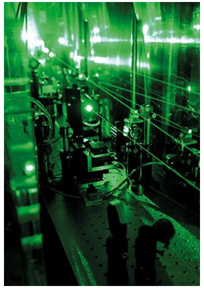
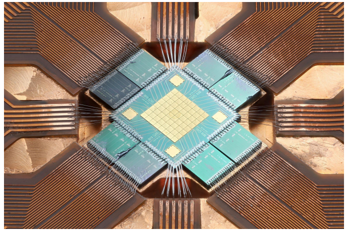
Nuclear Physics with Muonic X-ray Spectroscopy

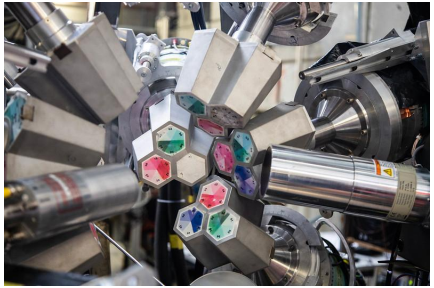
Charge radii of light and not so light muonic atoms

@ PAUL SCHERRER INSTITUT PSI

Frederik Wauters on behalf of the muX, CREMA, and QUARTET collaborations
Johannes Gutenberg University Mainz







Muonic atoms: what and how?

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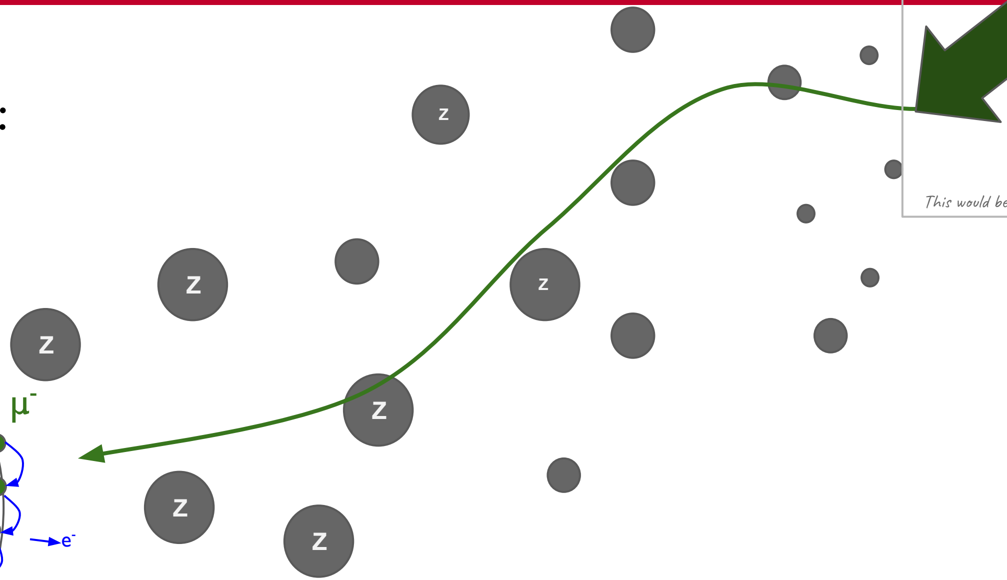
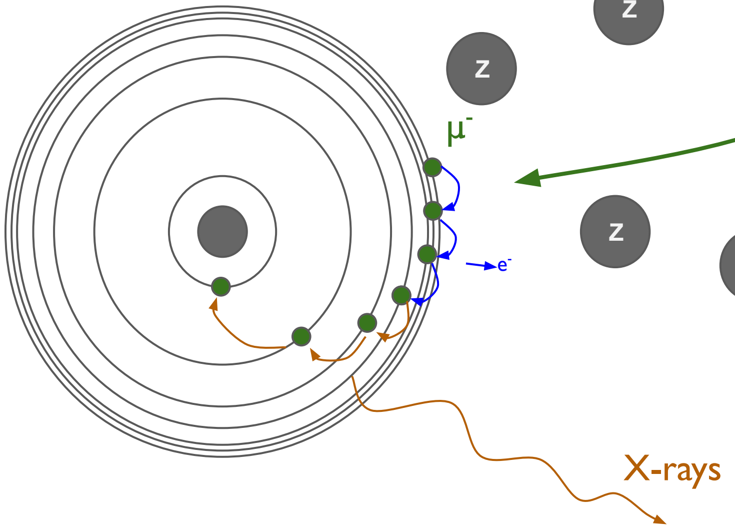
Negative cloud muon muon beam at e.g. the Paul Scherrer Institute

This would be 2 extra slides if I had more time

- Negative muons in matter:





Stopped negative muon:

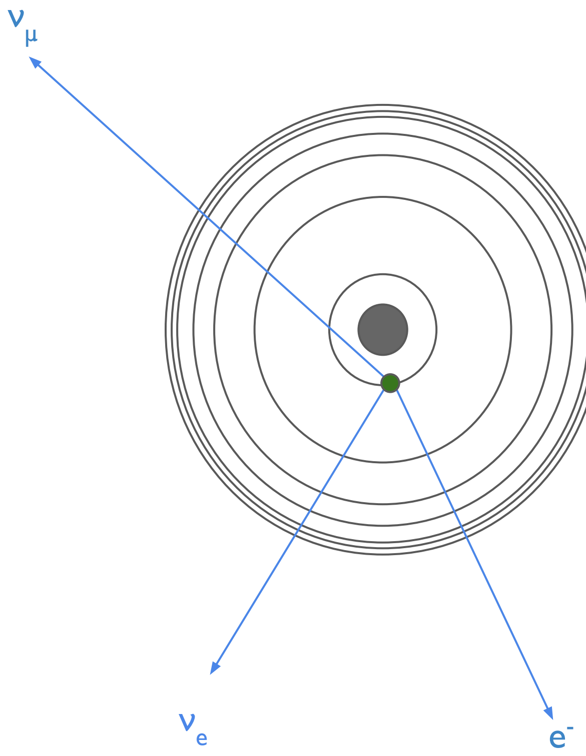
- Atomic capture @ n ≅ 14
- At high n: Auger transitions. Kick out "*all*" of the electrons
- At lower n radiative transitions dominate: **Muonic X-rays**

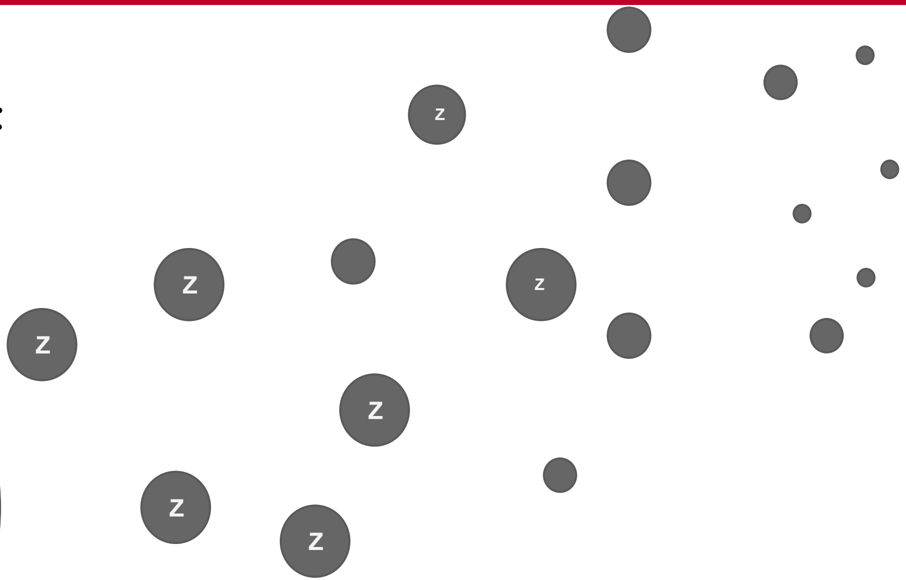
2 keV for μH, 6 MeV for μPb

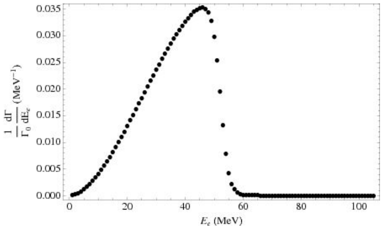
< 1 ns (<< μ lifetime)

Muonic atoms: what and how?

- Negative muons in matter:







Stopped negative muon:

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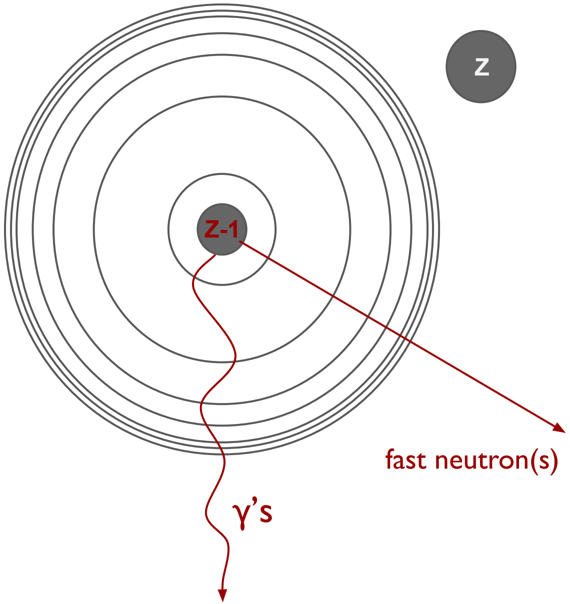
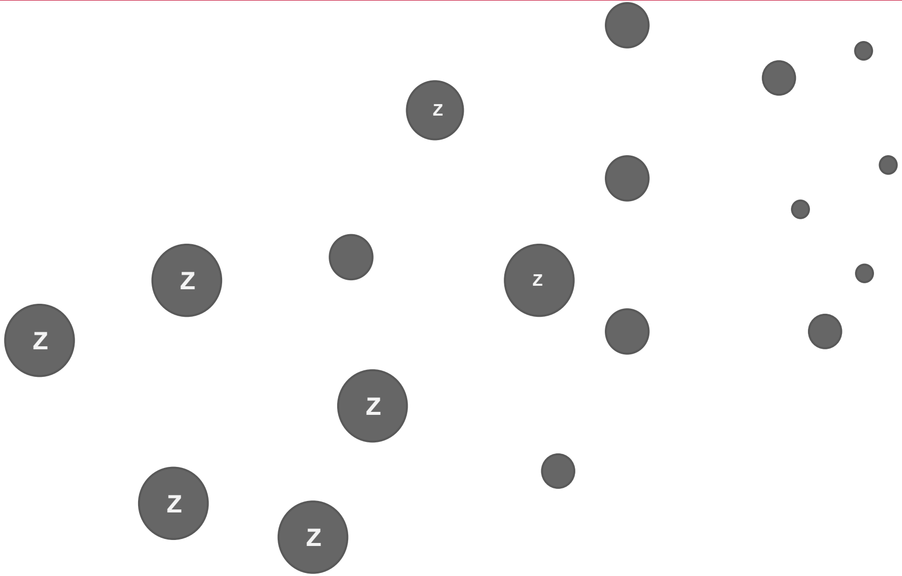
- **Decay in orbit**

Muonic atoms: what and how?

- Negative muons in matter:





Stopped negative muon:

- Atomic capture @ n ≅ 14
- At high n: Auger transitions. Kick out "*all*" of the electrons
- At lower n radiative transitions dominate: **Muonic X-rays**
- **Decay in orbit**

  or

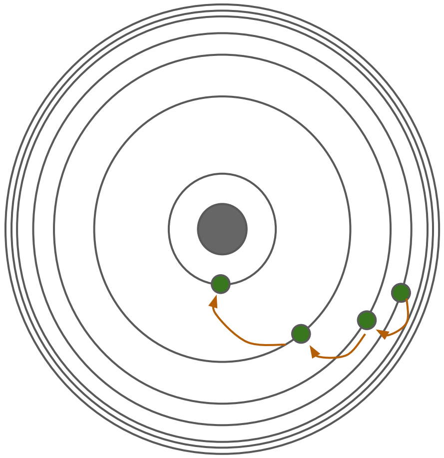
- **Muon capture + (very) excited nucleus**

Ordinary muon capture studies for the matrix elements in $\beta\beta$ decay

D. Zinatulina, V. Brudanin, V. Egorov, C. Petitjean, M. Shirchenko, J. Suhonen, and I. Yutlandov
Phys. Rev. C **99**, 024327 – Published 28 February 2019

Muonic atoms: what and how?

- Negative muons in matter



- Very much like the H atom, but:

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

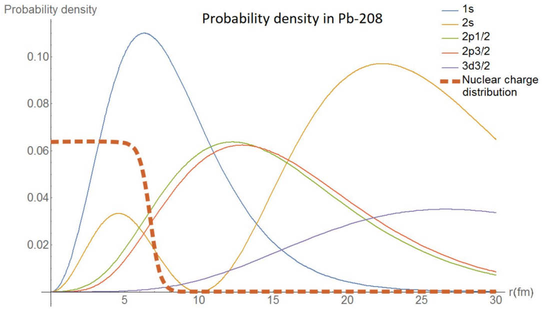
Bohr radii: $$r_n = \frac{n^2}{mc^2}\frac{\hbar c}{\alpha Z}$$

Energies 200 higher: 2 keV → few MeV range

Radii 200 times smaller: significant overlap with the nucleus

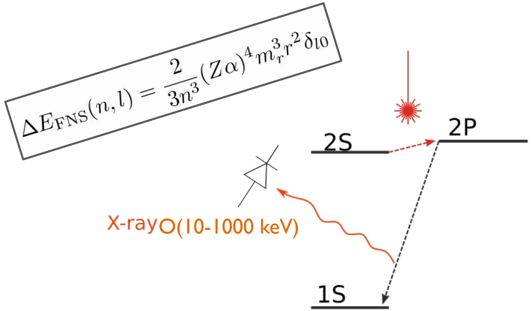
The muon lives partially inside the nucleus

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



What to do with muonic atoms transitions?

Modern approach with
low Z muonic atoms

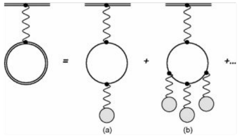


*P. Indelicato Phys. Rev. A 87, 022501

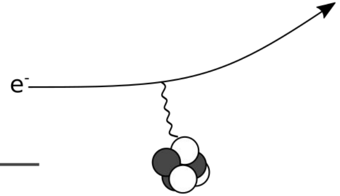
What to do with muonic atoms transitions?

Modern approach with
low Z muonic atoms

QED, R_∞, …

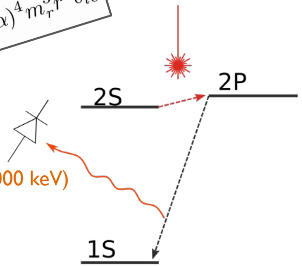


small



These people:

$$\Delta E_{\mathrm{FNS}}(n,l) = \frac{2}{3n^3}(Z\alpha)^4 m_r^3 r^2 \delta_{l0}$$

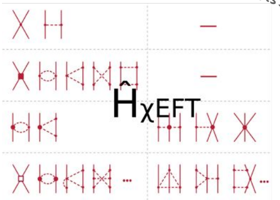


*Solve Dirac equation with all necessary QED contributions**

Most modern road. There are also Barrett moments, Rinker TPE, …

$<r^2>$

Or a more classical semi-empirical potential



\+ LECs

TPE *AKA nuclear polarization*

Your favorite way to tackle the few-body problem
HH, NCSM, GFMC, CC, …

Modern theory of nuclear forces
E. Epelbaum, H.-W. Hammer, and Ulf-G. Meißner
Rev. Mod. Phys. **81**, 1773 – Published 21 December 2009

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]

Ab initio no core shell model
Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

What is *ab initio* in nuclear theory?
A. Ekström[1*], C. Forssén[1], G. Hagen[2,3], G. R. Jansen[2,4], W. Jiang[1] and T. Papenbrock[2,3]

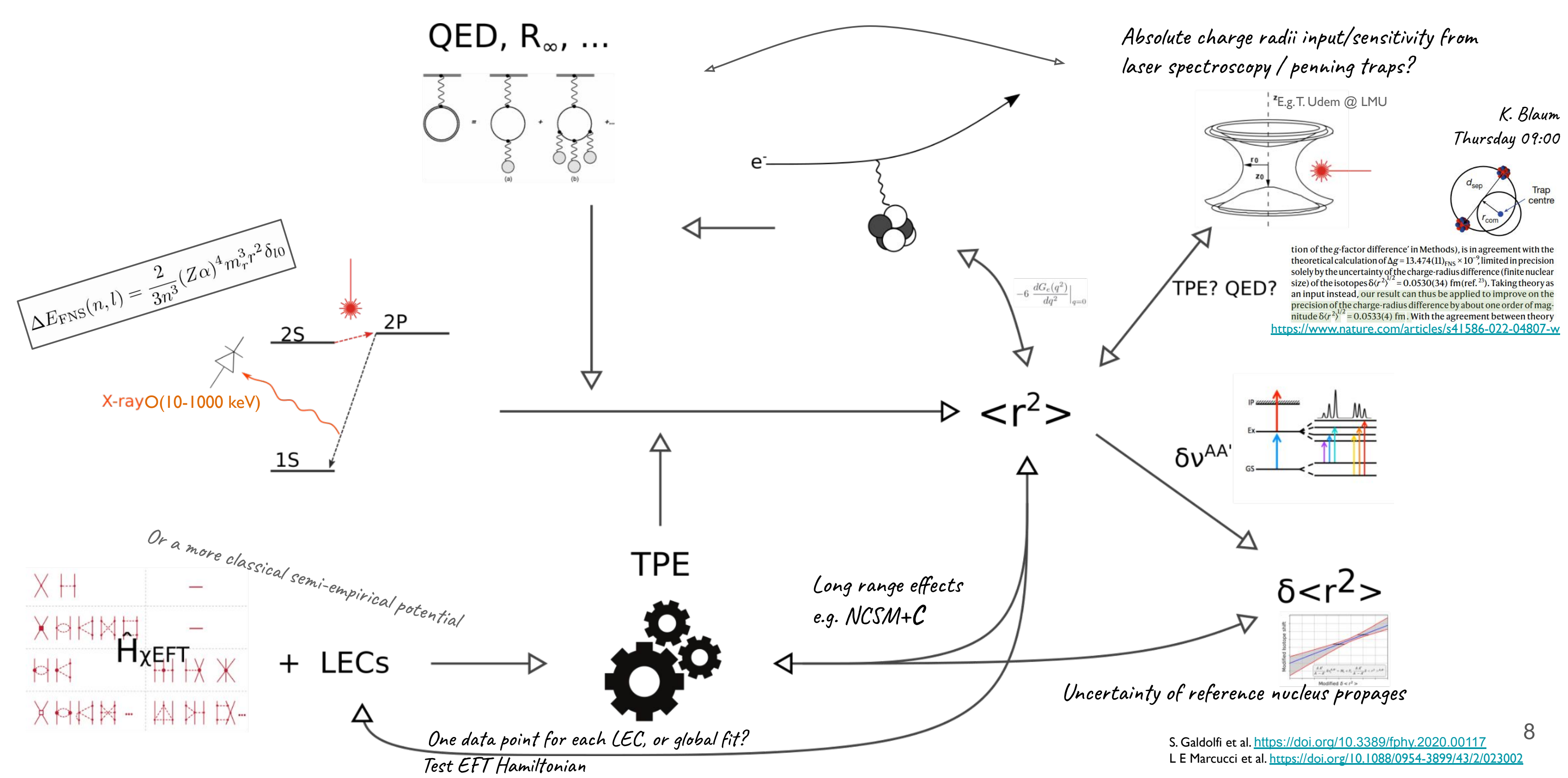
Trends of Neutron Skins and Radii of Mirror Nuclei from First Principles
S. J. Novario, D. Lonardoni, S. Gandolfi, and G. Hagen
Phys. Rev. Lett. **130**, 032501 – Published 19 January 2023

<u>Also heavy nuclei need input/help/insight/…</u>

Evidence Against Nuclear Polarization as Source of Fine-Structure Anomalies in Muonic Atoms
Igor A. Valuev, Gianluca Colò, Xavier Roca-Maza, Christoph H. Keitel, and Natalia S. Oreshkina
Phys. Rev. Lett. **128**, 203001 – Published 17 May 2022

*P. Indelicato Phys. Rev. A 87, 022501

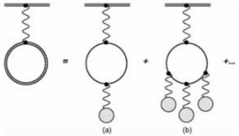
What to do with muonic atoms transitions?



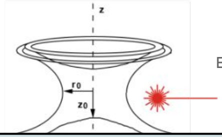
S. Galdolfi et al. https://doi.org/10.3389/fphy.2020.00117
L E Marcucci et al. https://doi.org/10.1088/0954-3899/43/2/023002

What to do with muonic atoms transitions?

QED, R_∞, ...



Absolute charge radii input/sensitivity from laser spectroscopy?



E.g. T. Udem @ LMU

e⁻

And stuff I forgot

$\Delta E_{FNS}(r$

Muons:

- Large NFS
- QED *easy*
- 2PE *hard/sensitive*

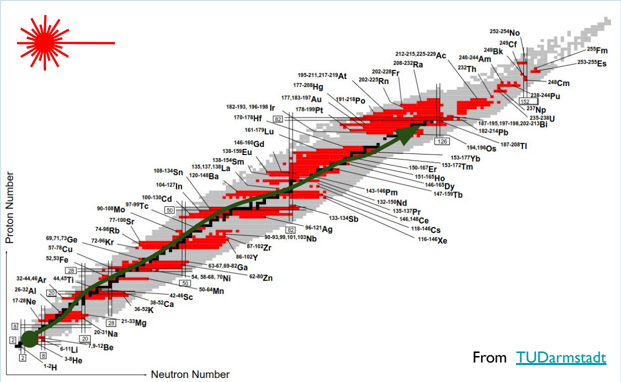
e-scattering:

- Shape *easy*
- Size *hard*

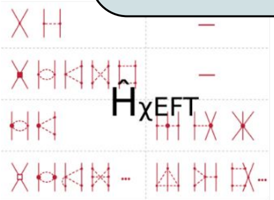
Laser spectroscopy (e-)

- Absolute NFS *hard*
- Very high precision on $\Delta\nu$

Walk in Z through muonic atom spectroscopy @ PSI



From TUDarmstadt

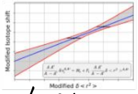


$\hat{H}_{\chi EFT}$ + LECs

Long range effects

e.g. NCSM+C

$\delta\langle r^2\rangle$



Uncertainty of reference nucleus propages

One data point for each LEC, or global fit?

Test EFT Hamiltonian

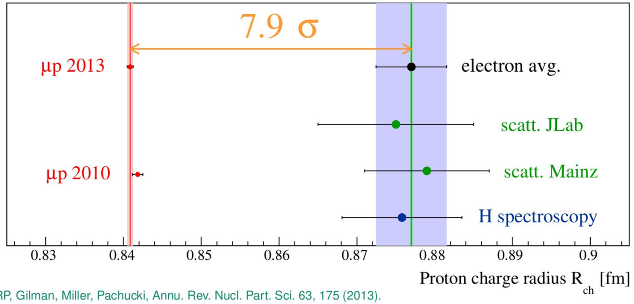
S. Galdolfi et al. https://doi.org/10.3389/fphy.2020.00117

L E Marcucci et al. https://doi.org/10.1088/0954-3899/43/2/023002

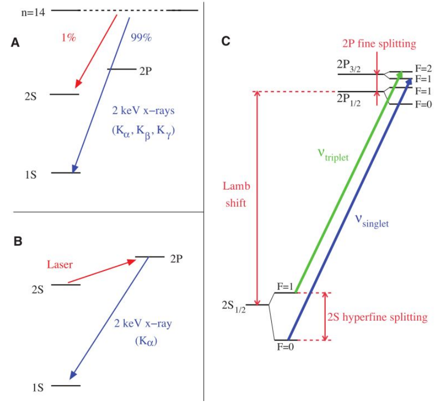
Laser spectroscopy on H, D, and He

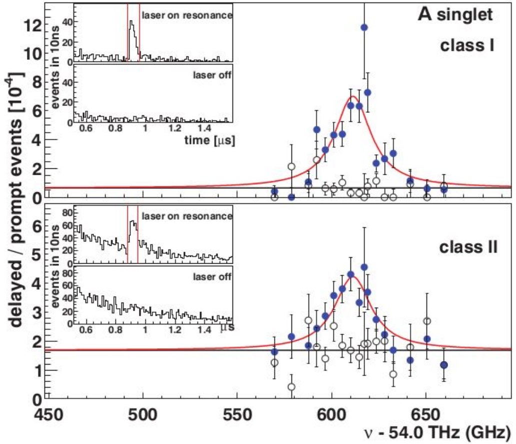
You might have heard about the proton size puzzle

- ❑ Muons ≠ Electrons?
- ❑ TPE? (nuclear polarization)
- ❑ Vacuum polarization?
- ❑ Rydberg constant wrong?



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).





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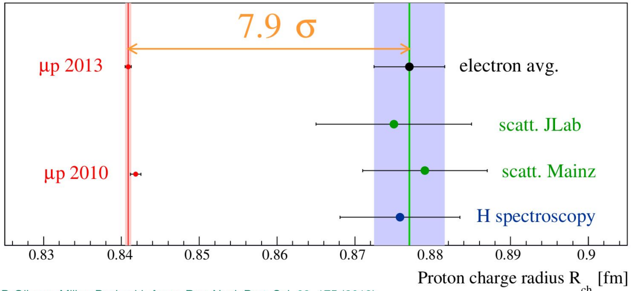
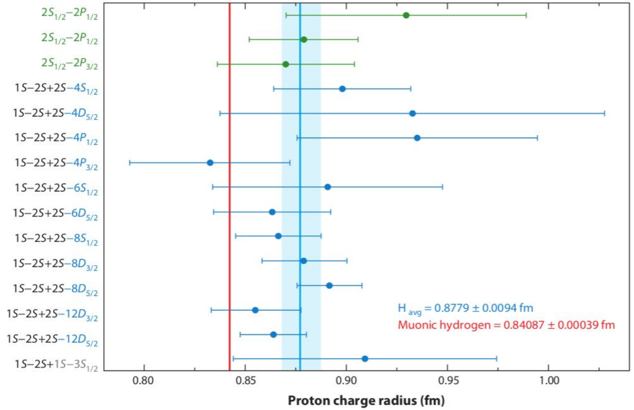


RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

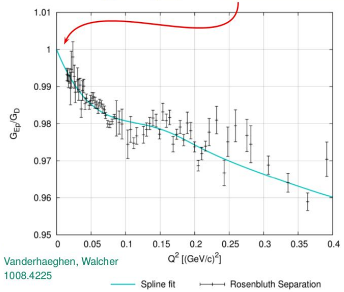
Not that simple →

From https://doi.org/10.1146/annurev-nucl-102212-170627



Electron scattering:

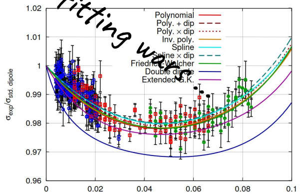
$$\langle r_p^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \quad \Rightarrow \quad \text{slope of } G_E \text{ at } Q^2 = 0$$



Vanderhaeghen, Walcher
1008.4225

Yes, it is the same thing:
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.99.035202

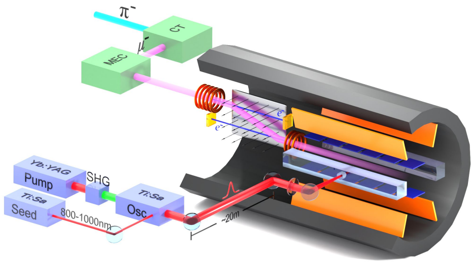
The fitting ways



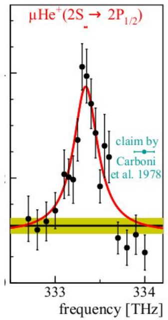
Laser spectroscopy on H, D, and He

Tremendous progress in

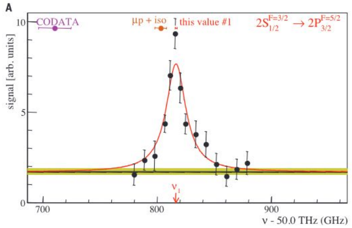
- ❏ e-scattering
- ❏ H spectroscopy
- ❏ Muonic atom laser spectroscopy
- ❏ ab-initio nuclear theory
- ❏ BSQED of exotic atoms

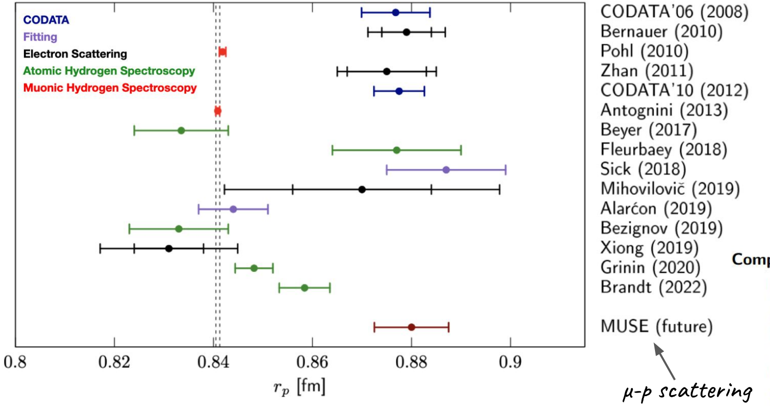


The CREMA collaboration also measured the $\langle r^2 \rangle$ of the deuteron, helium, and ^{3}He.
https://doi.org/10.1126/science.aaf2468
https://arxiv.org/abs/2305.11679
https://doi.org/10.1038/s41586-021-03183-1



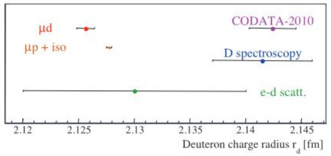
The proton and deuteron charge radius are from muonic atoms spectroscopy are now CODATA fundamental constants





μ-p scattering

From Dr. Tigran Armand Rostomyan (MUSE) @ https://indico.him.uni-mainz.de/event/172/



Comprehensive theory of the Lamb shift in light muonic atoms

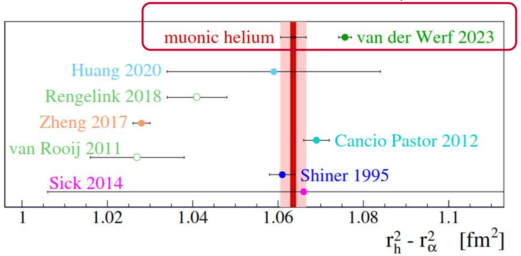
K. Pachucki,[1] V. Lensky,[2] F. Hagelstein,[2,3] S. S. Li Muli,[2] S. Bacca,[2,4] and R. Pohl[5]
[1] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[2] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*
[3] *Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[4] *Helmholtz-Institut Mainz, Johannes Gutenberg Universität Mainz, 55099 Mainz, Germany*
[5] *Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

(Dated: May 19, 2023)

We present a comprehensive theory of the Lamb shift in light muonic atoms, such as μH, μD, μ^3He$^+$, and μ^4He$^+$, with all quantum electrodynamic corrections included at the precision level constrained by the uncertainty of nuclear structure effects. This analysis can be used in the global adjustment of fundamental constants and in the determination of nuclear charge radii. Further improvements in the understanding of electromagnetic interactions of light nuclei will allow for a promising test of fundamental interactions by comparison with "normal" atomic spectroscopy, in particular, with H-D and ^{3}He-^{4}He isotope shifts.

https://arxiv.org/abs/2212.13782

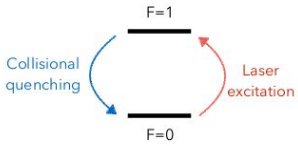
New tension

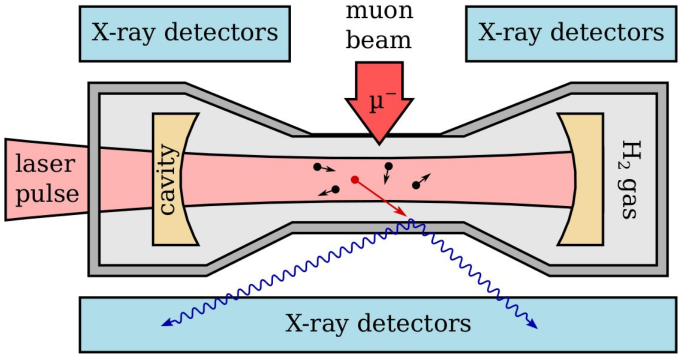


Laser spectroscopy on H, D, and He

Future: ground state hyperfine splitting in muonic hydrogen (and helium) *HyperMu* https://www.psi.ch/en/ltp/hypermu

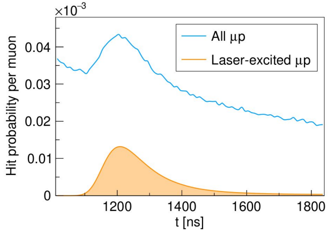
- ❑ Ground state excitation
- ❑ No spontaneous X-ray emission

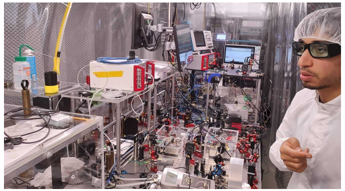




- ➢ Stop muon beam in 1 mm H2 gas at 22K
- ➢ Form F=0 1S μH
- ➢ Laser pulse: μH(F=0)+γ→ μH(F=1)
- ➢ De-excitation: μH(F=1)+H_2→ μH(F=0)+H_2+E_{kin}
- ➢ μH + Au (wall) → H + μAu + X-rays (2-6 MeV)

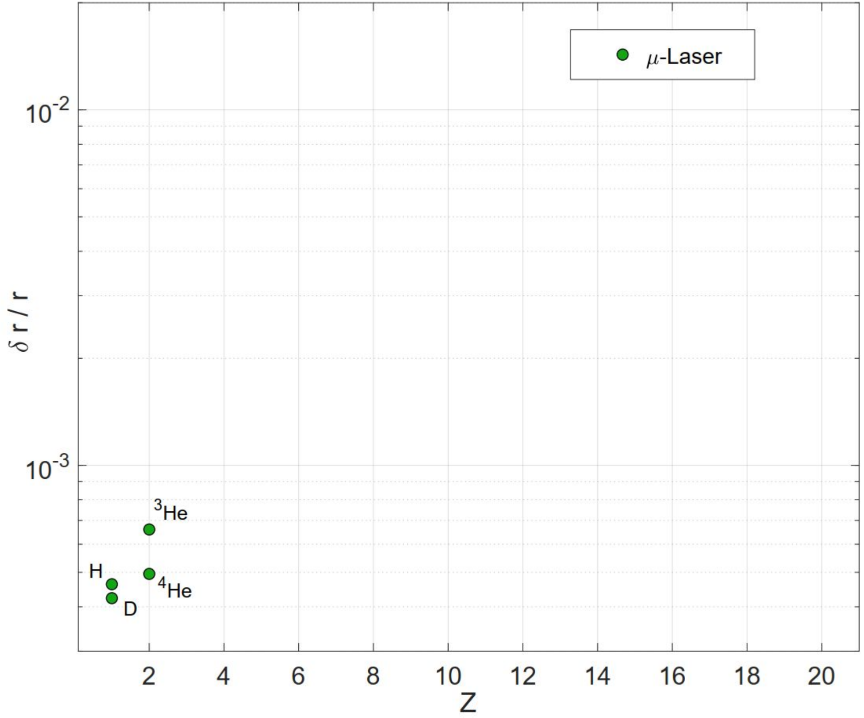
Detector system tested, excitation and detection scheme simulated, la
system almost ready





Charge radii from X-ray spectroscopy

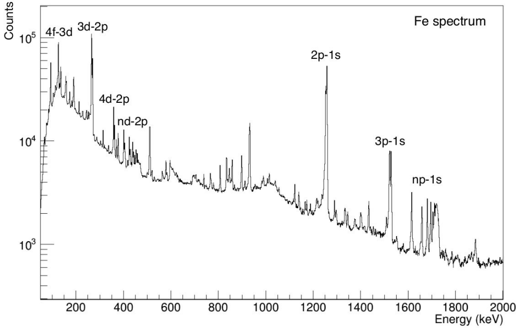
- Precision muonic atom data for Z=1,2 by the **CREMA collaboration**

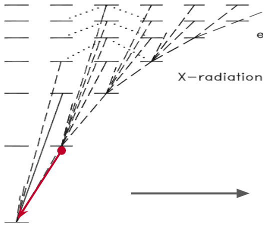


Charge radii from X-ray spectroscopy

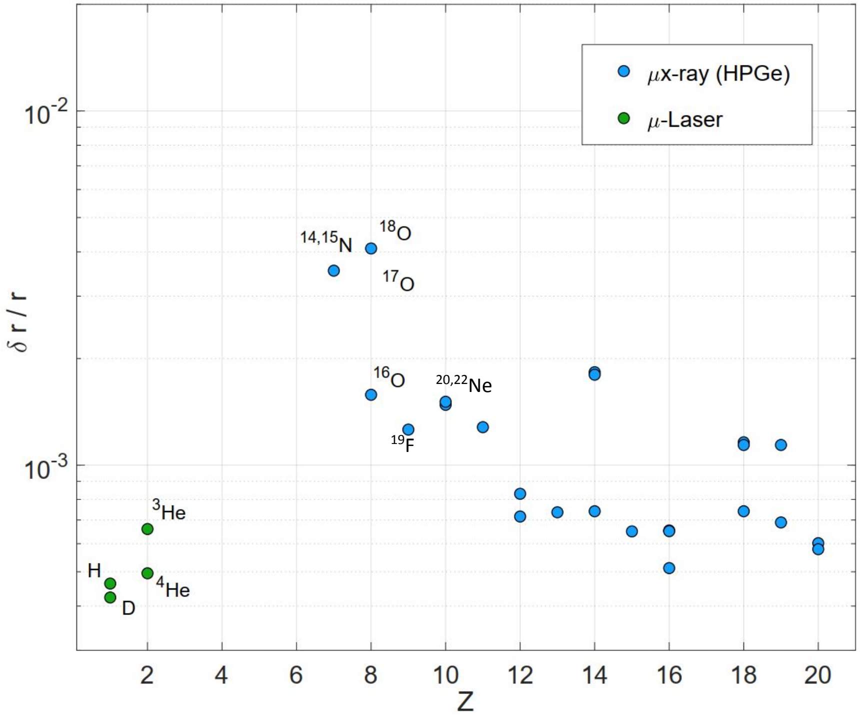
- Precision muonic atom data for Z=1,2 by the CREMA collaboration
- Most of the stable nuclei have been measured with HPGe
  - Z>10 limited by TPE corrections / Nuclear polarization
  - Z<10 limited by HPGe resolution

HPGe detector





Energy of 2P1S transition to < 10^{-4}



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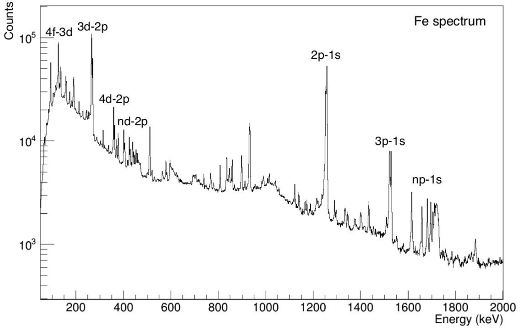
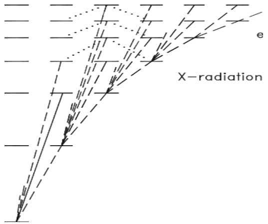


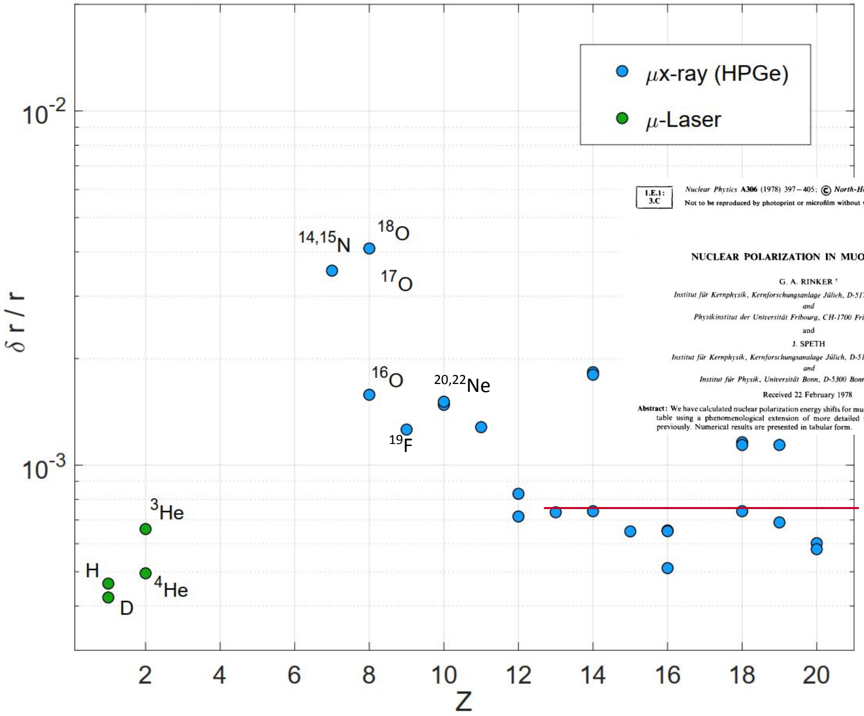


Fricke and Heilig *recipe*
https://doi.org/10.1006/adnd.1995.1007

ATOMIC DATA AND NUCLEAR DATA TABLES **60,** 177–285 (1995)

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]



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

NUCLEAR POLARIZATION IN MUONIC ATOMS

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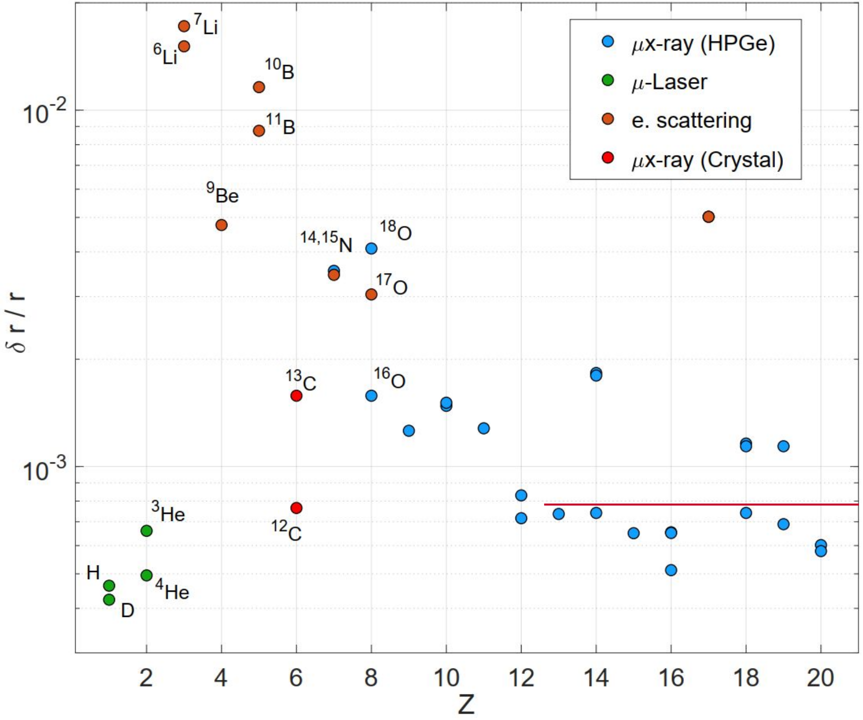
Received 22 February 1978

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.

Charge radii from X-ray spectroscopy

- Precision muonic atom data for Z=1,2 by the CREMA collaboration
- Most of the stable nuclei have been measured
  - Z>10 limited by TPE corrections / Nuclear polarization
  - Z<10 limited by HPGe resolution
- ~1% precise radii from e-scattering to fill the gap



I. Angeli / Atomic Data and Nuclear Data Tables 87 (2004) 185–206 195

Table 1
Nuclear rms charge radii. (For the neutron the entry is $\langle r^2 \rangle$ (fm^2) and for the proton and deuteron, see Section 2.) See page 194 for Explanation of Tables

Z	El	A	R (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
0	n	1	−0.1149	.0024	
1	H	1	0.8791	.0088	
		2	2.1402	.0091	
		3	1.7591	.0356	
2	He	3	1.9448	.0137	
		4	1.6757	.0026	
3	Li	6	2.5385	.0267	
		7	2.4312	.0281	
4	Be	9	2.5180	.0114	
5	B	10	2.4278	.0492	
		11	2.4059	.0291	
6	C	12	2.4703	.0022	
		13	2.4614	.0033	
		14	2.5037	.0081	
7	N	14	2.5579	.0068	
		15	2.6061	.0074	
8	O	16	2.7013	.0055	
		17	2.6953	.0073	
		18	2.7745	.0058	
9	F	19	2.8976	.0024	
10	Ne	17	3.0428	.0188	.0135
		18	2.9719	.0084	.0048
		19	3.0081	.0053	.0033
		20	3.0053	.0021	
		21	2.9672	.0026	
		22	2.9541	.0019	
		23	2.9126	.0105	.0057
		24	2.9032	.0104	.0044
		25	2.9305	.0133	.0069
		26	2.9268	.0153	.0081
		28	2.9632	.0245	.0159

Table 1 (*continued*)

Z	El	A	R (fm)
		37	3.3901
		38	3.4020
		39	3.4085
		40	3.4269
		46	3.436
19	K	38	3.426
		39	3.434
		40	3.437
		41	3.451
		42	3.451
		43	3.455
		44	3.455
		45	3.459
		46	3.455
		47	3.452
20	Ca	**40**	3.476
		41	3.476
		42	3.506
		43	3.492
		44	3.515
		45	3.493
		46	3.492
		47	3.477
		48	3.473
		50	3.514
21	Sc	45	3.544
22	Ti	46	3.605
		47	3.594
		48	3.591
		49	3.573
		50	3.570
23	V	51	3.599
24	Cr	50	3.660
		52	3.642

Fricke and Heilig *recipe*
https://doi.org/10.1006/adnd.1995.100

ATOMIC DATA AND NUCLEAR DATA TABLES **60**, 177–285 (1995)

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.
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Angeli recipe https://doi.org/10.1016/j.adt.2004.04.002

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  - Z>10 limited by TPE corrections / Nuclear polarization
  - Z<10 limited by HPGe resolution
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		45	3.45
		46	3.45
		47	3.45
23	V	51	3.59
24	Cr	50	3.66
		52	3.64

Fricke and Heilig *recipe*
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ATOMIC DATA AND NUCLEAR DATA TABLES 60, 177–285 (1995)

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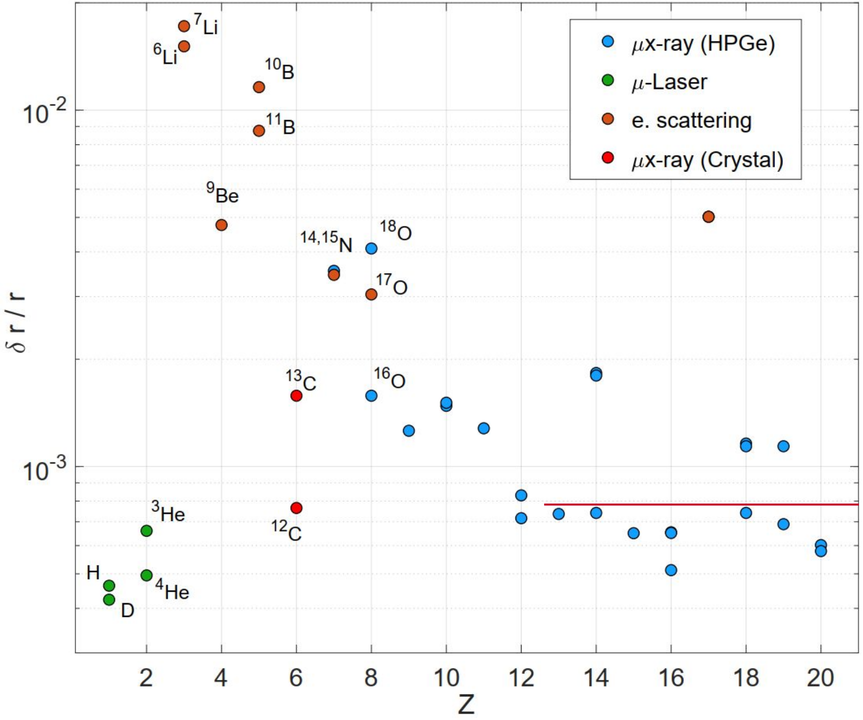
									3.8656 (26;33)	[Fr92]
	4			20					3.8163 (21;31)	[Fr92]
^{22}Ne	207.512 4	207.512	0.018	2.8706 11	2.954	0.0330	2.0439	-0.522	3.7986 (21;31)	[Fr92]

10^{-3} correction uncertainties on few 10^{-4} δr/r values quotes

- Barret moment → charge radius
- Charge distribution
- Nuclear polarization floor
  (and e.g. no nucleon TPE)

Angeli recipe https://doi.org/10.1016/j.adt.2004.04.002



Charge radii from X-ray spectroscopy

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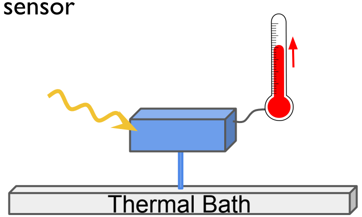
- ❑ Most of the stable nuclei have been measured
  - ❑ Z>10 limited by TPE corrections / Nuclear polarization
  - ❑ Z<10 limited by HPGe resolution
- ❑ ~1% precise radii from e-scattering to fill the gap
- ❑ Need for a 1-10 ppm precise energy determination if 2p1s transitions.

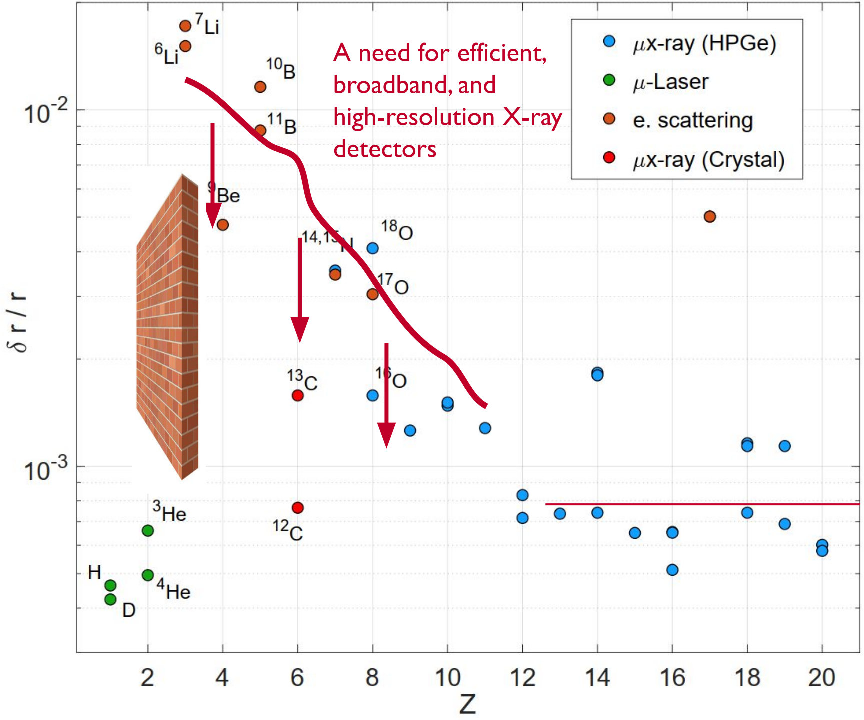
Limitations of solid state X-ray detectors:

- ❑ $\sigma_Q = \sqrt{F N_Q}$
- ❑ 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





Precision X-ray spectroscopy

Unit of heat ≪ Unit of Ionization

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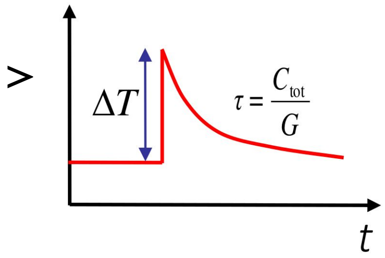
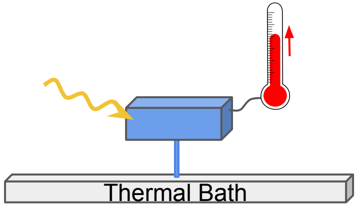
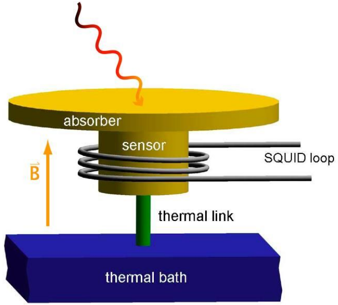
- ❏ A very good temperature sensor

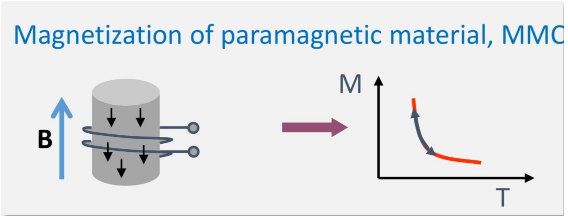
Metallic Magnetic Calorimeters → Unit of spin flip ≪ Unit of Ionization

- ❏ Paramagnetic Au:Er Alloy
- ❏ $\Delta\Phi_S \cong \delta M/\delta T \, \Delta T = \delta M/\delta T \times E_{deposited} / C_{tot}$







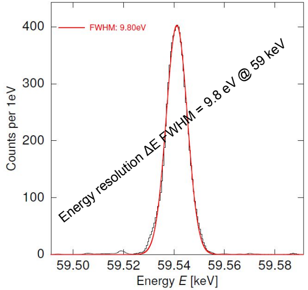


A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63
A.Fleischmann et al., AIP Conf. Proc. 1185 (2009) 571

Precision X-ray spectroscopy

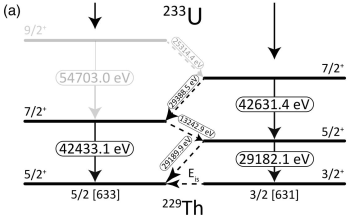
MMC detectors developed at the Kirchhoff Institut für Physik ([KIP]) in Heidelberg.

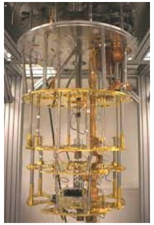
- ❏ From innovation to application with the maXs-* sensors
- ❏ maxS-30 sensor with 8x8 0.5 mm pixels, efficient up to ~ 60 keV
- ❏ Resolving power up to 6000

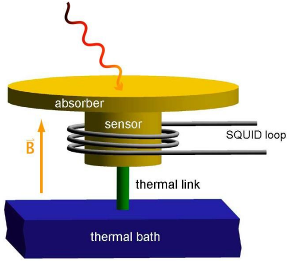


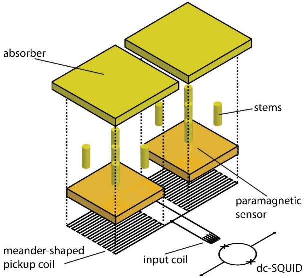
Used for a wide variety of (X-ray) spectroscopy experiments

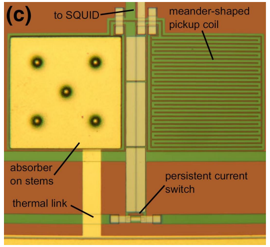
- ❏ IAXO arXiv:2010.15348
- ❏ ECHO arXiv:2111.09945
- ❏ Highly charged Ions https://doi.org/10.3390/atoms6040059
- ❏ Th isomer measurement arXiv:2005.13340

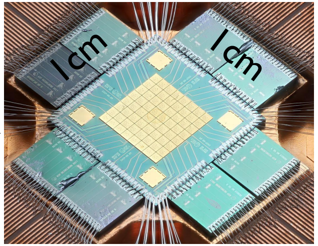












A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63
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Precision X-ray spectroscopy

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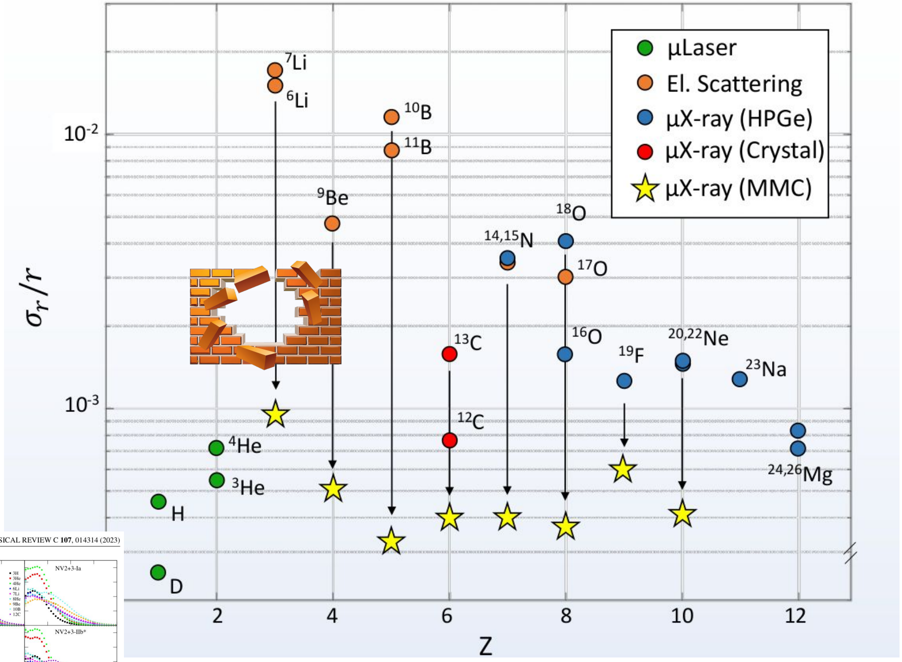
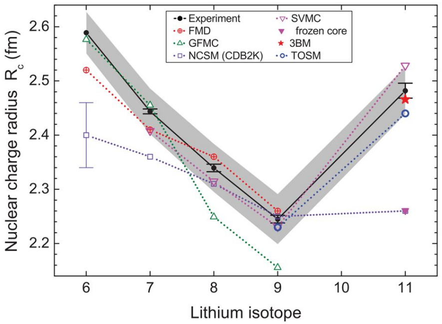
- ❑ Most of the stable nuclei have been measured
  - ❑ Z>10 limited by TPE corrections / Nuclear polarization
  - ❑ Z<10 limited by HPGe resolution
- ❑ ~1% precise radii from e-scattering to fill the gap
- ❑ 1-10 ppm precise energy determination if 2p1s transitions of lithium, beryllium, boron, … to determine $<r^2>$ to 10^{-3} **QUARTET Collaboration**

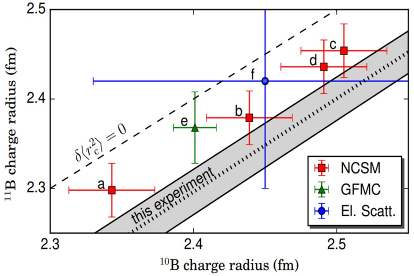
Isotope	Charge radius	2P1S energy	Sensitivity	2PE correction
^{6}Li	2.59(4) fm	18.7 keV	0.05 fm/eV	0.09 eV
^{7}Li	2.44(4) fm	18.7 keV	0.05 fm/eV	0.18 eV
^{9}Be	2.519(12) fm	33.4 keV	0.015 fm/eV	TBD
^{10}B	2.427(50) fm	52.2 keV	0.007 fm/eV	TBD
^{11}B	2.406(29) fm	52.2 keV	0.007 fm/eV	TBD

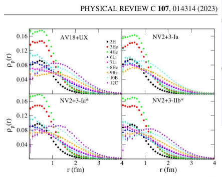
Motivation:

- ❑ Reference radii for laser spectroscopy
- ❑ Benchmark for ab-initio calculations
- ❑ Compare pairs of mirror nuclei radii
- ❑ …

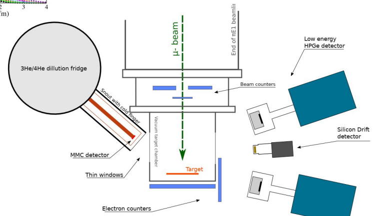


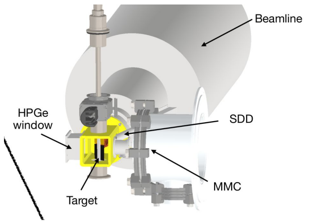






First 10 day beam time in October 2023





Radioactive targets

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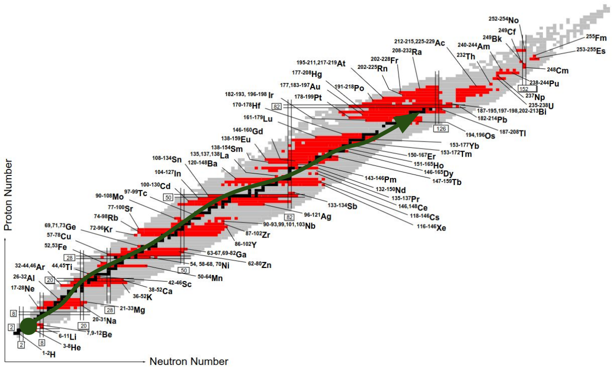
- What about radioactive nuclei? **muX Collaboration**
  - Reference for king plot analysis / mass & field shifts
  - Deformed heavy nuclei. E.g. ^{226}Ra is a candidate for APV experiments. Radius needed as an input.



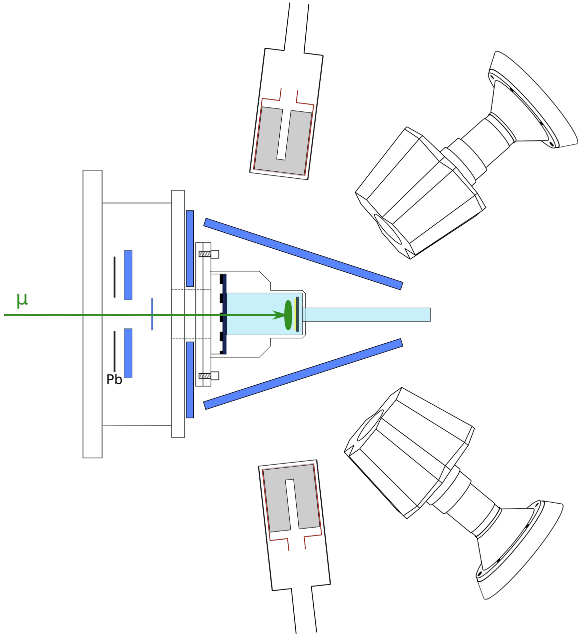
<u>Challenge:</u>

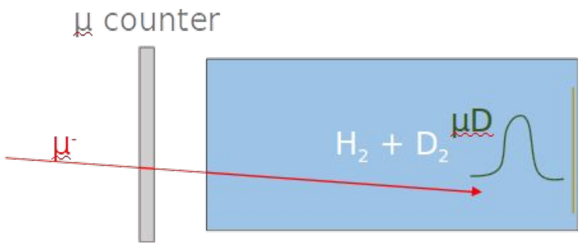
μ- beam has a momentum of 10-40 MeV/c, which needs O(mm) of material to stop the beam.

↕

Only micrograms of long lived isotopes allowed in the experimental area

Radioactive targets





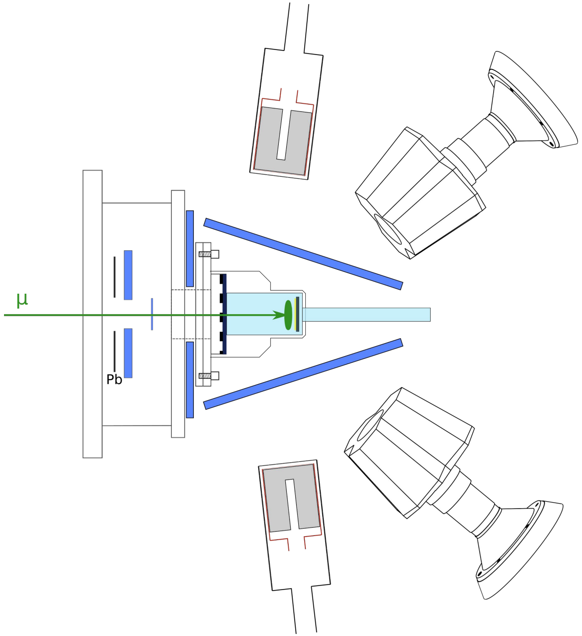
Stop 30 MeV/c muons in a small amount of material

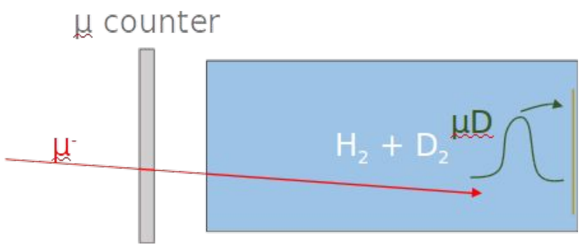
1. Stop in 100 Bar of H_2 + 0.25% - 1% of D_2
2. Transfer from μH to μD in ~100 ns + 45 eV of kinetic energy

So we have:

- μ-time → t=0
- Beam halo veto
- μ decay in orbit time
- X-ray time/energy/angle

Radioactive targets





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2. Transfer from μH to μD in ~100 ns + 45 eV of kinetic energy
3. μD moves freely through H2 gas at ca. 5 eV

So we have:

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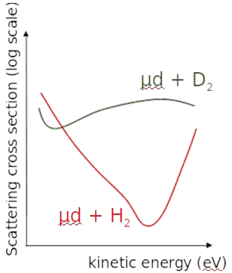
- Beam halo veto
- μ decay in orbit time
- X-ray time/energy/angle

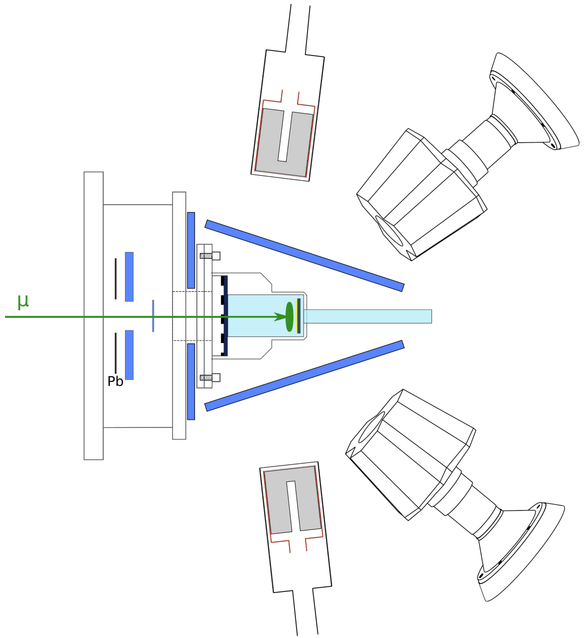


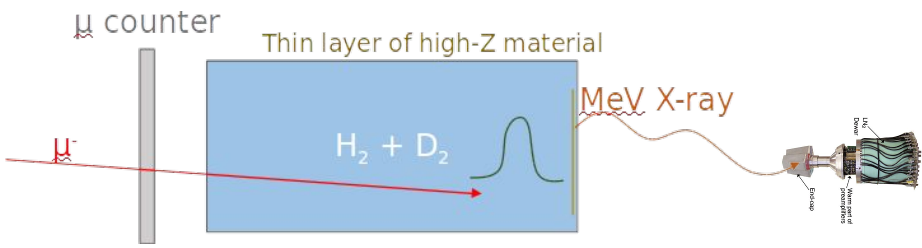
PHYSICAL REVIEW A **73**, 034501 (2006)

Ramsauer-Townsend effect in muonic atom scattering

F. Mulhauser,[1,*] A. Adamczak,[2,†] G. A. Beer,[3] V. M. Bystritsky,[4] M. Filipowicz,[5] M. C. Fujiwara,[6] T. M. Huber,[7] O. Huot,[1] R. Jacot-Guillarmod,[1,‡] P. Kammel,[8,*] S. K. Kim,[9] P. E. Knowles,[1] A. R. Kunselman,[10] G. M. Marshall,[6] A. Olin,[6] C. Petitjean,[11] T. A. Porcelli,[6] L. A. Schaller,[1] V. A. Stolupin,[4] J. Woźniak,[12] and J. Zmeskal[13]
(TRIUMF Muonic Hydrogen Collaboration)

Radioactive targets





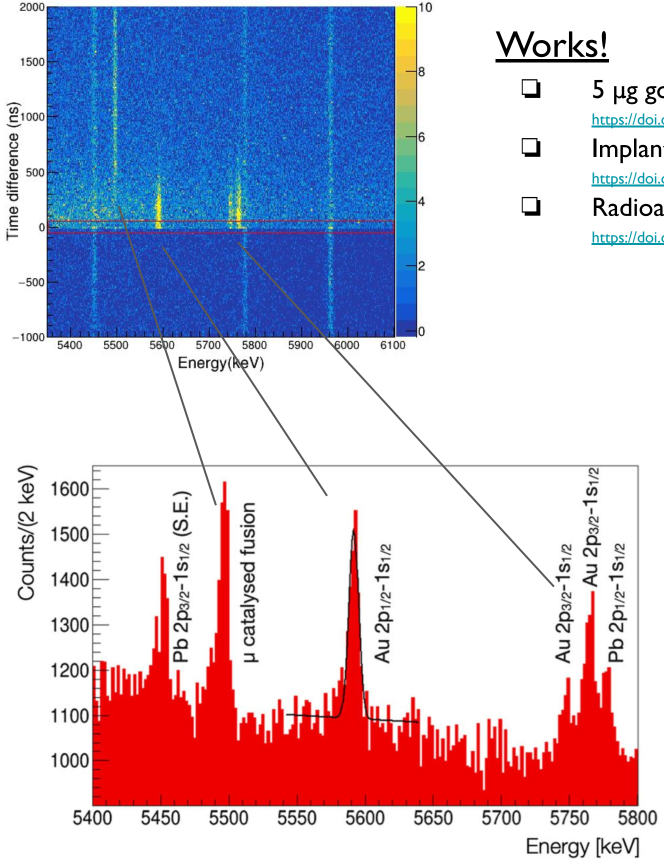
Stop 30 MeV/c muons in a small amount of material

1. Stop in 100 Bar of H_2 + 0.25% - 1% of D_2
2. Transfer from µH to µD in ~100 ns + 45 eV of kinetic energy
3. µD moves freely through H2 gas at ca. 5 eV
4. Upon hitting the chamber walls: µD → µZ transfer

So we have:

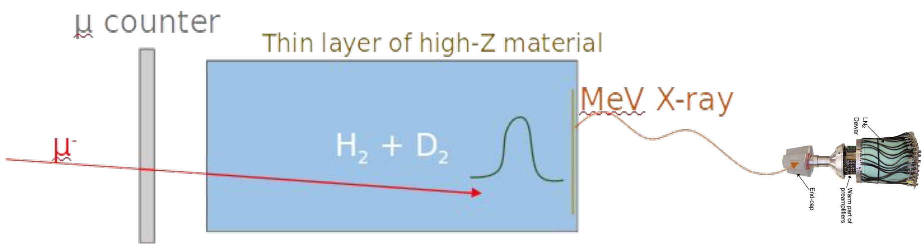
- µ-time → t=0
- Beam halo veto
- µ decay in orbit time
- X-ray time/energy/angle

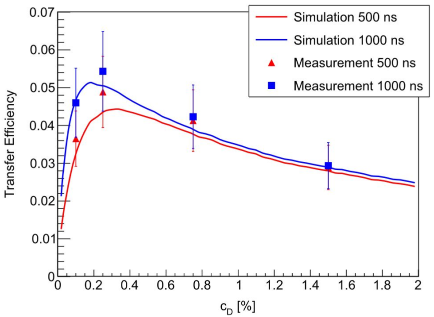
Radioactive targets

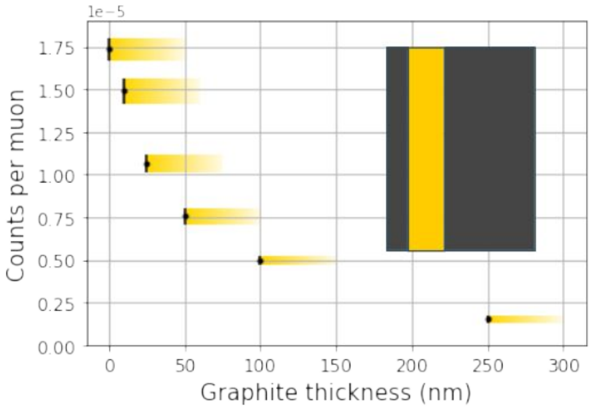


Works!

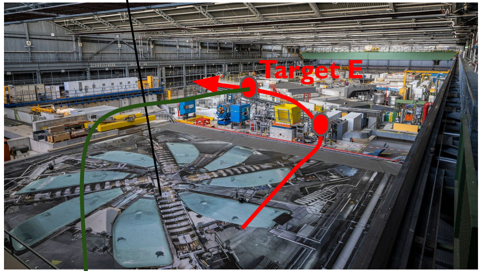
- 5 µg gold plating
  https://doi.org/10.1140/epja/s10050-023-00930-y
- Implanted potassium
  https://doi.org/10.1016/j.nimb.2023.05.036
- Radioactive 248Cm
  https://doi.org/10.3929/ethz-b-000612640







Radioactive targets



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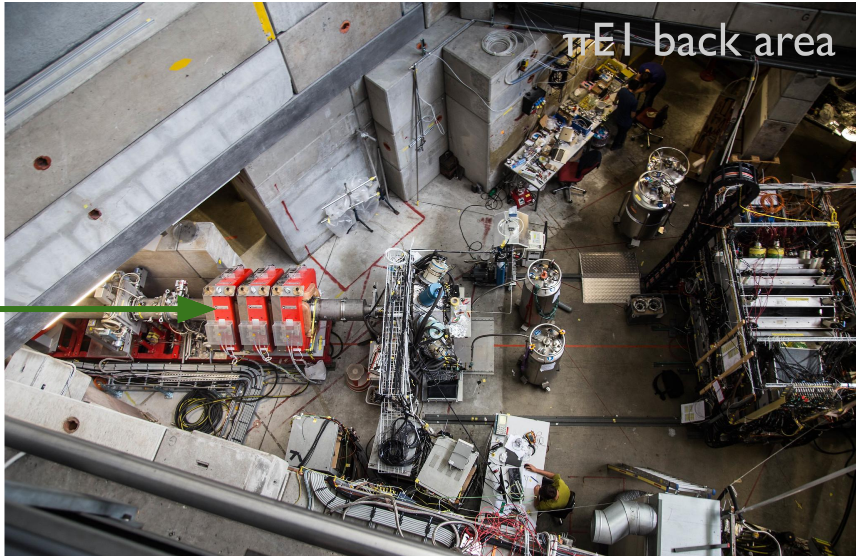
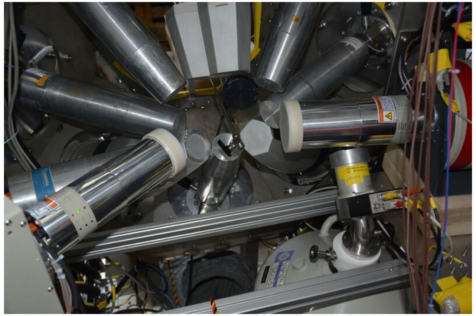
- Radioactive 248Cm
  https://doi.org/10.3929/ethz-b-000612640

10-100 kHz μ^- @ 20-40 MeV/c



Radioactive targets

2017/8: loan pool detectors + …



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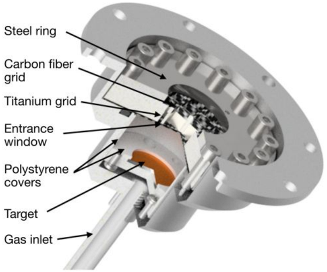
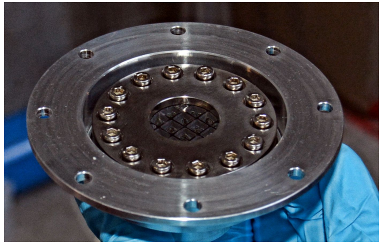
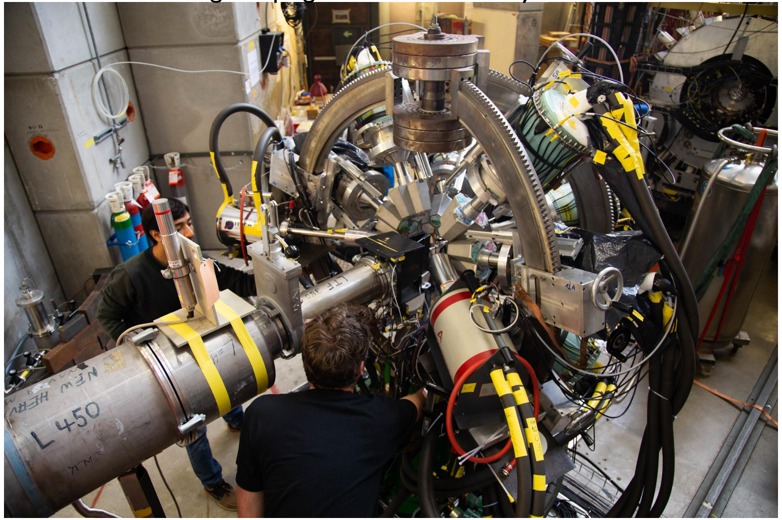
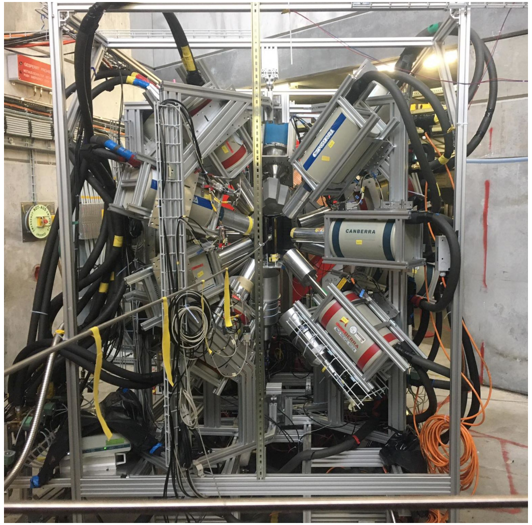




2019: 7 weeks long campaign with Miniball array + …



2021/2022/2023: muX + MIXE + MiniBall + TiGRESS + KULeuven + ….



HPGe detectors from different collaborating institutes, pooling muonic X-ray measurements:

- muX (this talk)
- Muon Capture for $\beta\beta 0\nu$
- Elemental analysis MIXE

Radioactive targets

Micro-gram target program:

- ❑ 5 µg gold plating
  https://doi.org/10.1140/epja/s10050-023-00930-y
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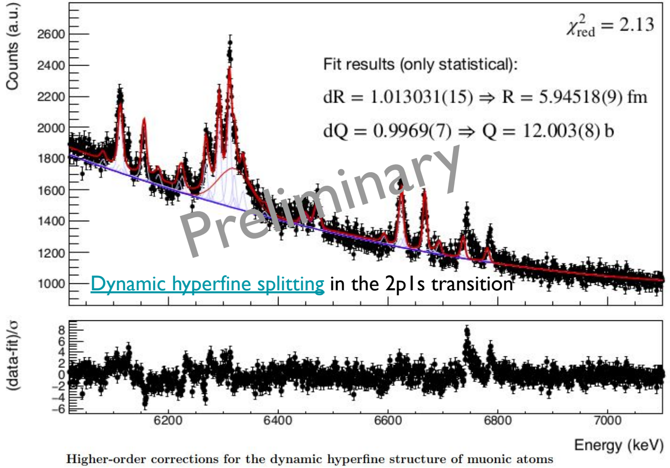
Done:

248Cm muonic X-ray spectrum



Dynamic hyperfine splitting in the 2p1s transition

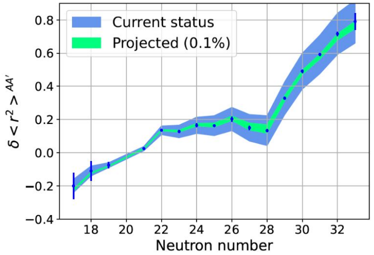
Higher-order corrections for the dynamic hyperfine structure of muonic atoms

Niklas Michel* and Natalia S. Oreshkina
Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany
(Dated: September 19, 2018)

Upcoming

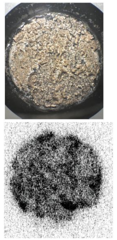
1. Reference radii T.E. Cocolios et al.
   Get precise set of 3 reference radii, extract Mass & Field Shift
   - Add ^{40}K to $^{39/41}$K
   - Add ^{108m}Ag to $^{107/109}$Ag

   Week 40 at PSI
   IS672 P552 (implantation)



2. Measure $<r^2>$ of 226Ra
   Primary goal of PSI proposal R-16-01.1
   First campaign in 2019 & 2022. Making Radium targets is hard …

15 µg of ^{248}Cm



4 µg of ^{226}Ra

- Palladium contamination
- Organic deposition
- clumping

$<r^2>$ as INPUT

$$E1_{PNC} = K_r Z^3 Q_w$$

Hyperfine Interact (2011) 199:9–19
DOI 10.1007/s10751-011-0296-6

Atomic parity violation in a single trapped radium ion

O. O. Versolato · L. W. Wansbeek · G. S. Giri · J. E. van den Berg · D. J. van der Hoek · K. Jungmann · W. L. Kruithof · C. J. G. Onderwater · B. K. Sahoo · B. Santra · P. D. Shidling · R. G. E. Timmermans · L. Willmann · H. W. Wilschut

Radioactive targets

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- ❑ Radioactive 248Cm
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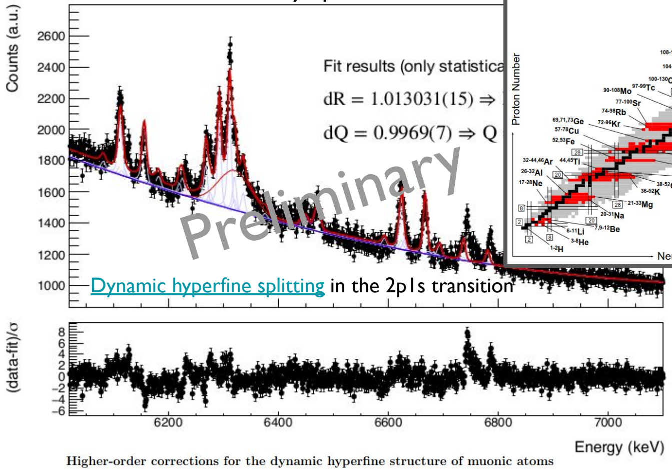
Done:

248Cm muonic X-ray spectrum



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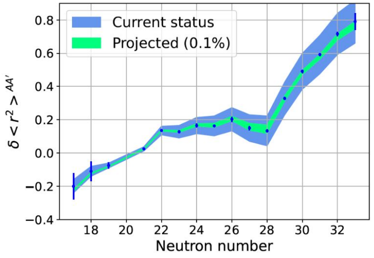
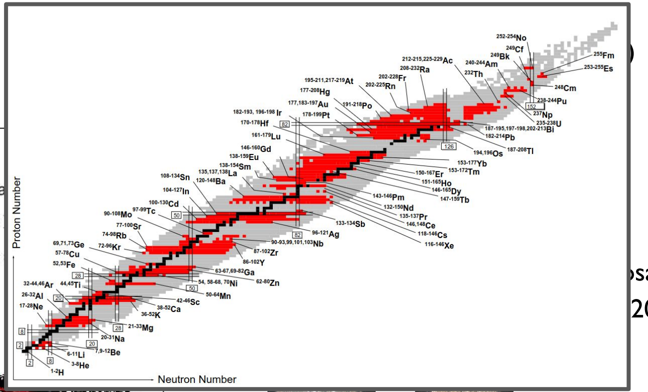
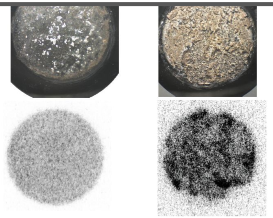




)

sal R-16-01.1

2022. Making Radium targets is hard …

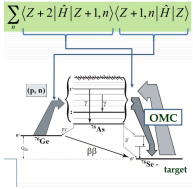


15 µg of ^{248}Cm   4 µg of ^{226}Ra

- Palladium contamination
- Organic deposition
- clumping

Muonic atoms are great!

- ❑ Ultimate precision for hydrogen and helium isotopes with laser spectroscopy. **CREMA collaboration**
- ❑ New project to measure charge radii of lithium, beryllium, boron, .. to 10^{-3} with metallic magnetic calorimeters the **Quartet Collaboration**
- ❑ Coordinated theory effort for light muonic atoms **uASTI**
- ❑ Charge radii measurements of Long lived radioactive isotopes with **muX**
- ❑ I have not talked about:
  - ❑ Quadrupole moments of $^{185/187}$Re
    https://link.aps.org/doi/10.1103/PhysRevC.101.054313
  - ❑ High-Field BSQED tests
    https://link.aps.org/doi/10.1103/PhysRevLett.126.173001
  - ❑ Muon Capture to highly excited states to supported excited for □□0ν **MONUMENT**
  - ❑ Muon capture on p & d to access nucleon/nucleus axial currents with **MuCap** and **MuSun**
    https://doi.org/10.1103/PhysRevLett.110.012504
  - ❑ …



Measuring the α-particle charge radius with muonic helium-4 ions

Julian J. Krauth, Karsten Schuhmann, Marwan Abdou Ahmed, Fernando D. Amaro, Pedro Amaro, François Biraben, Tzu-Ling Chen, Daniel S. Covita, Andreas J. Dax, Marc Diepold, Luis M. P. Fernandes, Beatrice Franke, Sandrine Galtier, Andrea L. Gouvea, Johannes Götzfried, Thomas Graf, Theodor W. Hänsch, Jens Hartmann, Malte Hildebrandt, Paul Indelicato, Lucile Julien, Klaus Kirch, Andreas Knecht, Yi-Wei Liu, Jorge Machado, Cristina M. B. Monteiro, Françoise Mulhauser, Boris Naar, Tobias Nebel, François Nez, Joaquim M. F. dos Santos, José Paulo Santos, Csilla I. Szabo, David Taqqu, João F. C. A. Veloso, Jan Vogelsang, Andreas Voss, Birgit Weichelt, Randolf Pohl, Aldo Antognini & Franz Kottmann

— Show fewer authors

Nature **589**, 527–531 (2021) | Cite this article

LETTER OF INTENT

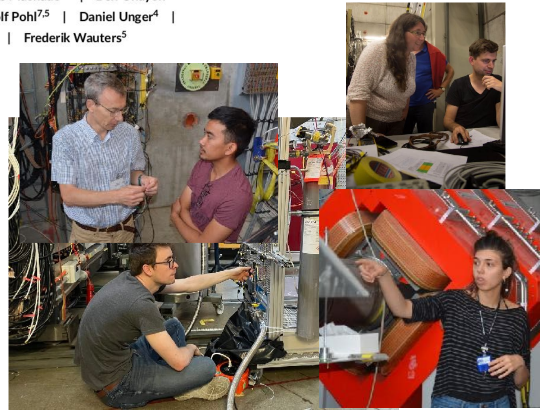
QUARTET
QUAntum inteRacTions with Exotic aToms

Andreas Fleischmann[4] | Loredana Gastaldo[4] | César Godinho[3,8] | Paul Indelicato[3] | Klaus Kirch[1,6] | Andreas Knecht[6] | Jorge Machado[8] | Ben Ohayon[1,2] | Nancy Paul[3] | Randolf Pohl[7,5] | Daniel Unger[4] | Katharina von Schoeler[1,6] | Frederik Wauters[5]

BVR 54: Progress Report R-16-01.1

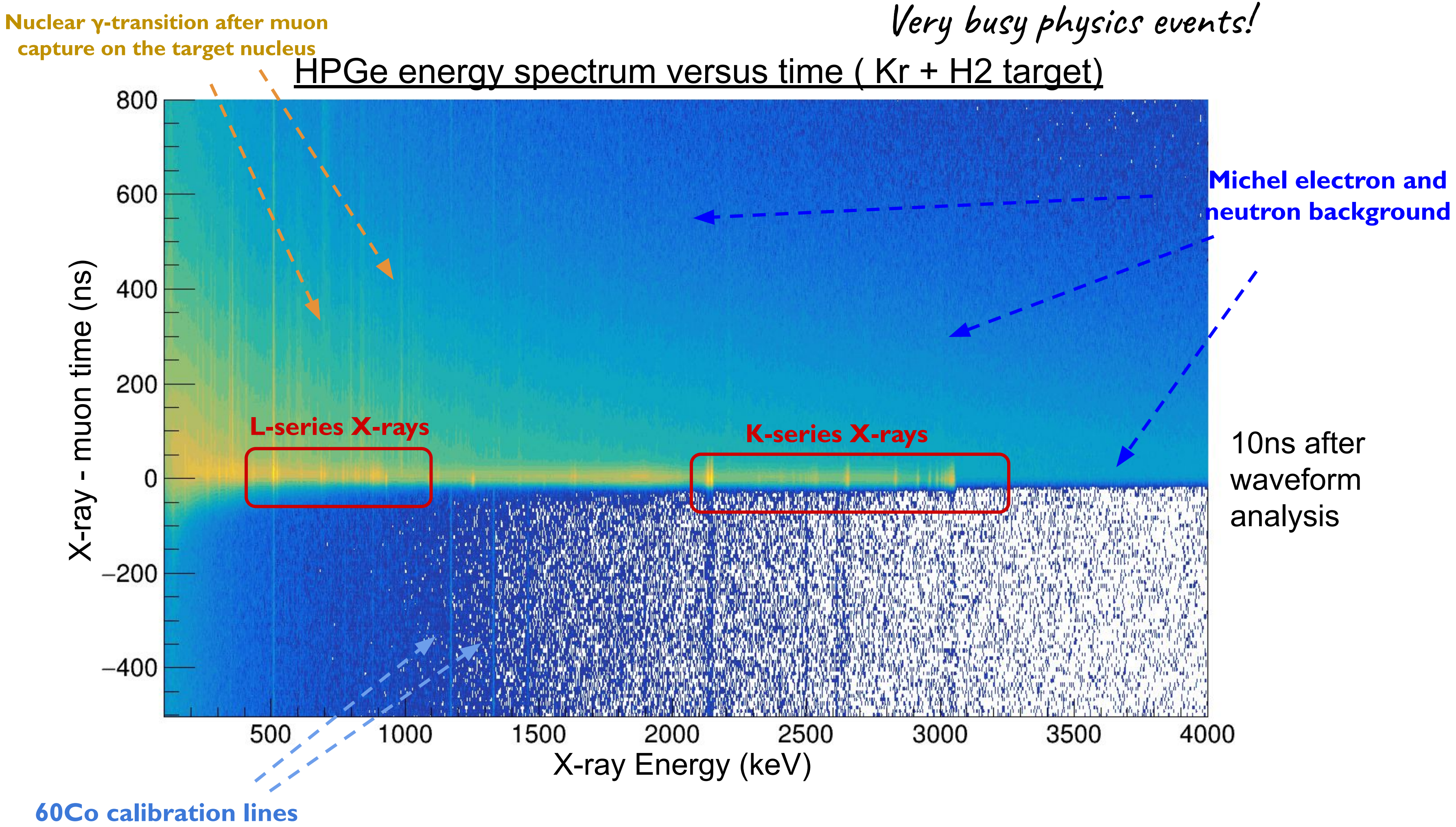
Measurement of the charge radius of radium

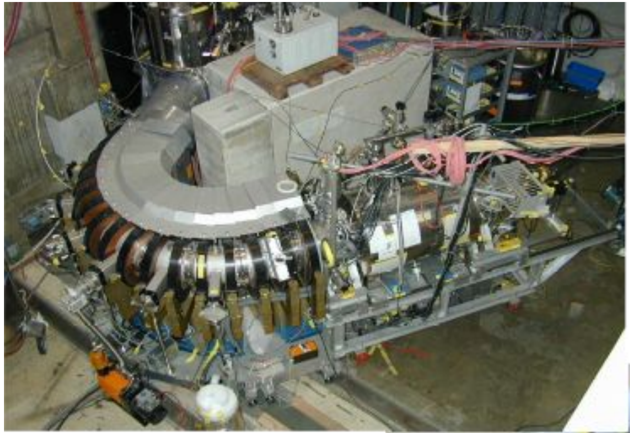
A. Adamczak[1], A. Antognini[2,3], E. Artes[4], N. Berger[4], T.E. Cocolios[5], N. Deokar[4], R. Dressler[2], Ch.E. Düllmann[4,6,7], R. Eichler[2], M. Heines[5], H. Hess[8], P. Indelicato[9], K. Jungmann[10], K. Kirch[2,3], A. Knecht[2], E. Maugeri[2], L. Morvaj[2], C.-C. Meyer[4], J. Nuber[2,3], A. Ouf[4], A. Papa[2,11], N. Paul[9], R. Pohl[4], M. Pospelov[12,13], D. Renisch[4,7], P. Reiter[8], N. Ritjoho[2,3], M. Seidlitz[8], N. Severijns[5], K. von Schoeler[3], S.M. Vogiatzi[2,3], N. Warr[8], F. Wauters[4], and L. Willmann[10]

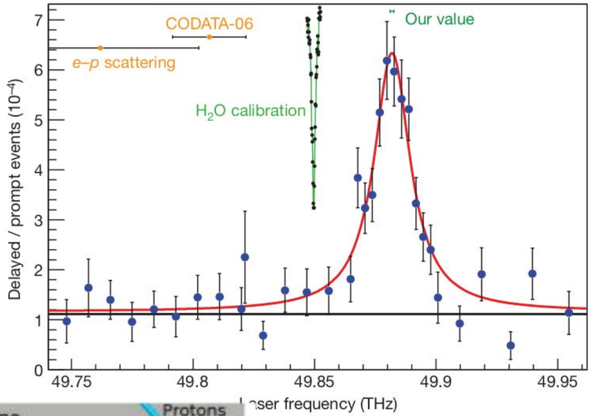


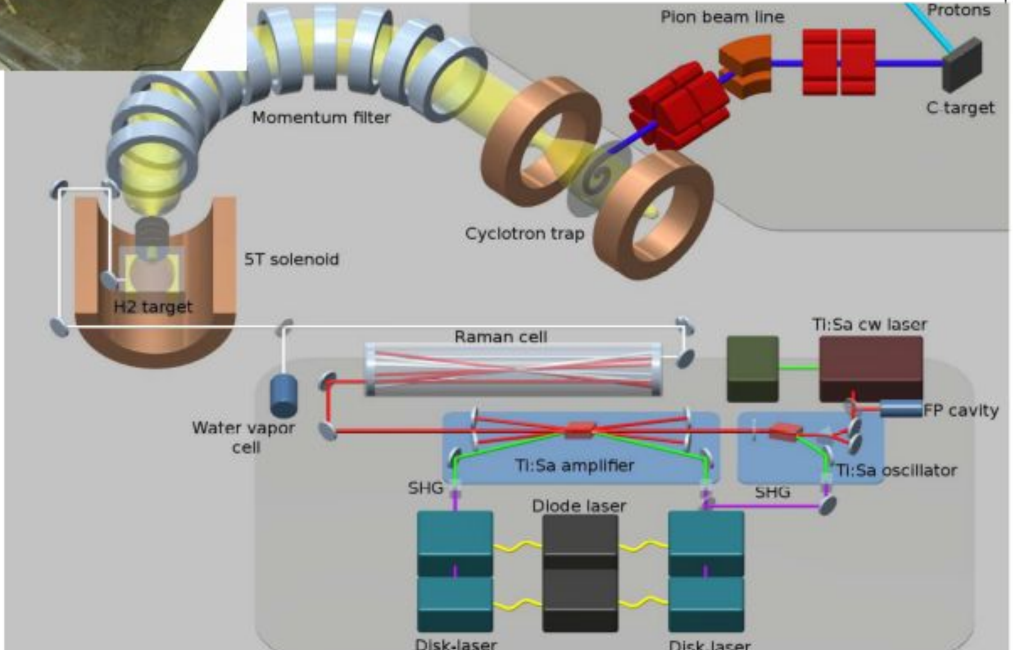
extra

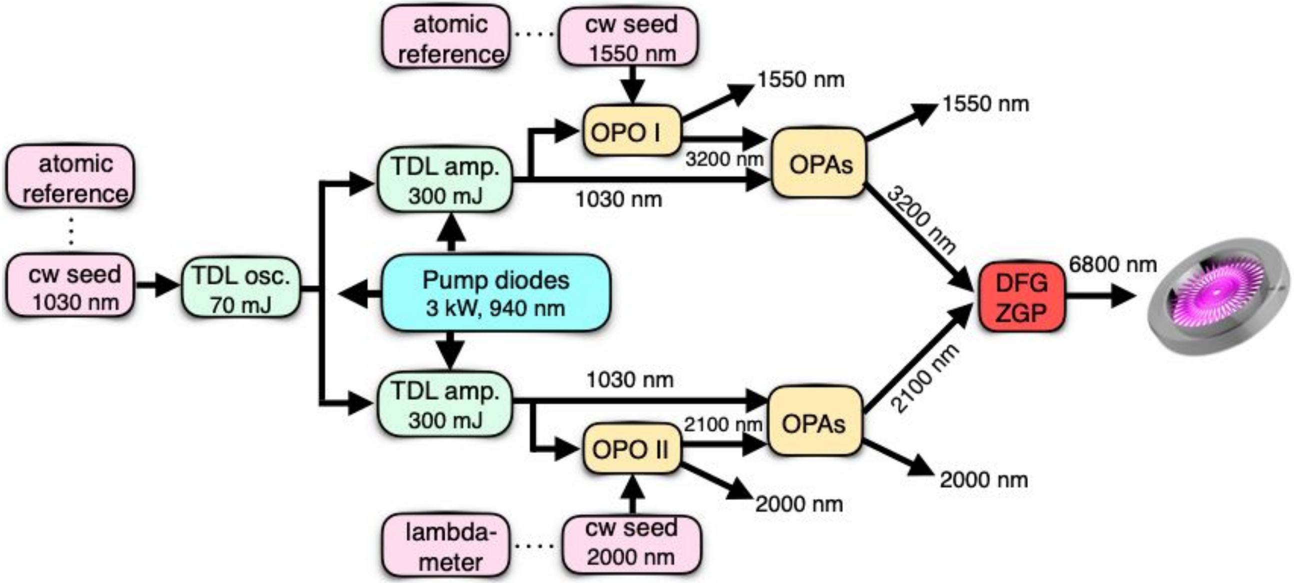
Very busy physics events!



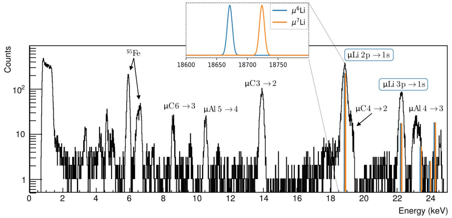


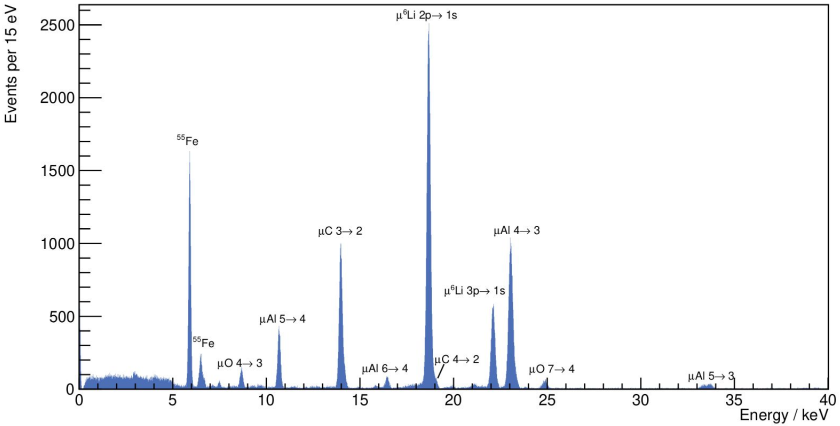

Our value
CODATA-06
e–p scattering
H2O calibration
Delayed / prompt events (10−4)
0
1
2
3
4
5
6
7
49.75
49.8
49.85
49.9
49.95
Laser frequency (THz)

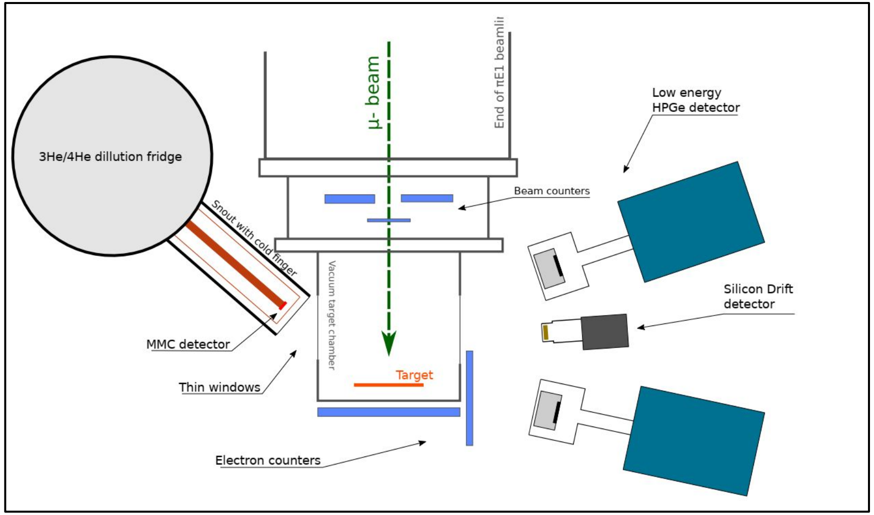

Protons
Pion beam line
C target
Momentum filter
Cyclotron trap
5T solenoid
H2 target
Raman cell
Ti:Sa cw laser
FP cavity
Water vapor cell
Ti:Sa amplifier
Ti:Sa oscillator
SHG
SHG
Diode laser
Disk-laser
Disk-laser

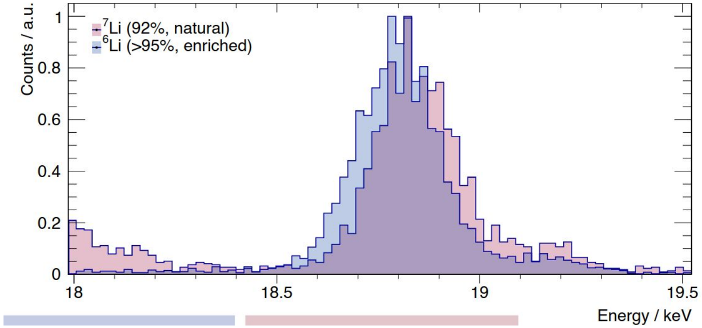


atomic reference
cw seed 1550 nm
1550 nm
OPO I
3200 nm
OPAs
1550 nm
atomic reference
cw seed 1030 nm
TDL osc. 70 mJ
TDL amp. 300 mJ
1030 nm
3200 nm
Pump diodes 3 kW, 940 nm
DFG ZGP
6800 nm
TDL amp. 300 mJ
1030 nm
2100 nm
OPAs
2100 nm
OPO II
2000 nm
2000 nm
lambda-meter
cw seed 2000 nm


μ⁶Li
μ⁷Li
Counts
Energy (keV)
⁵⁵Fe
μC6 →3
μAl 5 →4
μC3 →2
μLi 2p →1s
μC4 →2
μLi 3p →1s
μAl 4 →3


Events per 15 eV
Energy / keV
μ⁶Li 2p→ 1s
⁵⁵Fe
μC 3→ 2
μAl 4→ 3
μ⁶Li 3p→ 1s
μAl 5→ 4
⁵⁵Fe
μO 4→ 3
μAl 6→ 4
μC 4→ 2
μO 7→ 4
μAl 5→ 3


3He/4He dilution fridge
μ- beam
End of πE1 beamli
Low energy
HPGe detector
Beam counters
Snout with cold finger
Vacuum target chamber
Silicon Drift
detector
MMC detector
Thin windows
Target
Electron counters


Counts / a.u.
⁷Li (92%, natural)
⁶Li (>95%, enriched)
Energy / keV

- First extract quadrupole moment
- For higher muonic transitions measure full quadrupole moment
  → typically chosen: 5g-4f transition
- Drawback:
  - Transitions not separated
  - Effect only through widening of peaks