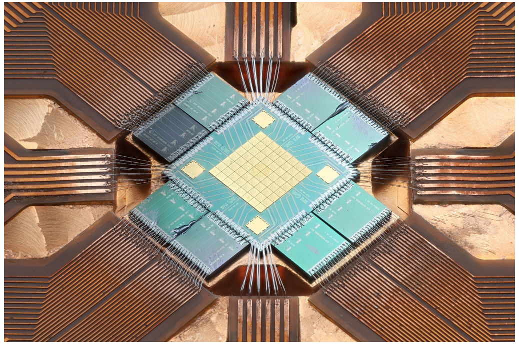
Precision radii of light elements from muonic atoms spectroscopy using Metallic Magnetic Calorimeters

Frederik Wauters
Johannes Gutenberg University Mainz



Muonic atoms: what is happening here?

Negative cloud muon beam at e.g. the Paul Scherrer Institute

Negative muons in matter:

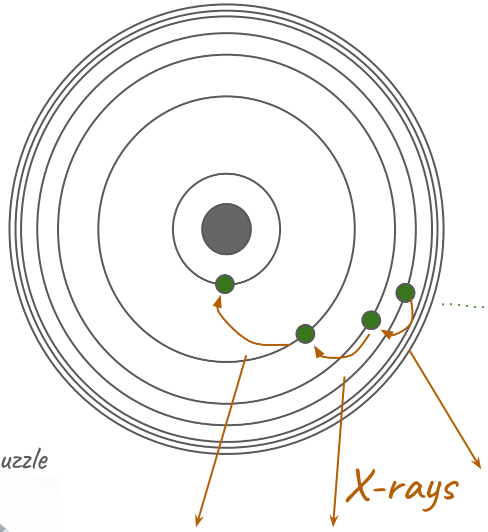
Very much like the H atom, but:

Bohr energies: $$E_n = \frac{mc^2}{2}\frac{\alpha^2 Z^2}{n^2}$$

Bohr radii: $$r_n = \frac{n^2}{mc^2}\frac{\hbar c}{\alpha Z}$$

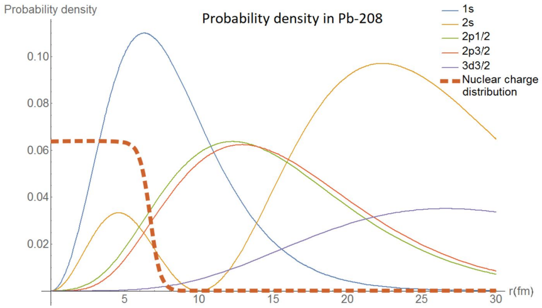
Energies 200 higher: 2 keV → few MeV range

Bohr radii 200 times smaller: significant overlap with the nucleus



The muon lives partially inside the nucleus

$E_{1s}(Z=82)$
→ 19 MeV (point nucleus)
→ 11 MeV (finite size)

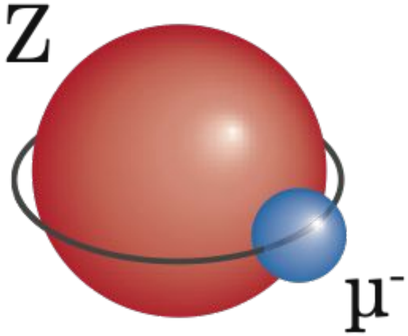


Proton size puzzle

+ $\langle r^2 \rangle$ of most stable nuclei

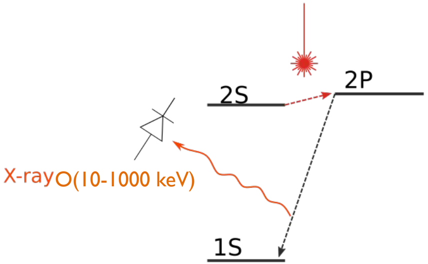
Muonic atoms: what is happening here?

Measuring nuclear finite size effects



Muonic atoms: what is happening here?

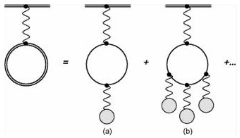
Modern approach with
(*low* Z) muonic atoms



Muonic atoms: what is happening here?

Modern approach with (*low* Z) muonic atoms

QED, R_∞, …



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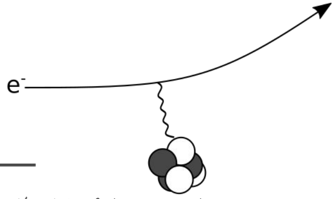
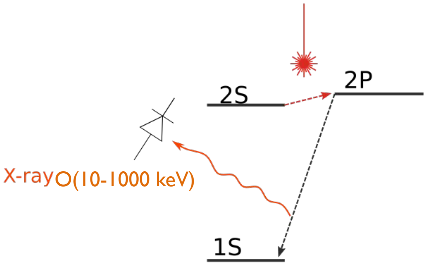


Need a model and/or data of the nuclear charge distribution.



*Solve Dirac equation with all necessary QED contributions**

Absolute

$<r^2>$

Muonic x-ray measurements of most stable elements
→ Barrett radii in the Fricke & Heilig compilations

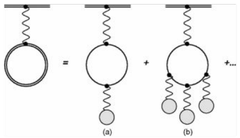
For Z>2 a modern & consistent description and error treatment is often missing, beware of the <r2> values in the *standard tables* (Angeli etc.)

TPE *AKA nuclear polarization*

Muonic atoms: what is happening here?

Modern approach with (*low* Z) muonic atoms

QED, R_∞, ...



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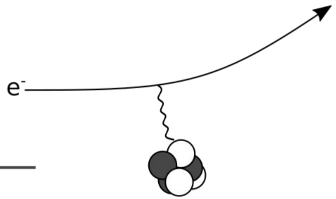
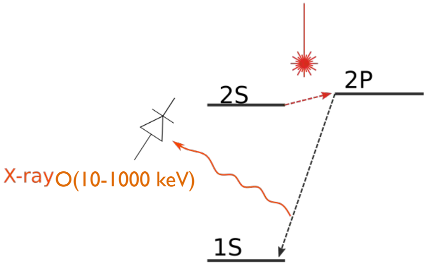


Need a model and/or data of the nuclear charge distribution.

Solve Dirac equation with all necessary QED contributions



Absolute

$\langle r^2 \rangle$

TPE *AKA nuclear polarization*

Need a nuclear model and most applicable way to tackle the many-body problem NCSM, CC, ...

Ab initio calculation of nuclear structure corrections in muonic atoms

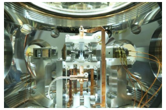
C. Ji[1], S. Bacca[2,3,4], N. Barnea[5], O. J. Hernandez[2,3,6], N. Nevo-Dinur[3]

Put ab-initio nuclear theory to the test

Trends of Neutron Skins and Radii of Mirror Nuclei from First Principles

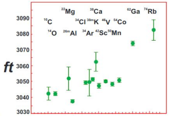
S. J. Novario, D. Lonardoni, S. Gandolfi, and G. Hagen
Phys. Rev. Lett. **130**, 032501 – Published 19 January 2023

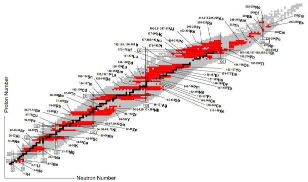
Combine with laser spectroscopy → fundamental constants R_∞, r_p



e.g. Thomas Udem @ MPI Munich

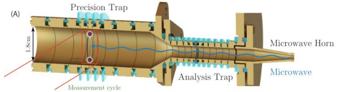
Input for $\delta\nu_i^{AA'} = \frac{A'-A}{AA'} M_i + F_i\, \delta \langle r^2 \rangle^{AA'}$

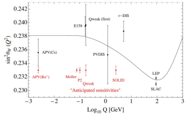




NFS input for precision physics experiments

g-factor measurements at MPI Heidelberg

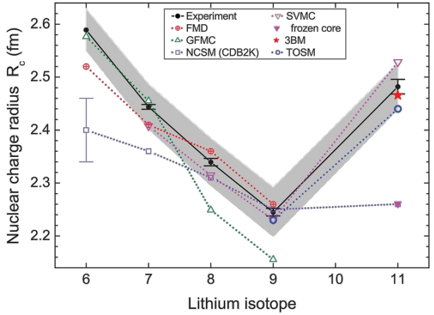




APV with deformed nuclei

Muonic atoms: what is happening here?

Calibrating isotopic chain measurements + crossing Z



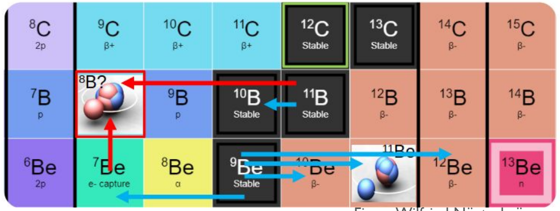
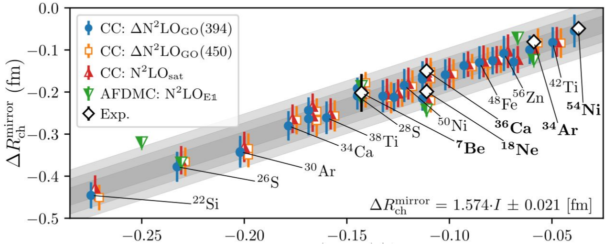


Figure Wilfried Nörterhäuser

$$R_c(A) = \sqrt{R_c^2(A_{\mathrm{ref}}) + \delta\langle r_c^2\rangle^{A_{\mathrm{ref}},A}}$$

$$\delta\langle r^2\rangle^{A,A'} = \frac{1}{F_i}\left(\delta\nu_i^{A,A'} - \frac{A - A'}{A\,A'}M_i\right)$$

Improving radii for Vud
Charge radii in isospin triplet
Isospin ↔ charge radii differences

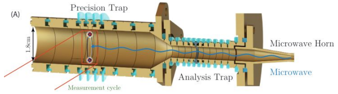


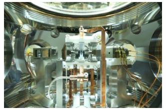
$$\rho_{cw}(r) = \rho_{ch,1}(r) + Z_0\left(\rho_{ch,0}(r) - \rho_{ch,1}(r)\right)$$

$\Delta r \rightarrow \rho_w \rightarrow C(E) \rightarrow ft \rightarrow Ft$

Combine muonic radii with electronic atom spectroscopy and precision trap experiment

Ne g-factor measurements at MPI Heidelberg: NFS effects





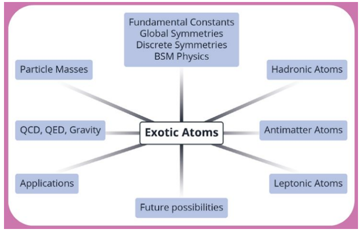
H,He,Li ... spectroscopy in e.g. Mainz and Munich

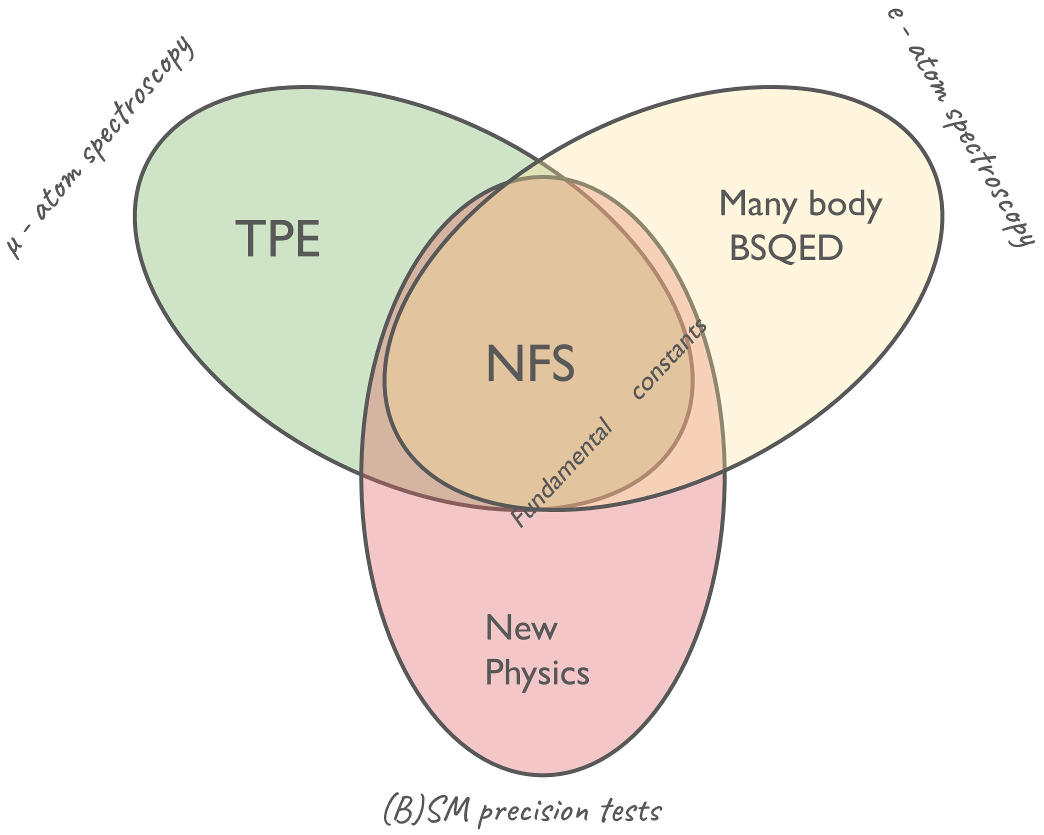
Robust treatment of finite nuclear size effects reduces CKM unitarity deficit

Mikhail Gorchtein,[1,2,*] Vaibhav Katyal,[3] B. Ohayon,[4,†] B. K. Sahoo,[5,‡] and Chien-Yeah Seng[6,7,§]

... simple ...

NuPECC LTP version





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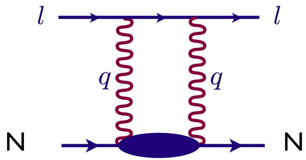
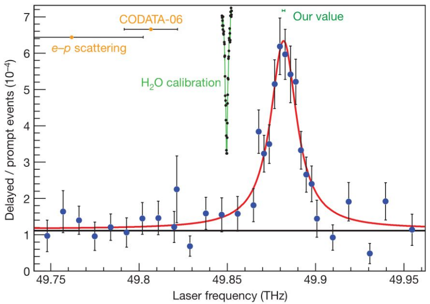


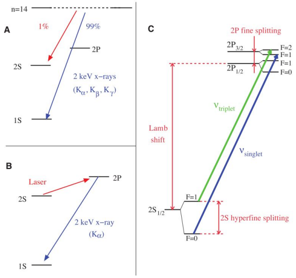
Two **P**hoton **E**xchange
Nuclear **F**inite **S**ize
Bound State QED

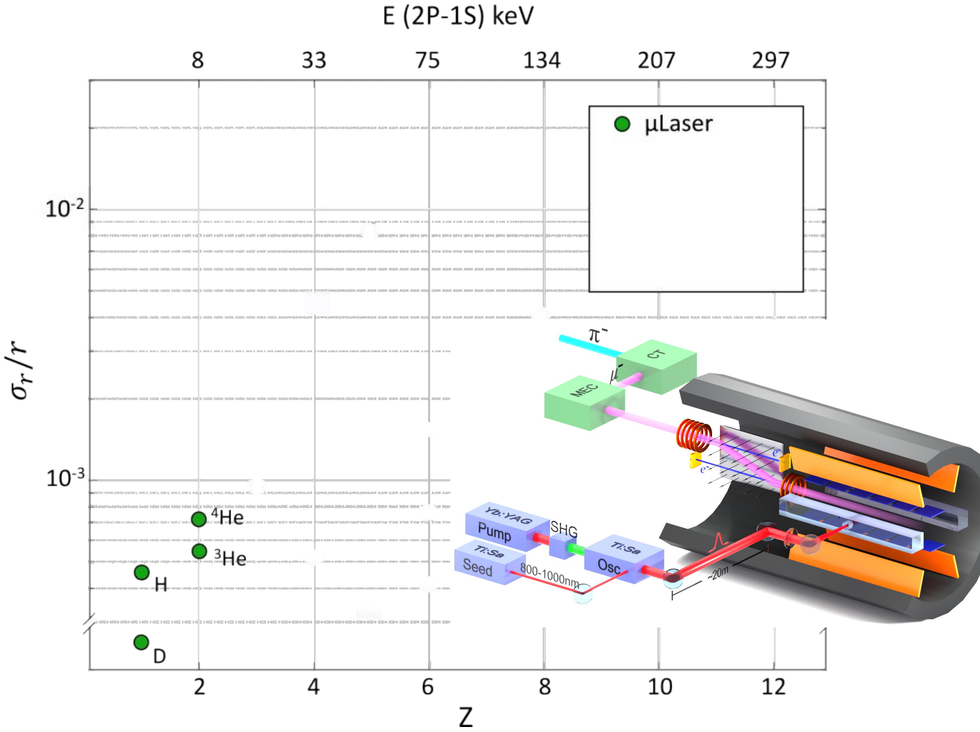
Experimental situation

- Precision muonic atom data for Z=1,2 by the **CREMA collaboration**
  - Proton size
  - Deuterium charge radius
  - Alpha particle radius
  - Helion charge radius

Ultimate precision, however limited the exotic atom transition in-range of lasers and meta-stable initial states







Experimental situation

- Precision muonic atom data for Z=1,2 by the CREMA collaboration
- Most of the stable nuclei have been measured with HPGe (70s / 80s)
  - Z>10 limited by Nuclear polarization / nuclear charge distribution
  - Z<10 limited by HPGe resolution

Fricke and Heilig *recipe*
https://doi.org/10.1006/adnd.1995.1007

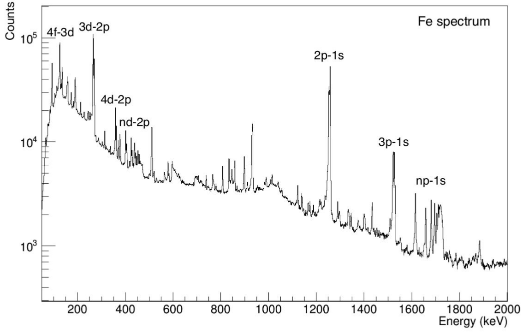
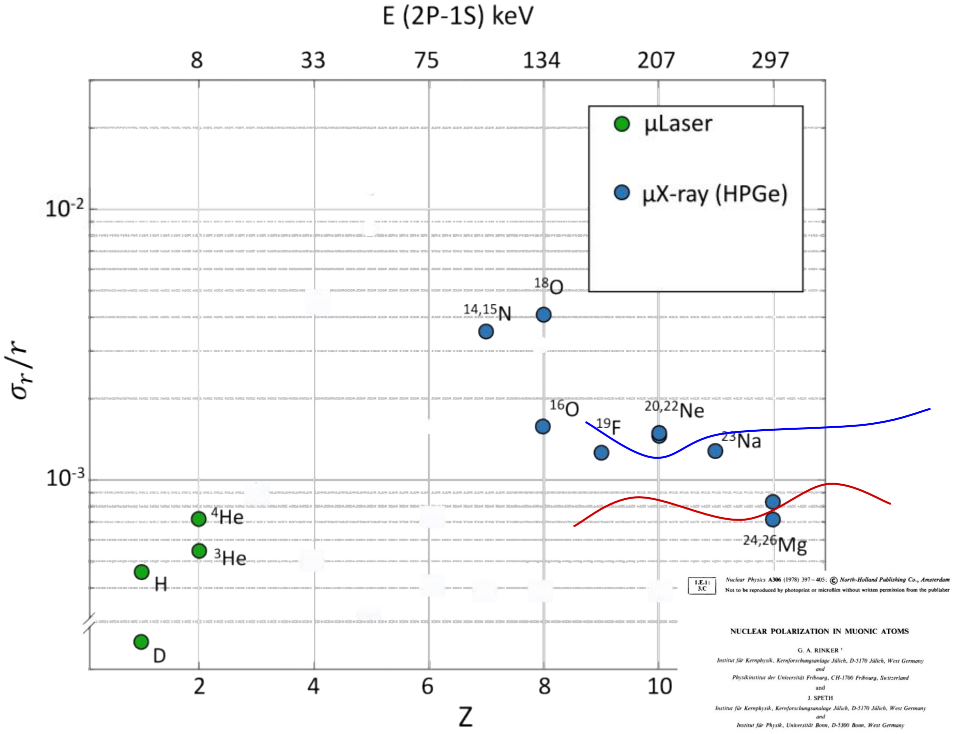


TABLE IIIA. Muonic $2p \rightarrow 1s$ Transition Energies and Barrett Radii for $Z < 60$ and $Z > 77$
See page 194 for Explanation of Tables

Isotope	$E_{exp.}$ [keV]	$E_{theo.}$ [keV]	NPol [keV]	c [fm]	$\langle r^2 \rangle^{1/2}_{model}$ [fm]	α [1/fm]	k	C_z [am/eV]	$R^{\mu}_{k\alpha}$ [fm]	Ref.
$^{9}Be^{\dagger}$	33.402 10	33.402	0.001	1.7890 3700	2.390	0.0420	2.1160	-20.80	3.0725 (2080;60)	[Sc80a]
$^{nat}B^{\dagger}$	52.257 7	52.262	0.001	1.9280 900	2.452	0.0440	2.1190	-8.600	3.1549 (602;30)	[Sc80a]
^{12}C	75.2582 5	75.2582	0.0025	2.0005 23	2.468	0.0208	2.0231	-4.141	3.1996 (21;33)	[Ru84a] [Sc82]
$^{13}C^{\ddagger}$	75.3127 40	75.3127	0.0025	1.9958 187	2.466	0.0208	2.0231	-4.135	3.1967 (165;31)	[Sc82] [Ru84a]
$^{14}C^{\ddagger}$	75.3514 30	75.3514	0.0025	2.0445 137	2.492	0.0208	2.0234	-4.095	3.2273 (123;29)	[Sc82] [Ru84a]
$^{nat}N^{\dagger}$	102.403 5	102.404	0.003	2.1510 230	2.560	0.0470	2.1120	-2.200	3.2921 (110;20)	[Sc80a]
^{16}O	133.535 2	133.534	0.005	2.4130 26	2.693	0.0272	2.0330	-1.287	3.4694 (26;22)	[Fr92]
^{18}O	133.572 9	133.572	0.005	2.5540 130	3.586	0.0258	2.0287	-1.258	3.5680 (113;21)	[Fr92]
^{19}F	168.515 2	168.515	0.009	2.7759 15	2.898	0.0300	2.0392	-0.782	3.7291 (16;24)	[Fr92]
^{20}Ne	207.282 5	207.282	0.019	2.9589 24	3.006	0.0329	2.0445	-0.516	3.8656 (26;33)	[Fr92]
^{21}Ne	207.429 4	207.430	0.018	2.8941 20	2.967	0.0330	2.0441	-0.521	3.8163 (21;31)	[Fr92]
^{22}Ne	207.512 4	207.512	0.018	2.8706 11	2.954	0.0330	2.0439	-0.522	3.7986 (21;31)	[Fr92]



1.E.1: 3.C
Nuclear Physics **A306** (1978) 397–405; © *North-Holland Publishing Co., Amsterdam*

NUCLEAR POLARIZATION IN MUONIC ATOMS

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and
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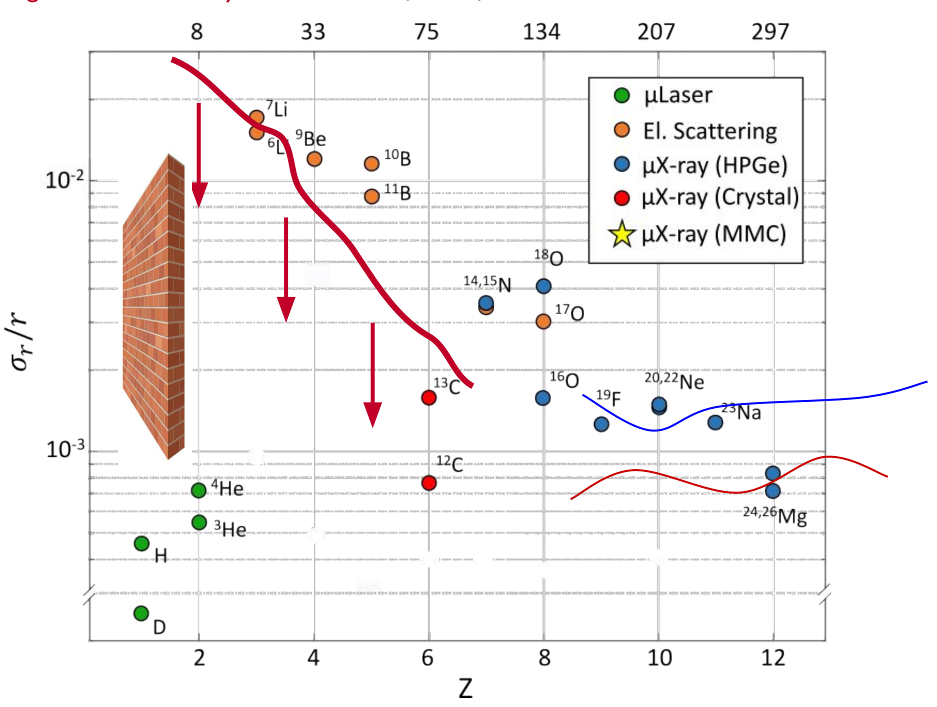
Received 22 February 1978

Abstract: We have calculated nuclear polarization energy shifts for muonic atoms throughout the periodic table using a phenomenological extension of more detailed microscopic calculations reported previously. Numerical results are presented in tabular form.

Experimental situation

- ❑ Precision muonic atom data for Z=1,2
- ❑ Most of the stable nuclei have been measured with HPGe (70s / 80s)
  - ❑ Z>10 limited by Nuclear polarization / nuclear charge distribution
  - ❑ Z<10 limited by HPGe resolution
- ❑ ~1% precise radii from e-scattering to fill the gap

A need for efficient, broadband, and high-resolution X-ray detectors



Experimental situation

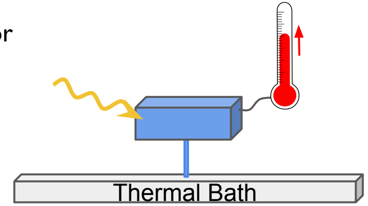
- Precision muonic atom data for Z=1,2
- Most of the stable nuclei have been measured with HPGe (70s / 80s)
  - Z>10 limited by Nuclear polarization / nuclear charge distribution
  - Z<10 limited by HPGe resolution
- ~1% precise radii from e-scattering to fill the gap
- Need for a 1-10 ppm precise energy determination if 2p1s transitions.

Limitations of solid state X-ray detectors:

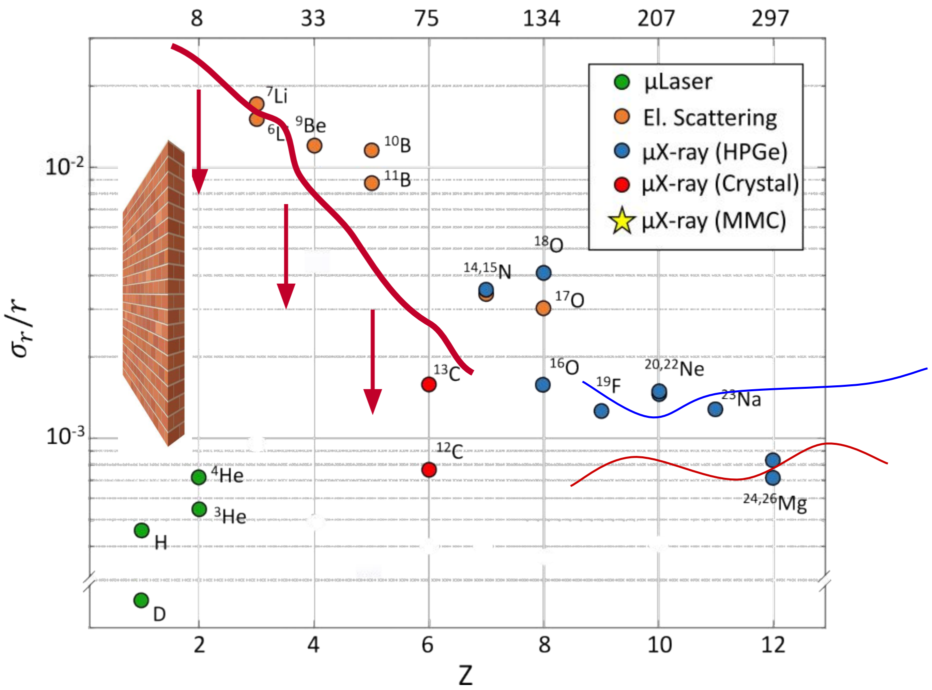
- $\sigma_Q = \sqrt{FN_Q}$
- S/N with ENC a few 100 e-

Unit of heat ≪ Unit of Ionization:

- $\Delta T \cong E_{deposited} / C_{tot}$
- $\Delta T / T$ large → operate < 0.1 K
- A very good temperature sensor



A need for efficient, broadband, and high-resolution X-ray detectors



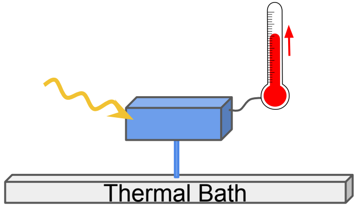
Experimental situation

Unit of heat ≪ Unit of Ionization

- ❑ $\Delta T \cong E_{deposited} / C_{tot}$
- ❑ $\Delta T / T$ large ⟶ operate < 0.1 K
- ❑ A very good temperature sensor

Metallic Magnetic Calorimeters → Unit of spin flip ≪ Unit of Ionization

- ❑ Paramagnetic Ag:Er Alloy
- ❑ $\Delta\Phi_S \cong \delta M/\delta T \; \Delta T = \delta M/\delta T \times E_{deposited} / C_{tot}$



Magnetization of paramagnetic material, MMC

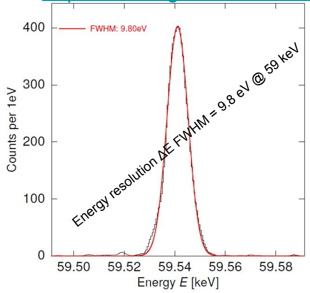
KIRCHHOFF-
INSTITUT
FÜR PHYSIK

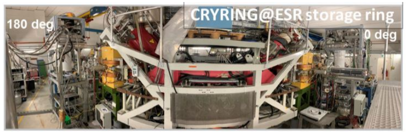
METALLIC MAGNETIC CALORIMETERS

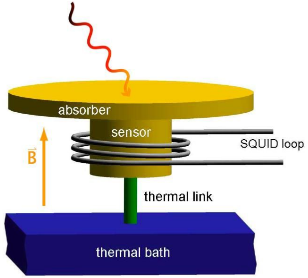
In recent years there has been important progress in Astro- and Particle Physics,which has led to a deeper understanding of the fundamental properties of matter and the nature of the universe. Much of the experimental progress was only possible due to technological developments in other areas, like optics, electronics and computer science. In the vein of these developments the new technology of cryogenic particle detectors are about to make important contributions to a wide range of astrophysics experiments. Examples are the search for dark matter, the observation of the cosmic microwave background and several projects in x-ray astronomy. But not only in astrophysics experiments such detectors have high potential, there are also attractive application possibilities in atomic and nuclear physics.

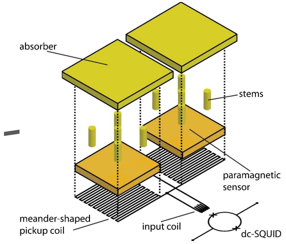
*MaXs-*** sensors developed by HD-KIP for e.g. the ECHO/IAXO experiment , see D. Unger et al., AG prof. Dr. Gastaldo, Dr. A. Fleischmann*

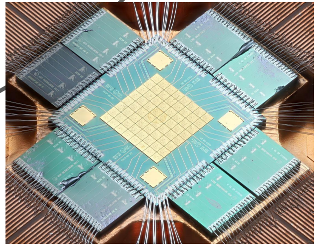
https://arxiv.org/abs/2005.13340







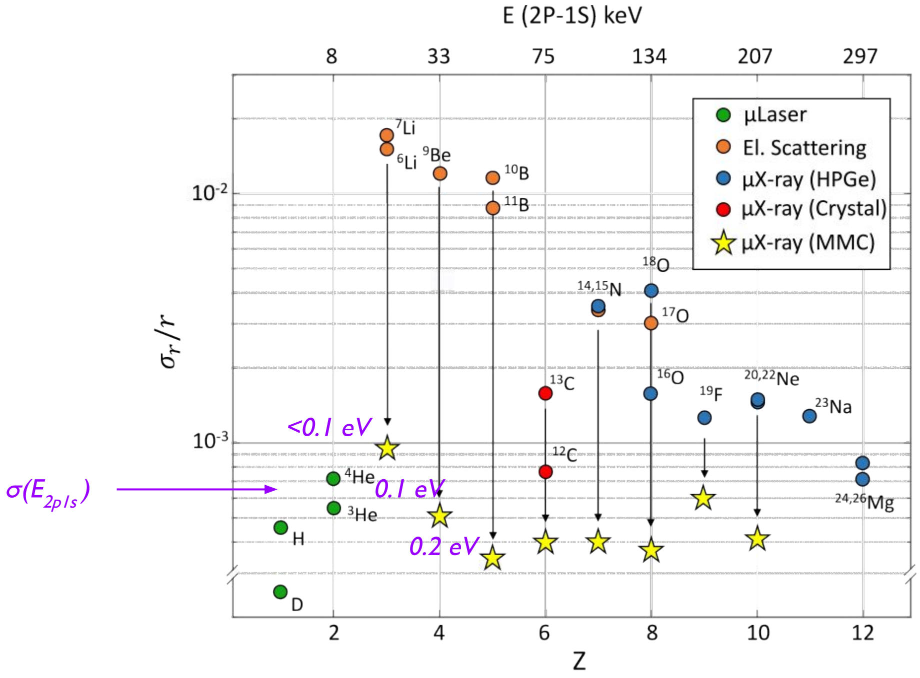


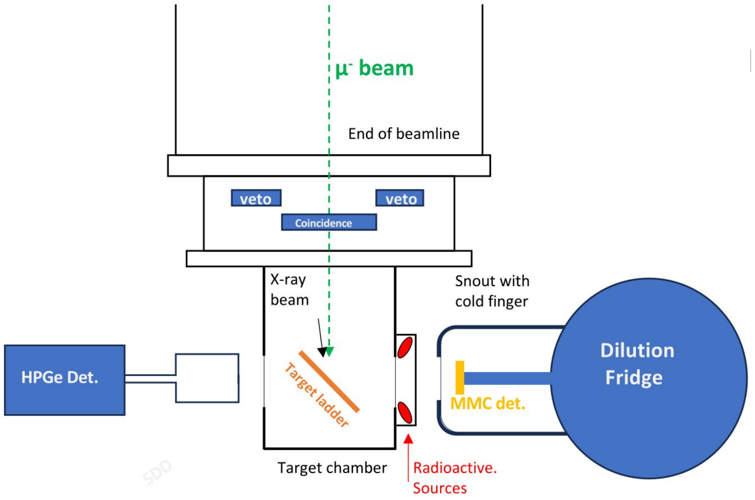


Spectroscopy with MMCs

Quartet: precision muonic X-ray spectroscopy on low Z nuclei with MMCs

https://doi.org/10.1007/s10909-024-03141-x https://doi.org/10.3390/physics6010015

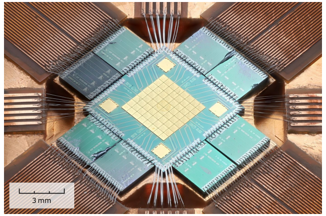


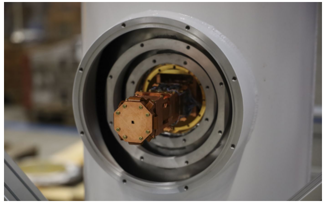


Spectroscopy with MMCs

Quartet: MMC from the *basement* to an online experimental environment

→ 2023 test beam at PSI..

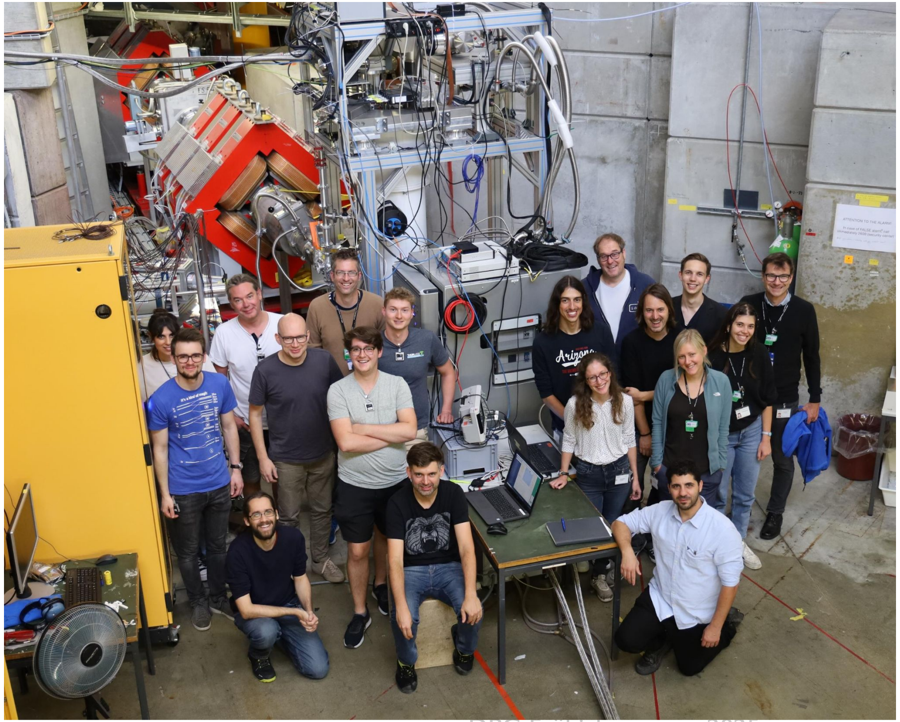


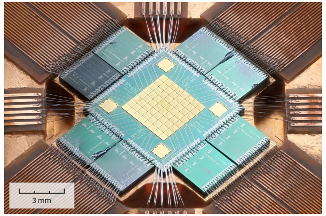
- ➢ Accelerator facility
- ➢ Beamline elements
- ➢ Neutron / electron / x-ray backgrounds (correlated and uncorrelated to the muon)
- ➢ Limited beamtime

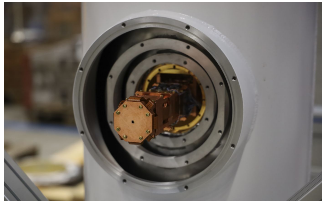
Spectroscopy with MMCs

Quartet: MMC from the *basement* to an online experimental environment

→ 2023 test beam at PSI.







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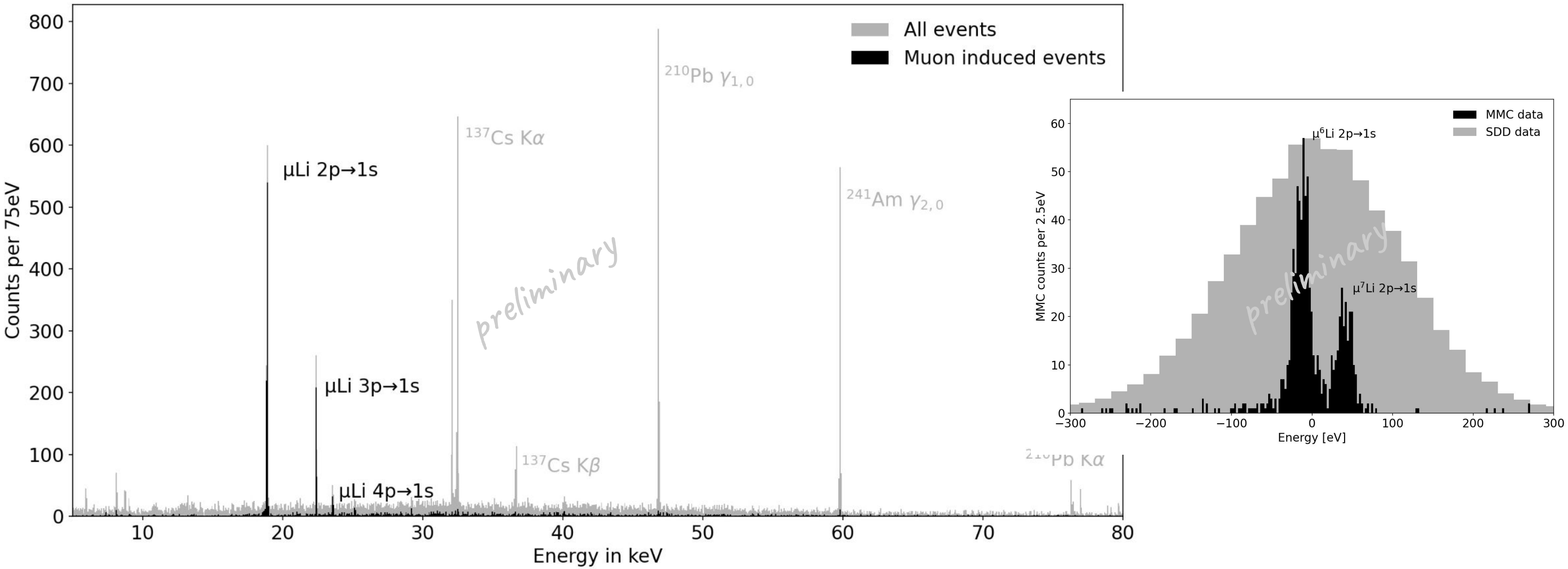
Spectroscopy with MMCs

Quartet: MMC from the *basement* to an online experimental environment

→ 2023 test beam at PSI.

→ First 6Li and 7Li measurements.

Yes, MMC work at a secondary beamline at PSI!



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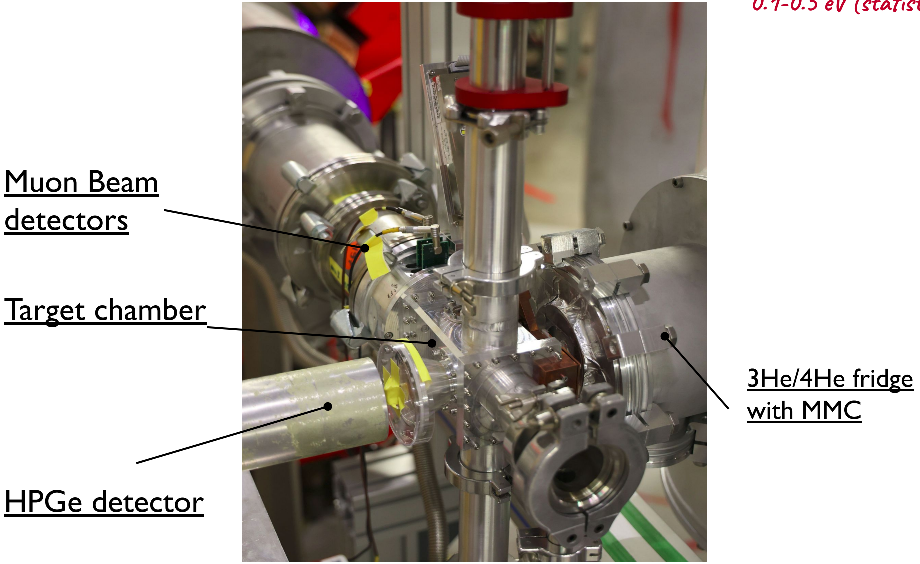
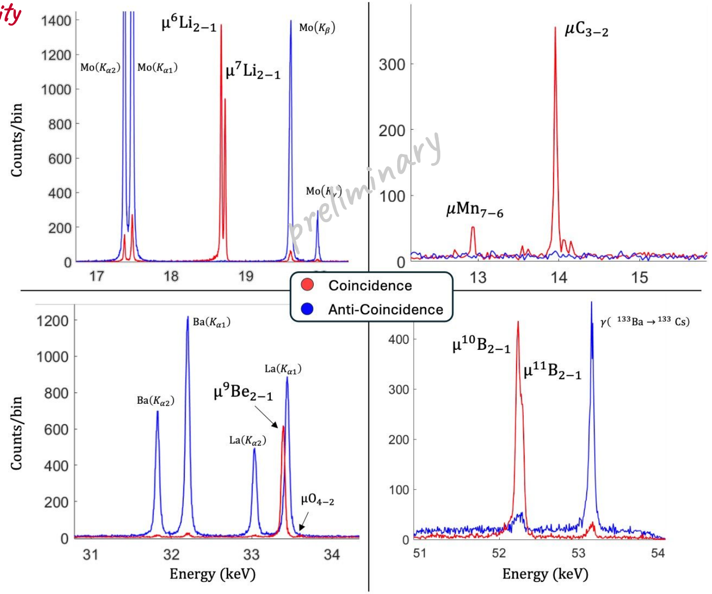
→ Full proposal + two week 2024 Physics beamtime with ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B

Energy resolutions achieved of 10-15 eV @ 18-50 keV !
0.1-0.5 eV (statistical) sensitivity





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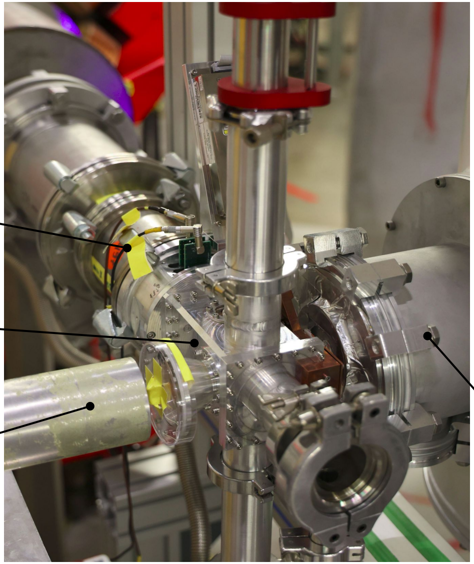
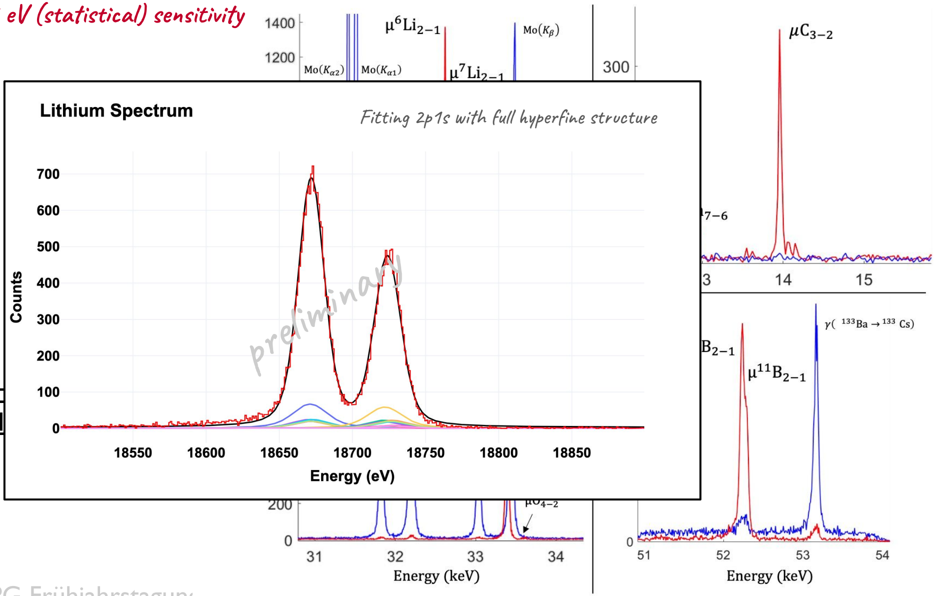
Muon Beam detectors

Target chamber

HPGe detector



3He/4H
with M



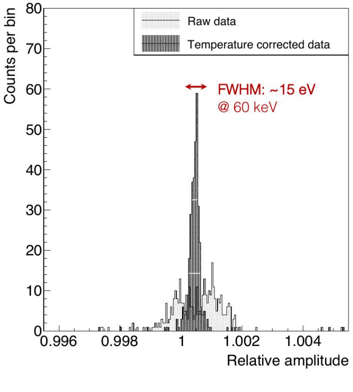
Spectroscopy with MMCs

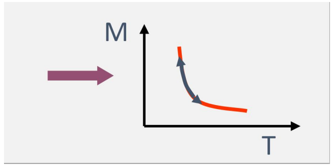
MMC with muonic atoms: low-temperature quantum sensors in beam-on-target experiment

(Not that easy …)

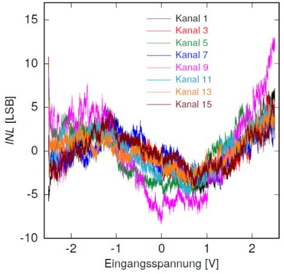
→ Combine data from 64 pixels
→ Every x-ray cascade comes with a 50 MeV e- from μ-decay
→ < 10 pmm accuracy envisioned

Temperature correction: Correct each pixel for back to its stable working point

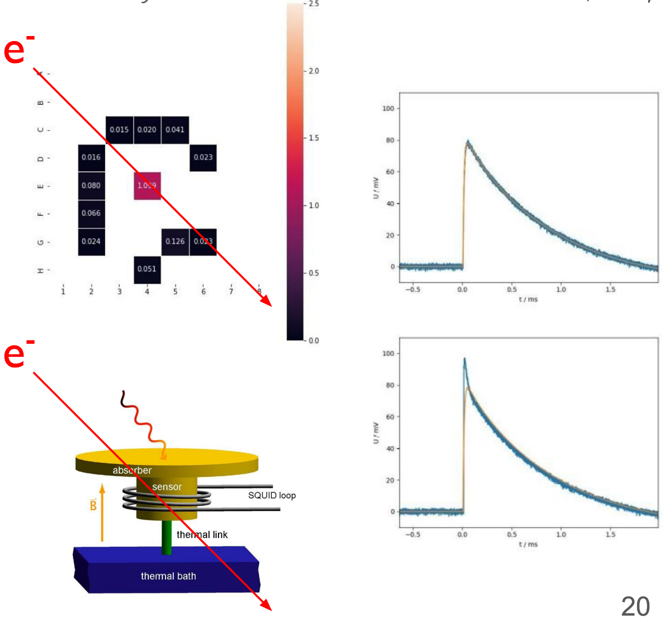




Very stable readout electronics needed. With 16-bit: σ_E < LSB



Each x-ray of interest comes with a 50 MeV electron from μ-decay



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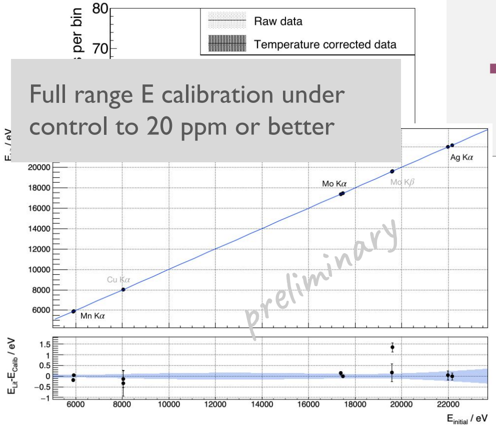
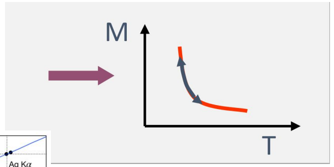
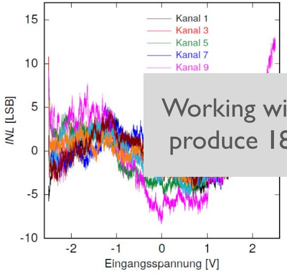




Full range E calibration under control to 20 ppm or better

Very stable readout electronics needed. With 16-bit: σ_E < LSB



Working with Struck Gmbh to produce 18-bit ADC modules

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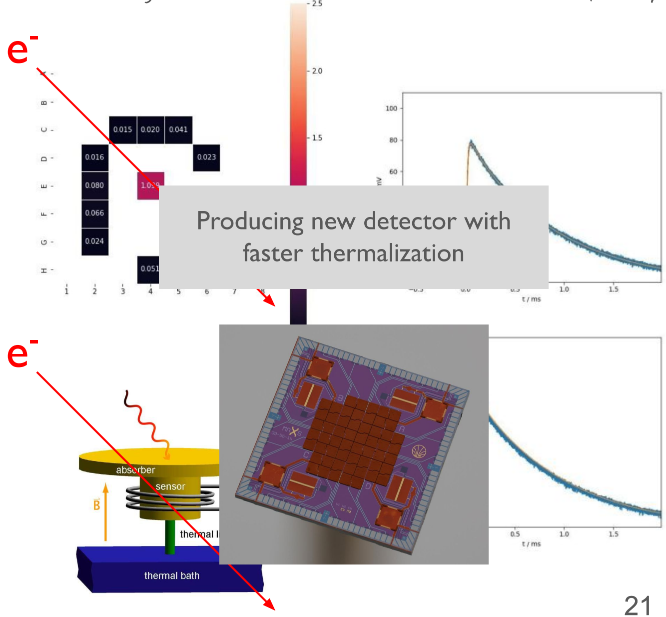
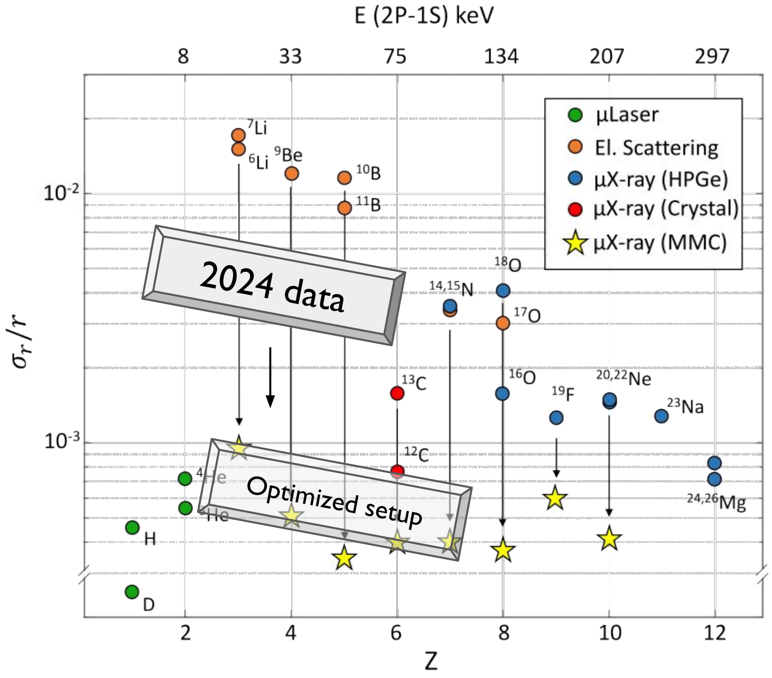


Producing new detector with faster thermalization

Radii of light nuclei



Radii of light nuclei

Isotope	Current $\sigma_{stat}(E)$	Goal $\sigma(E) \rightarrow \sigma(r)$	Nuclear polarization
$^{6}Li/^{7}Li$	~ 0.1- 0.2 eV	0.05 eV→ 0.3 fm	0.1-0.2 eV
^{9}Be	~ 0.2 eV	0.1 eV → 0.2 fm	0.5-1 eV
$^{10}B/^{11}B$	< 0.5 eV	0.1 eV → 0.2 fm	~1 eV
$^{12}C/^{13}C$	2025 campaign	0.2 eV → 0.2 fm	2 eV
^{14}N	(2025 campaign)	0.2 eV → 0.3 fm	~3-4 eV
$^{16}O/(^{17}O)/^{18}O$	2025 campaign	0.2 eV → 0.3 fm	~5-8 eV

Ab-initio from S. Bacca et al.

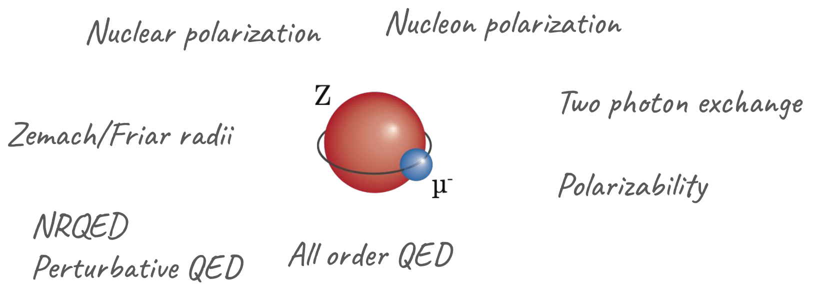
Rinker nuclear polarization 1979

Gorstein 2024

Future:

10Be
19F
20Ne
54Mn
...

and improved Li/Be/B



Conclusions

Significant progress (expected) all over the nuclear chart

- ❑ Light nuclei with Quartet / MMC detectors
  - ❑ Modern HPGe detector array at PSI and
  - ❑ A novel HD-transfer target for ug targets

All aiming for ~0.1 % accuracy on charge radii

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Future:

- ❑ Li, B, Be, … data under analysis
- ❑ Push MMC + muonic-rays combo to the limits
- ❑ Eying ^{7}Be-^{7}Li, ^{8}B-^{8}Li, ^{18}Ne-^{18}O, ^{19}F-^{19}Ne mirror pairs (Vud NFS corrections)
- ❑ ^{10}Be combining MMC with transfer target
- ❑ Work in progress: consistent description for A=6→ …
  - ❑ $^{26/27}$Al, $^{28/29/30}$Si, ^{108m}Ag, … reference radii

KIRCHHOFF-INSTITUT FÜR PHYSIK

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Laboratoire Kastler Brossel
Physique quantique et applications

KATHOLIEKE UNIVERSITEIT LEUVEN

TECHNION Israel Institute of Technology

NOVA UNIVERSIDADE NOVA DE LISBOA

Some challenges & needs:

- ❑ Run MMC at optimal performance with muon stopping target at moderately high rates
- ❑ Need NP input to go from E to <r^2> from A=6→ …