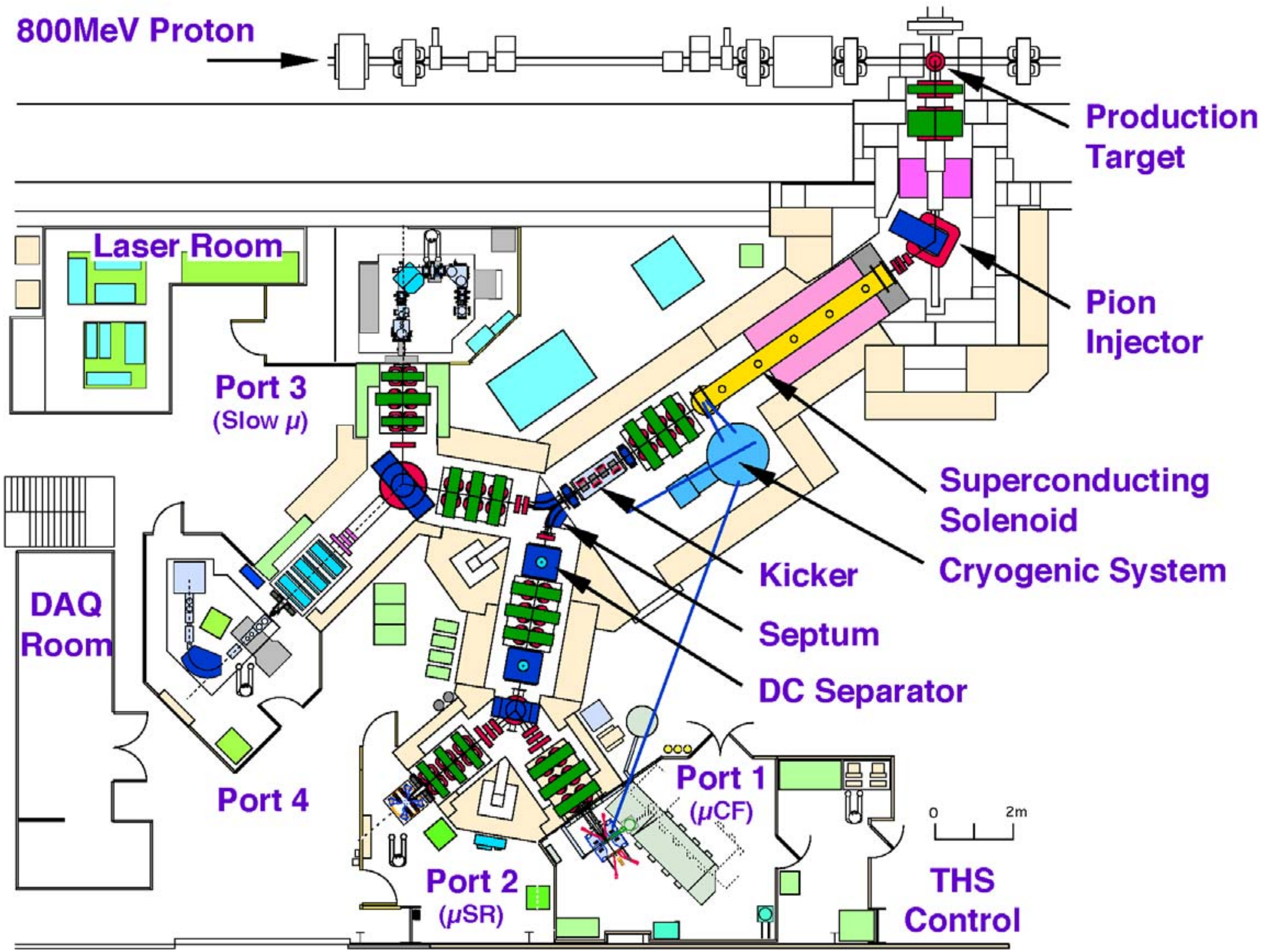
- **Advantages**
  - **WINDOWLESS TARGET** in vacuum
  - **WELL-DEFINED** interaction region
  - **EASY TARGET EVAPORATION** and **REPLACEMENT**
  - **RI BEAM**: Impurities, Emittance, Energy spread, ... ⇒ **NOT CRITICAL**
- **Disadvantages**
  - **SPUTTERING**
  - **ACCUMULATION** of **DAUGHTER NUCLEI**

  ⇒ **NEW IDEAS !** e.g., using sputtering vs. daughter nuclei accumulation
- **Other Considerations**
  - Magnetic confinement field
  - Pulsed muon beam

Feasibility Study

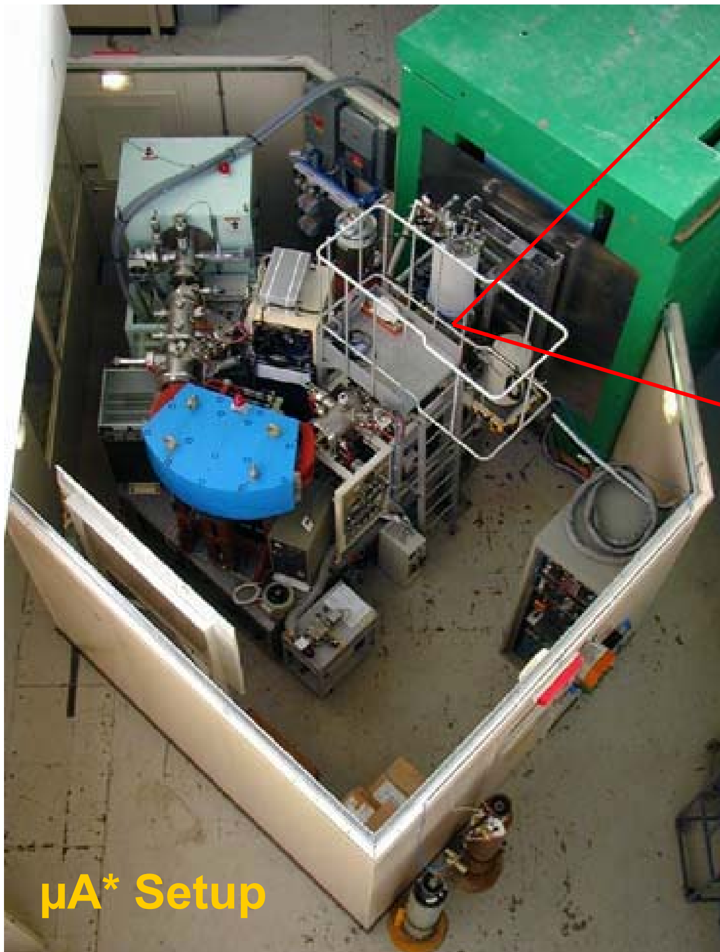
- **EXPERIMENTAL SETUP** for X-ray spectroscopy of muonic atoms formed from implanted ions in solid hydrogen
- **TEST EXPERIMENT** at RIKEN-RAL Muon facility.
- Establish the feasibility of this method by using **STABLE IONS**.
- **μCF RELATED STUDY**: Helium transfer in Solid Hydrogen Films
- In the near future, experiment using **LONG-LIVED ISOTOPES**.

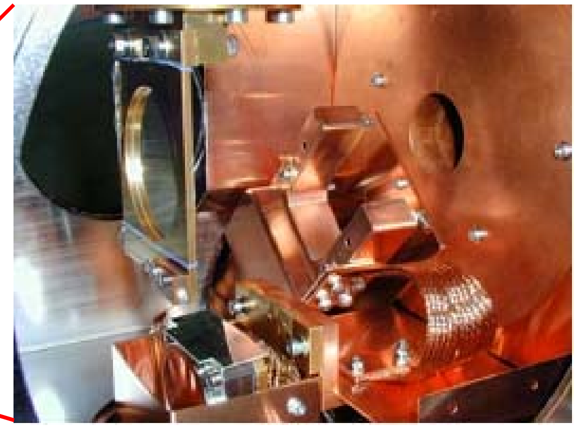
RIKEN-RAL Muon Facility at ISIS



μA* Setup at RIKEN-RAL Port 4

Test Experiment to Implant Stable Ions in Solid Hydrogen Films

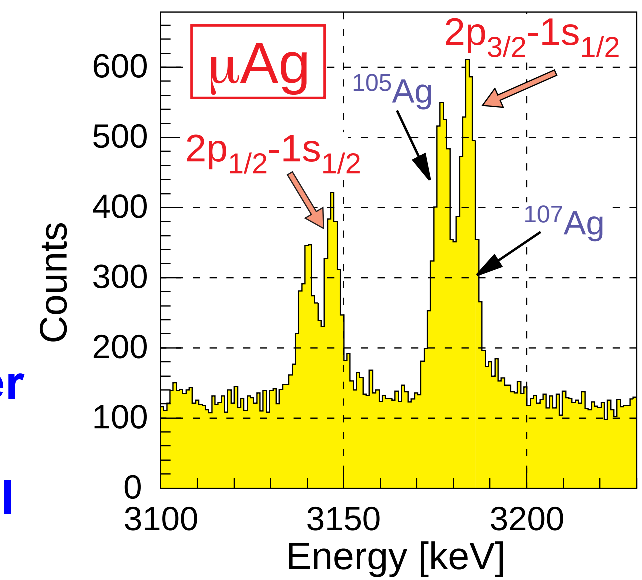




μA* Target System

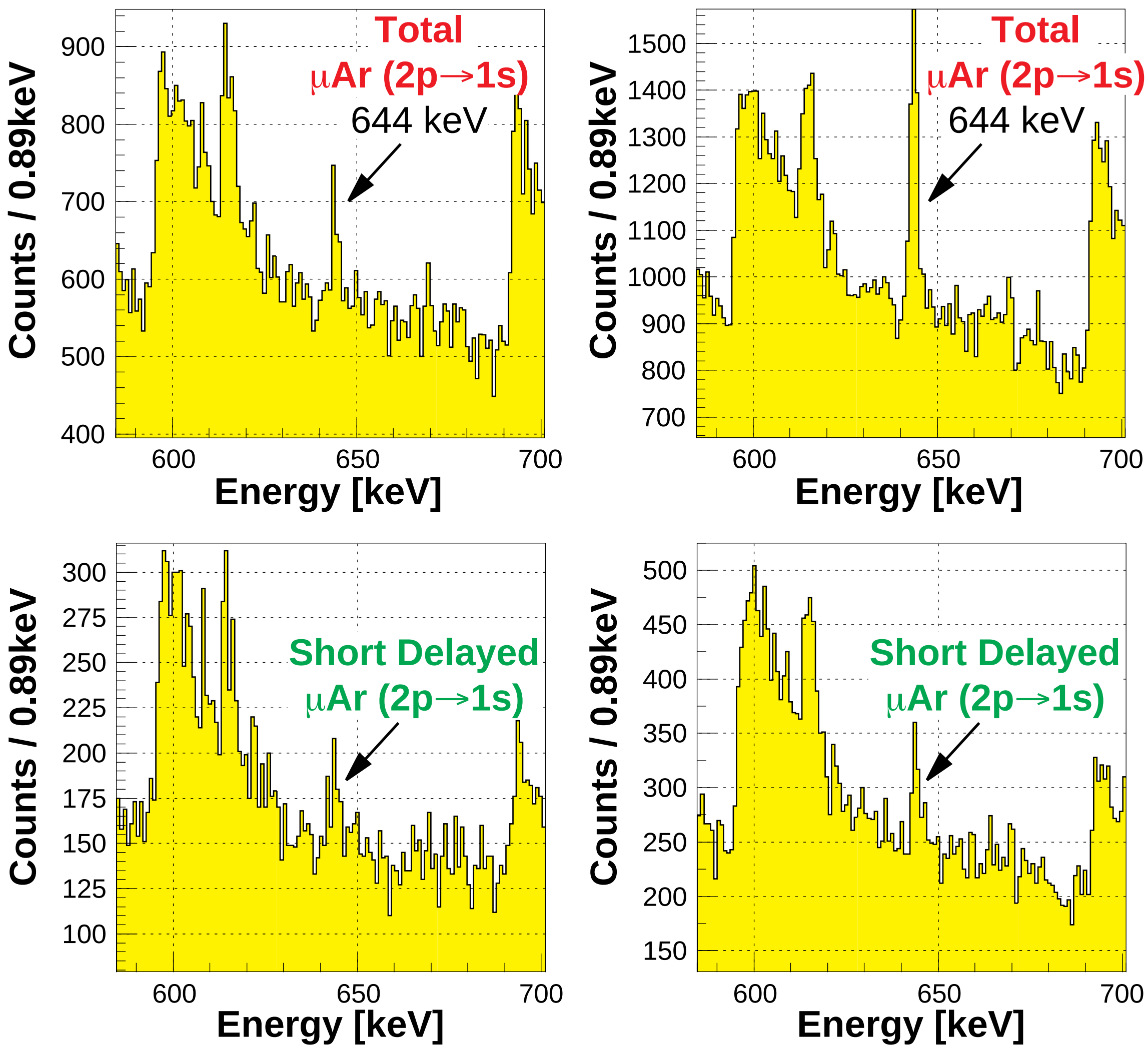
Germanium γ-Ray Detector

Muonic Silver X-rays from the Cold Foil



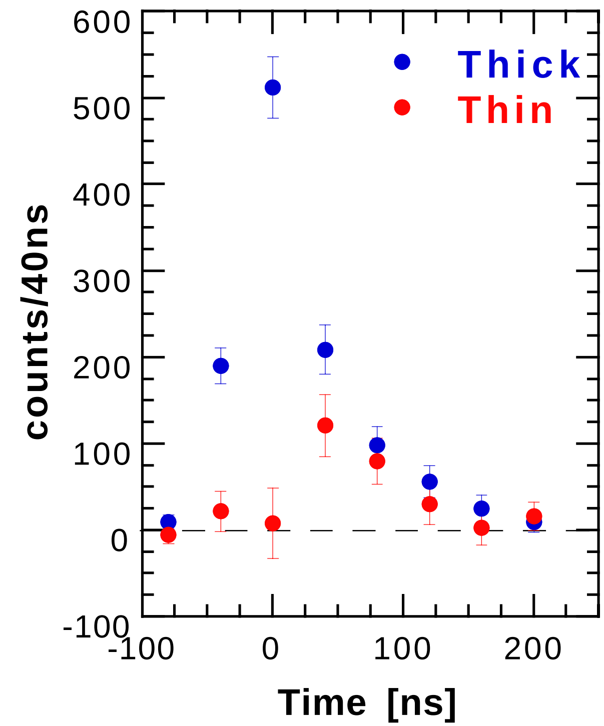
Control Targets: Deposited Argon Films

Thin Film **Thick Film**



Target:
0.5-mm H_2/D_2 + 7-μm D_2 + Ar

μAr (2p→1s) Time Spectrum

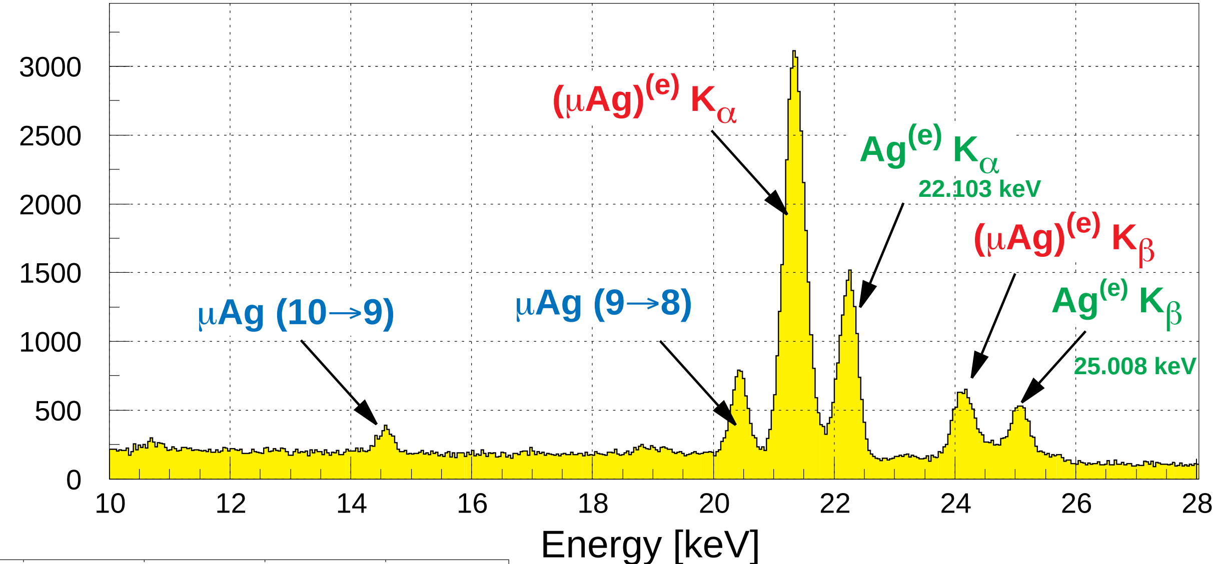


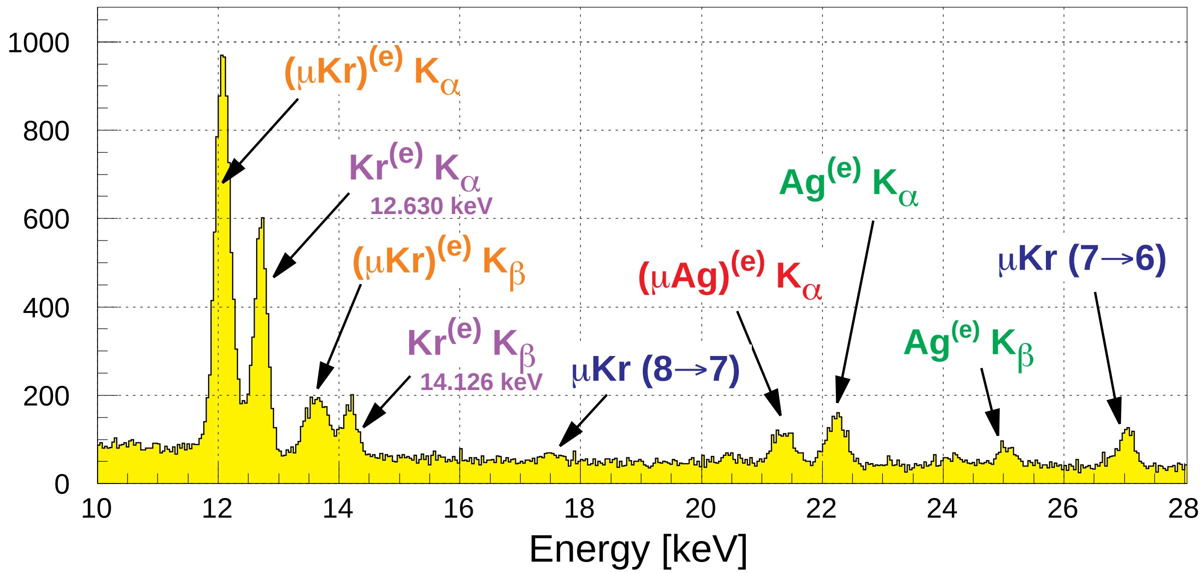
Electronic X-Rays from Muonic Atoms

(1) Normal Target:

0.5-mm H_2/D_2 + 7-μm D_2

RUN 341-349:
0.5-mm H_2/D_2 + 7-μm D_2 (Ar-multi)



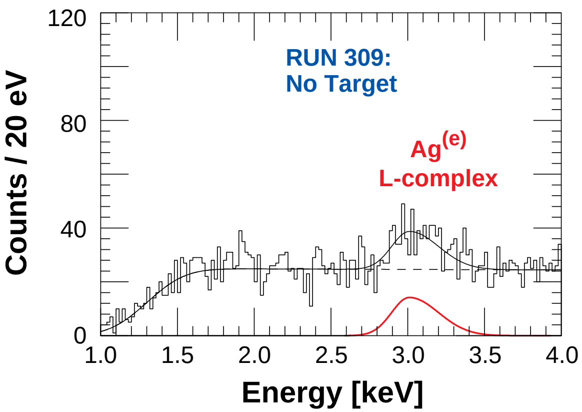


(2) With a Thick Krypton Film added

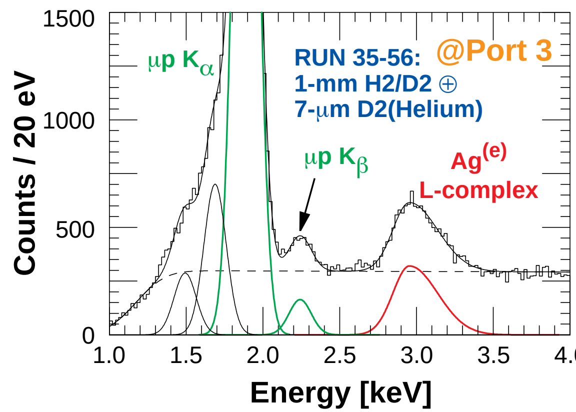
RUN 350: 0.5-mm H_2/D_2 + 7-μm D_2 (Ar-multi) + Kr-layer

Muonic Argon Electronic X-Rays

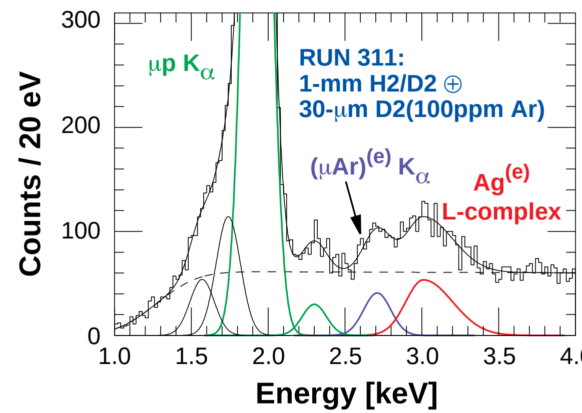
NO TARGET



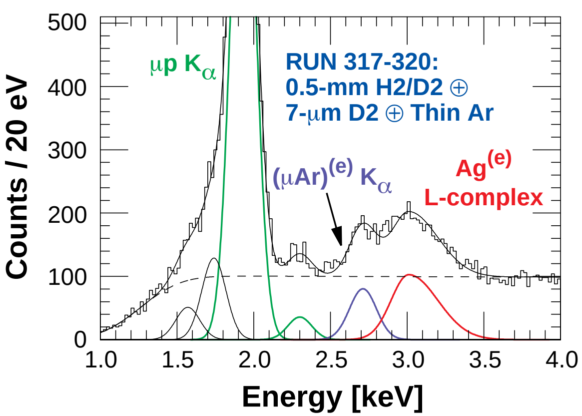
1-mm H_2/D_2 + 7-μm D_2 (Helium)



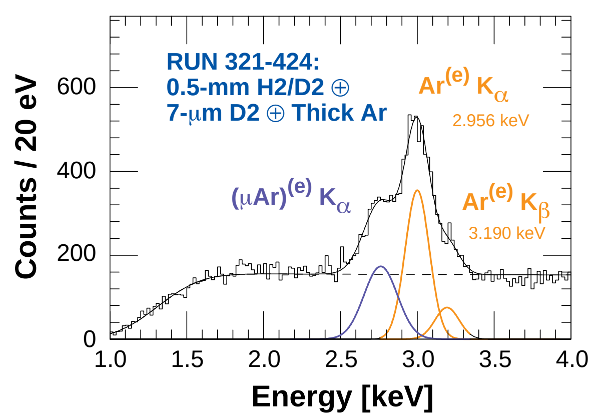
1-mm H_2/D_2 + 30-μm D_2 (100 ppm Ar)



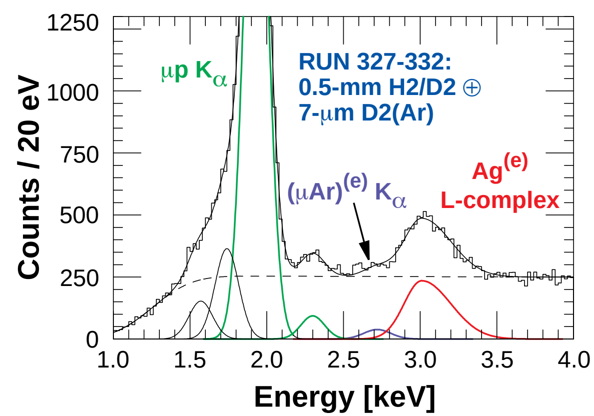
0.5-mm H_2/D_2 + 7-μm D_2 + Thin Ar Film



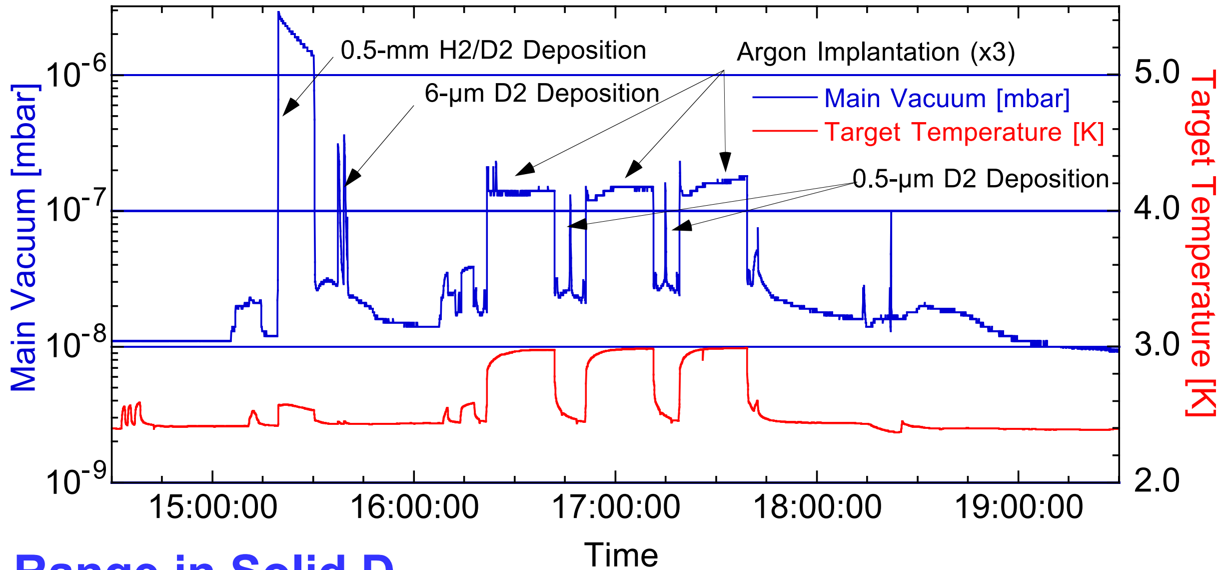
0.5-mm H_2/D_2 + 7-μm D_2 + Thick Ar Film



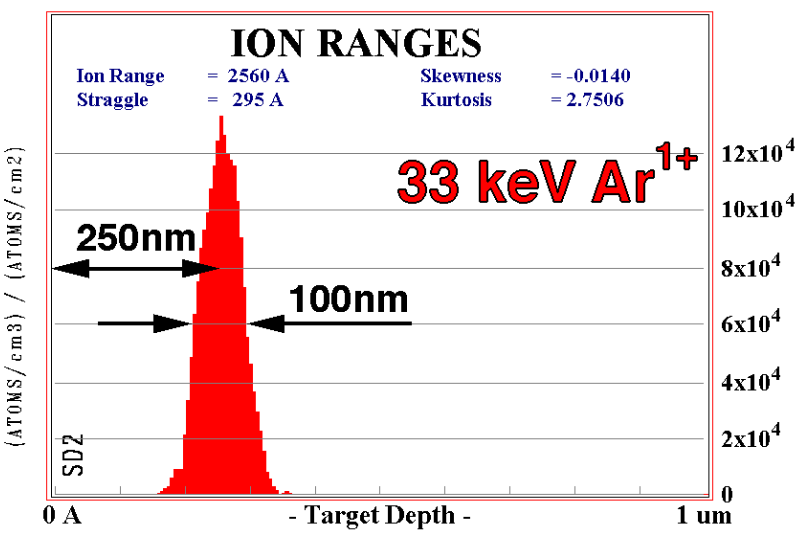
0.5-mm H_2/D_2 + 7-μm D_2(Ar Implanted)



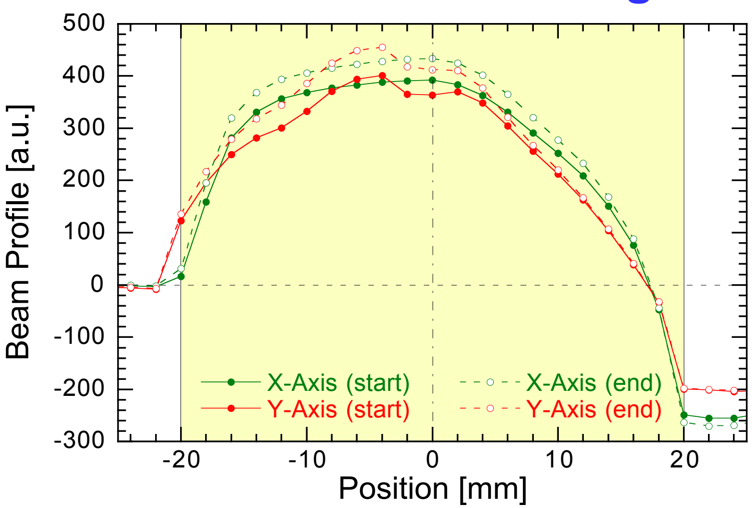
Target Preparation



Argon Ion Range in Solid D_2

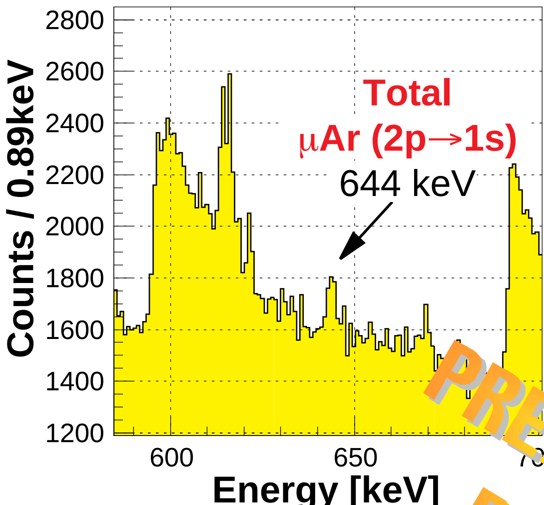


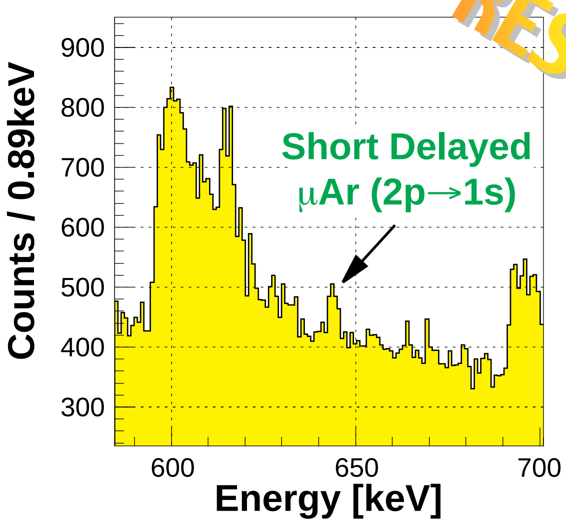
Beam Profile on Target

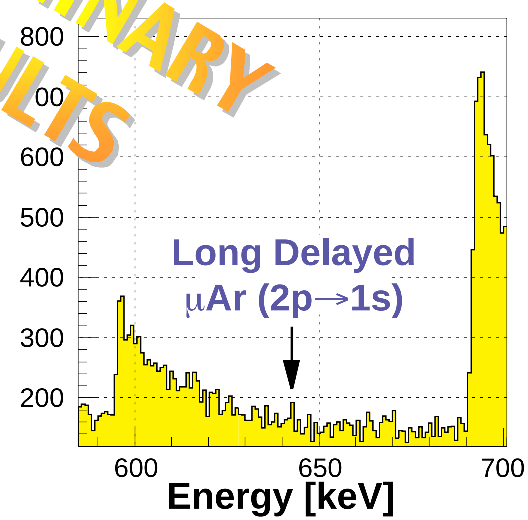


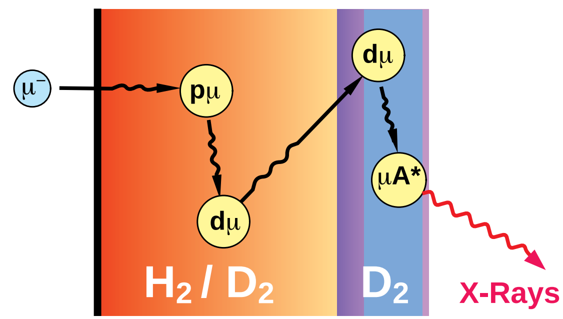
(1) 0.5-mm H_2/D_2 + 7-μm D_2(Ar-multi)

Ge(coaxial) γ-Ray Energy Spectra





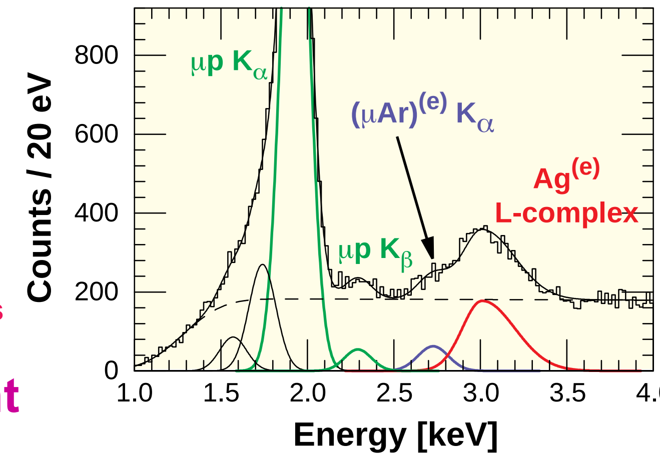




Two-Layer Arrangement

PRELIMINARY RESULTS

Si(Li) X-Ray Energy Spectrum

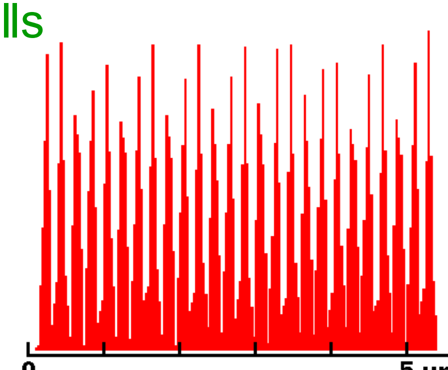


Implanted ^{40}Ar Ions in 5 μm

~10^{16} at/cm^2 (500 ppm)

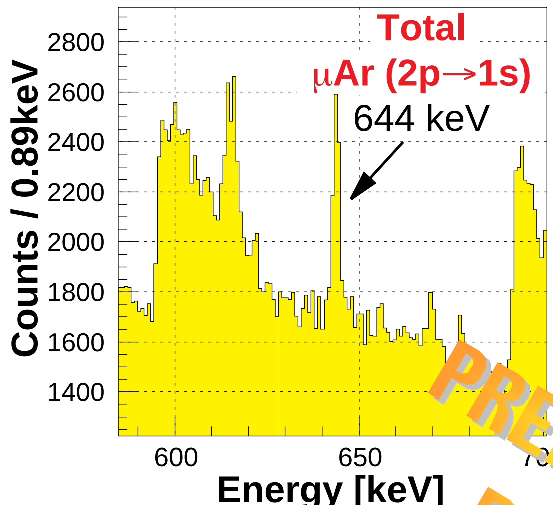
12'170 kspills

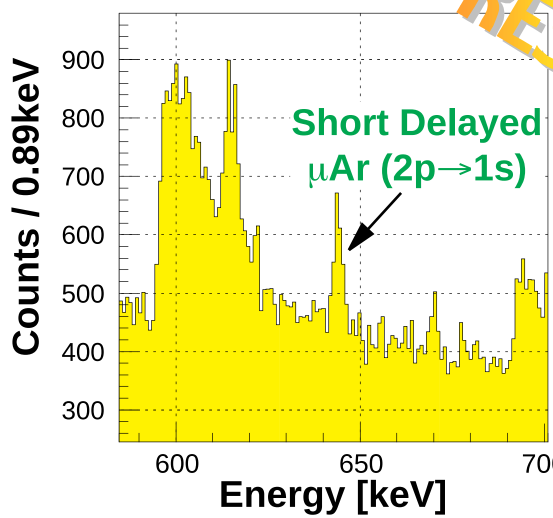
(67.6 hrs)

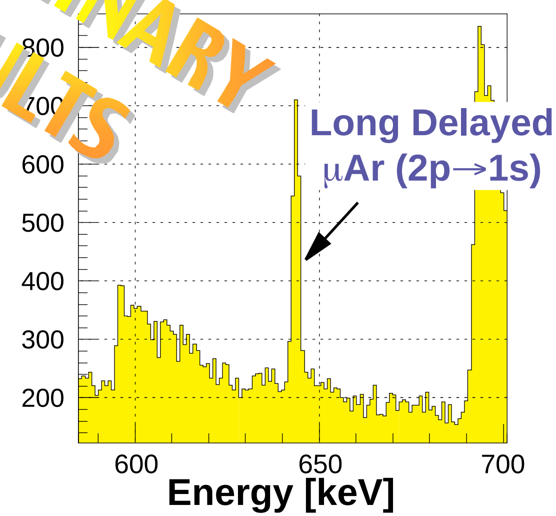


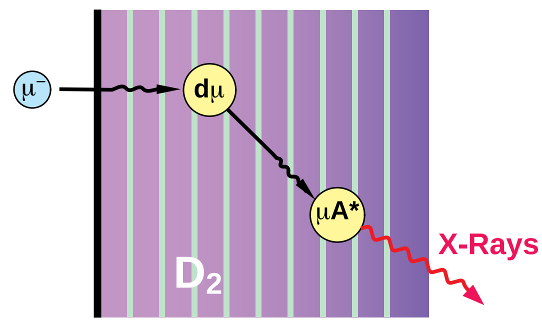
(2) 0.5-mm D_2(Ar-multi)

Ge(coaxial) γ-Ray Energy Spectra



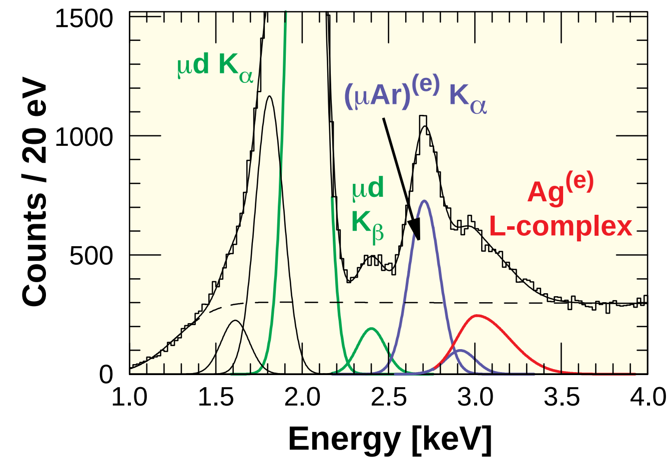






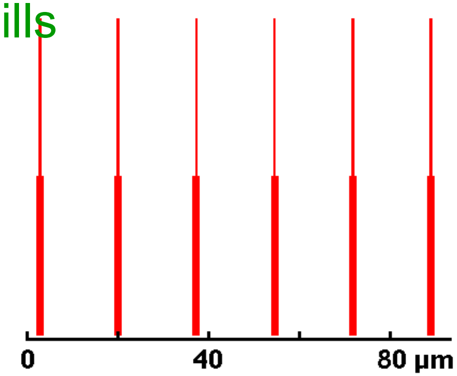
Single-Layer D_2 Layer

Si(Li) X-Ray Energy Spectrum



Implanted ^{40}Ar Ions in 0.5 mm
~10^{16} at/cm^2 (5 ppm)

12’560 kspills
(69.8 hrs)



dμ Atom Scattering in Solid Deuterium

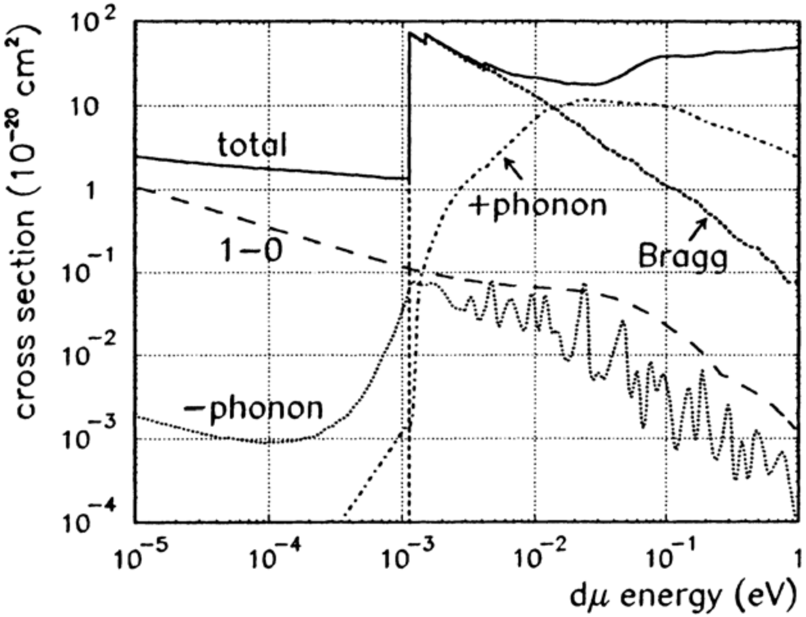
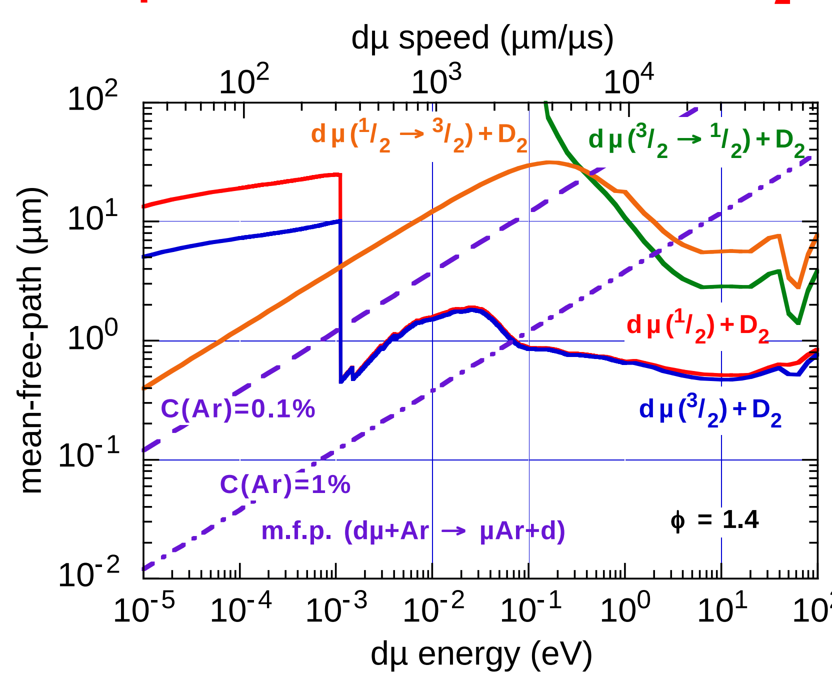


Figure 5. Total cross-section for $d\mu(F = 1/2)$ scattering in 3 K solid deuterium ($K = stat$). The label 1–0 denotes the rotational de-excitation $K = 1 \rightarrow K = 0$.

Deceleration of Muonic Hydrogen Atoms in Solid Hydrogens

A. Adamczak, Hyperfine Interactions **119** (1999) 23.

dμ Mean-Free-Path in Solid D_2



Summary

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- **FIRST TEST EXPERIMENT WITH ARGON SUCCESSFUL**
  - Clear muon transfer X-rays observed from implanted argon ions.
  - Sputtering yield form solid deuterium can be measured with our setup
  - **Improvements:** target purity, Ge detector S/N, ...

- **FUTURE PLANS**
  - Yield optimization using stable ions (Ar, Kr, Xe, ...)
  - Experiment using long-lived isotopes under consideration, e.g., radium isotopes of special interest for P&T violation in atoms (K. Jungmann, KVI).

If proven successful, this method would allow studies of the nuclear properties on unstable nuclei using muonic atom spectroscopy at facilities where intense μ^- and RI beams are available.

Unique opportunity at a **NEUTRINO FACTORY** !