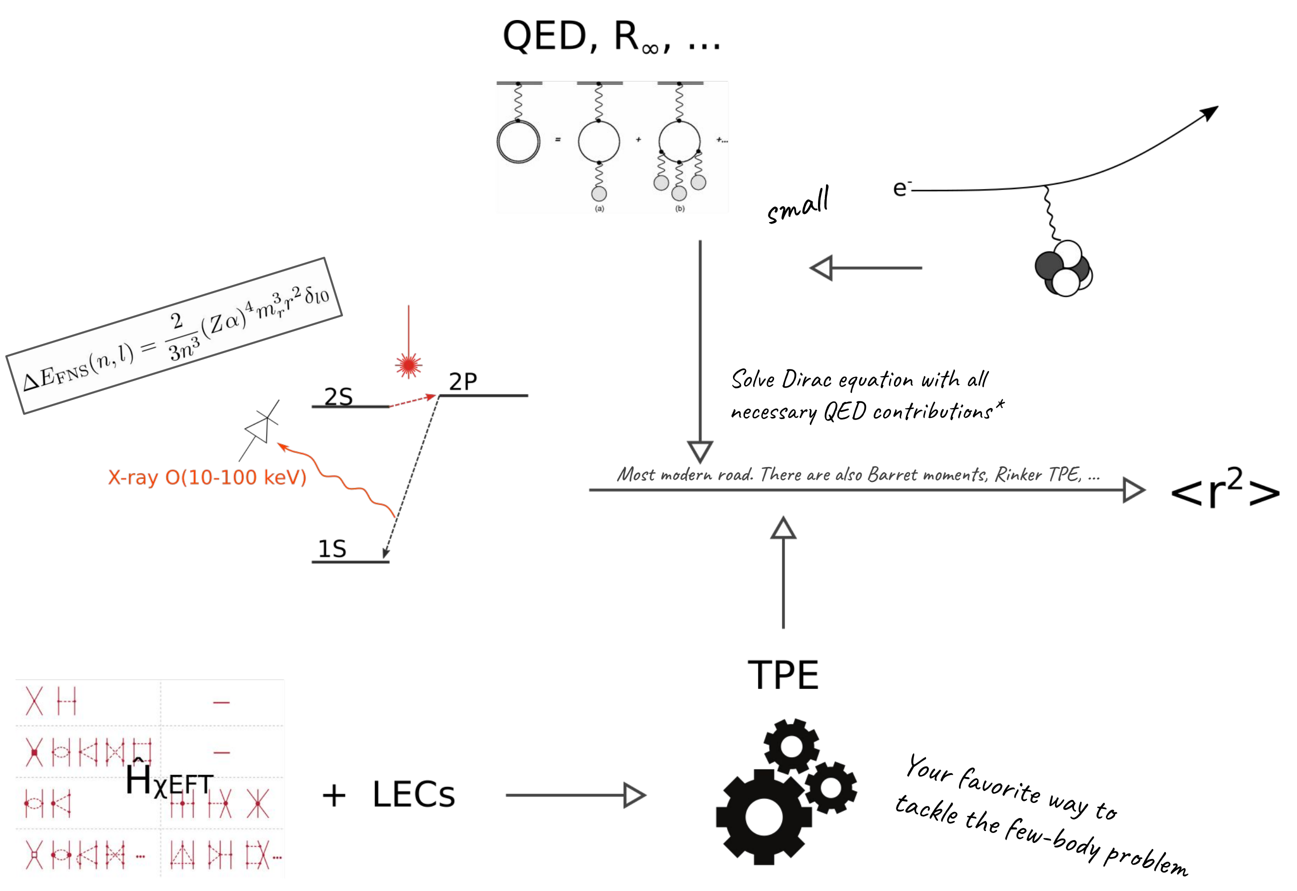
Precision muonic X-ray spectroscopy with metallic magnetic calorimeters

+ me learning about light muonic atoms

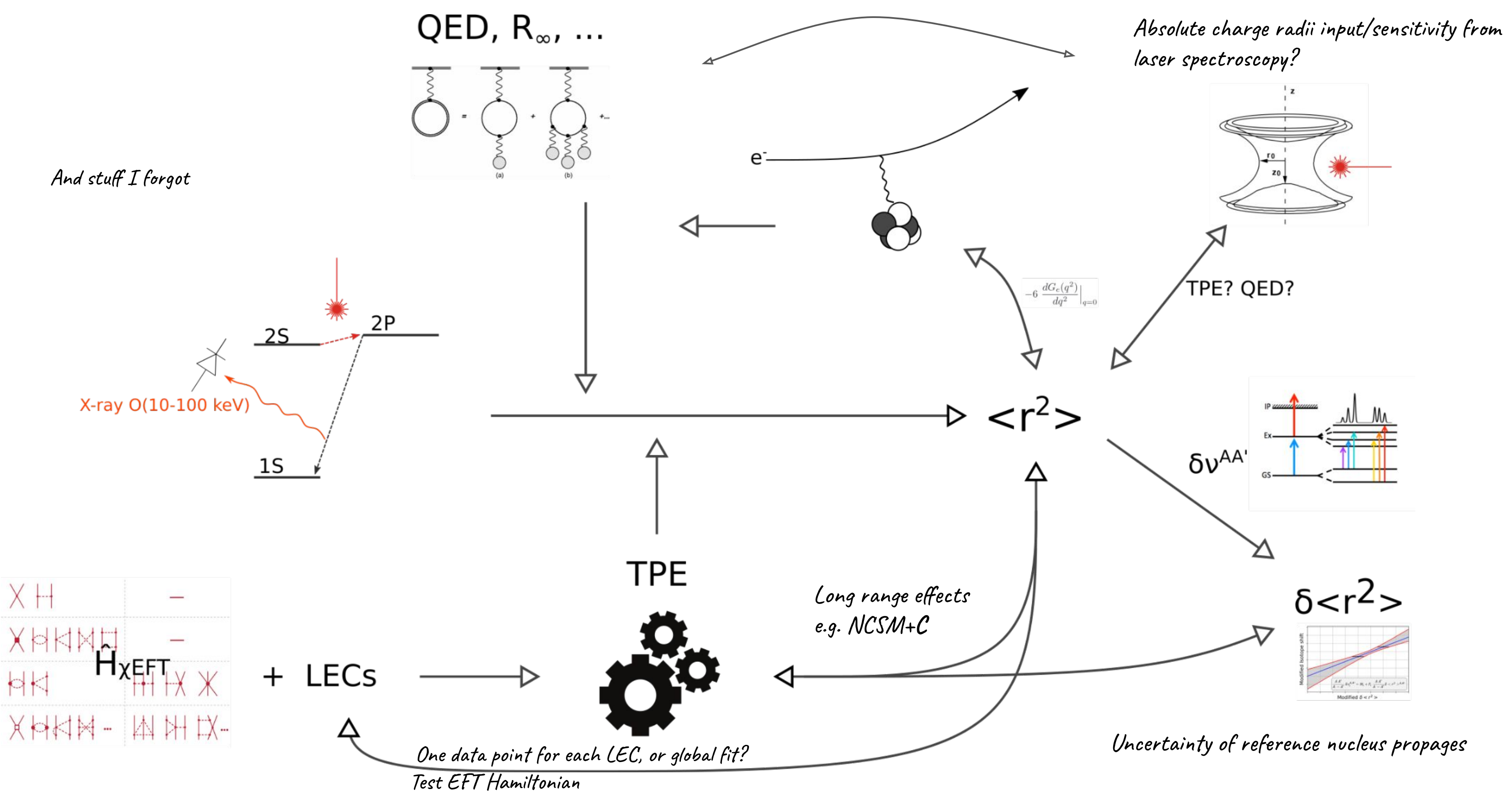
Frederik Wauters on behalf of the Quartet collaboration
Johannes Gutenberg University Mainz

Muonic atoms and (light) nuclear charge radii



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

Muonic atoms and (light) nuclear charge radii



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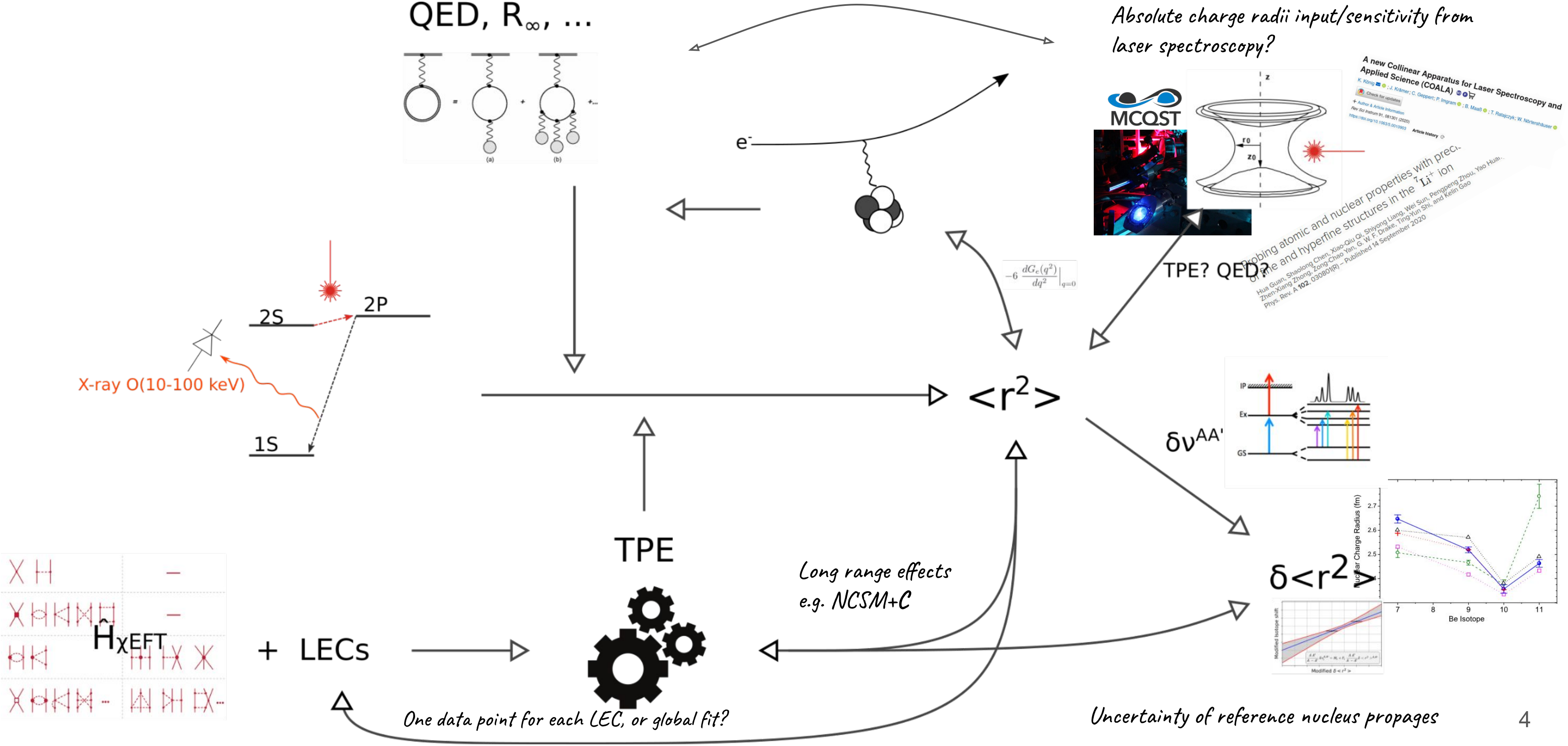


Muonic atoms and (light) nuclear charge radii

Data?

Reference radii from e-scatter and μZ

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

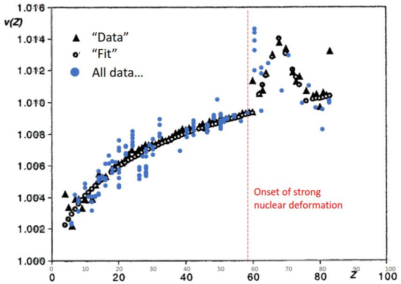
Z	El	A	R (fm)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
0	n	1	−0.1149	.0024	
1	H	1	0.8791	.0088	
		2	2.1402	.0091	
		3	1.7591	.0356	
2	He	3	1.9448	.0137	
		4	1.6757	.0026	
3	Li	6	2.5385	.0267	
		7	2.4312	.0281	
4	Be	9	2.5180	.0114	
5	B	10	2.4278	.0492	
		11	2.4059	.0291	
6	C	12	2.4703	.0022	
		13	2.4614	.0033	
		14	2.5037	.0081	
7	N	14	2.5579	.0068	
		15	2.6061	.0074	
8	O	16	2.7013	.0055	
		17	2.6953	[illegible]	
		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)	$\Delta_{tot}R$ (fm)	$\Delta_{rel}R$ (fm)
		37	3.3901	.0028	.0013
		38	3.4020	.0017	
		39	3.4085	.0105	.0099
		40	3.4269	.0017	.0006
		46	3.4363	.0068	.0032
19	K	38	3.4262	.0067	.0057
		39	3.4346	.0017	
		40	3.4378	.0027	.0003
		41	3.4514	.0030	.0004
		42	3.4512	.0074	.0020
		43	3.4551	.0089	.0013
		44	[illegible]	.0104	.0014
		45	3.4599	.0121	.0017
		46	3.4552	.0129	.0016
		47	3.4529	.0141	.0017
20	Ca				
21	Sc				
22	Ti				
23	V				
24	Cr				

Angeli 2002

Varying precision and quality/accuracy



Basis for all later reviews...

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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Institut für Kernphysik, Kernforschungsanalage Jülich, D-5170 .
and
Institut für Physik, Universität Bonn, D-5300 Bonn, W

Received 22 February 1978

Abstract: We have calculated nuclear polarization energy shifts for muonic
table using a phenomenological extension of more detailed mic
previously. Numerical results are presented in tabular form.

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†	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†	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‡	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‡	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†	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]

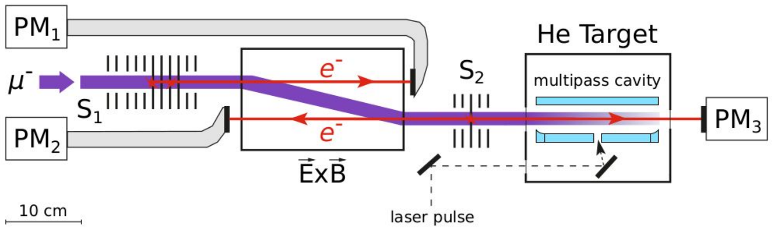
10^{4} data points with σ 10^{-3} corrections

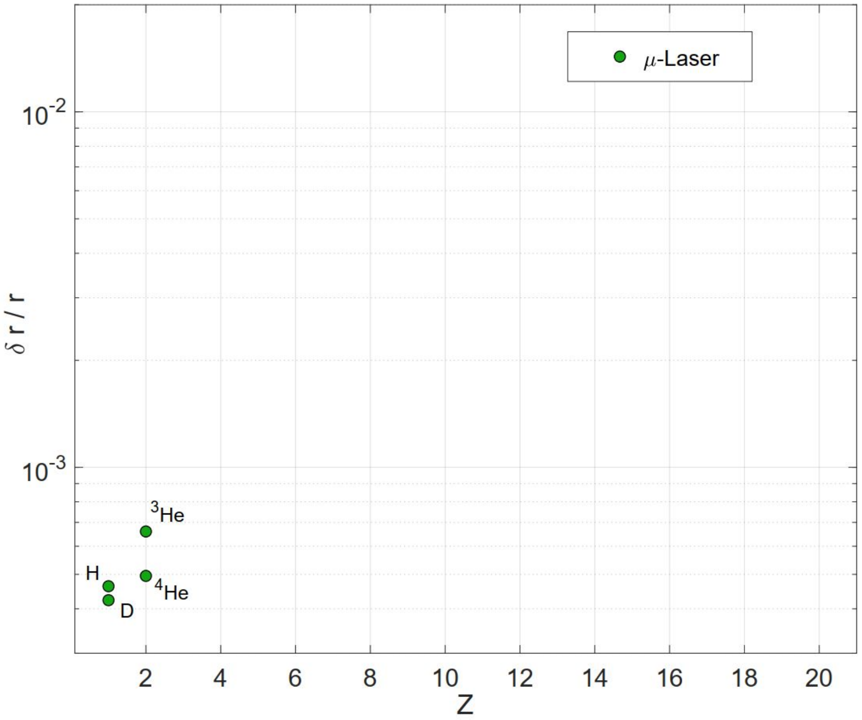
Barret moment → charge radius

The experimental *gap*

- We are all talking about hydrogen and helium because …

<u>Gaseous low pressure target with metastable 2S μZ</u>





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  - Accessible by nucleon and few-body theory
  - Accessible by laser spectroscopy
- Most of the stable nuclei have been measured
  - Z>10 limited by TPE corrections
  - Z<10 limited by semiconductor resolution

$$\sigma_Q = \sqrt{FN_Q}$$

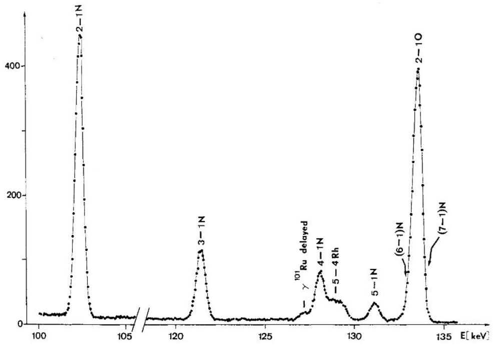
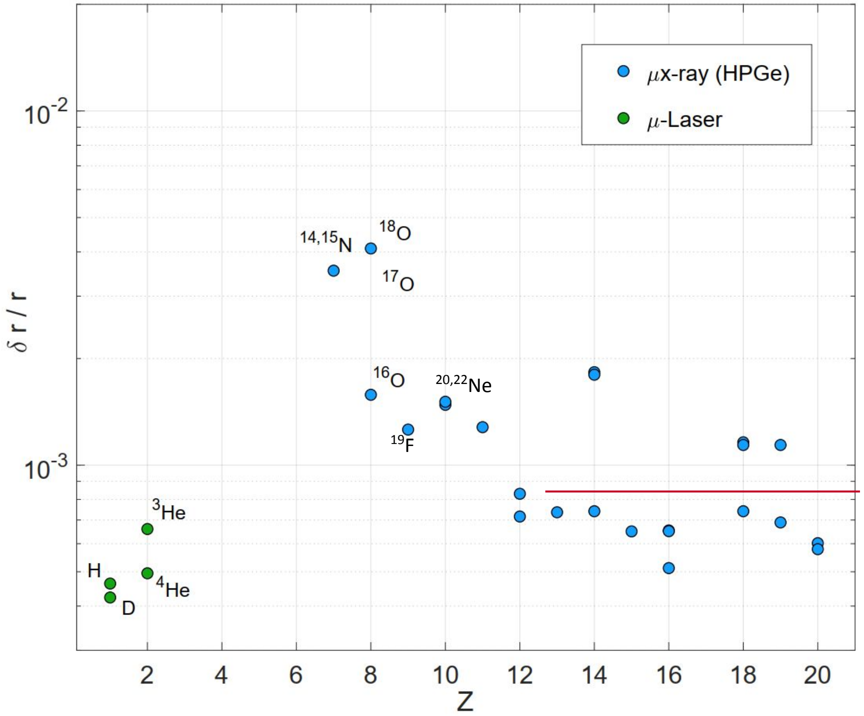


Fig. 1. Part of the μ X-ray spectrum of the $C_4H_8N_2O_2$+Rh target.

~15 eV accurate?



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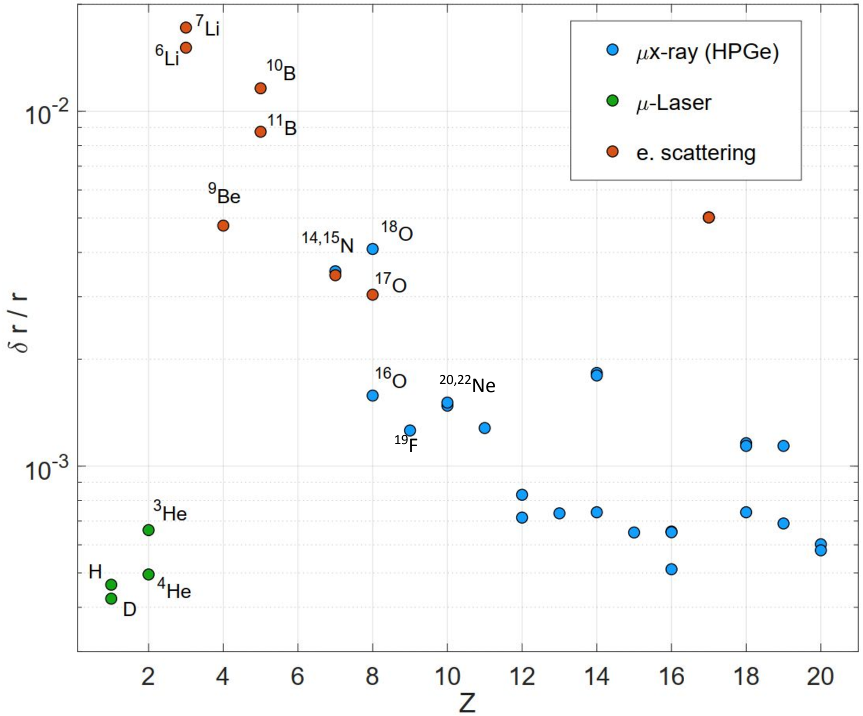
  Currently the reference data for light nuclei Z>2



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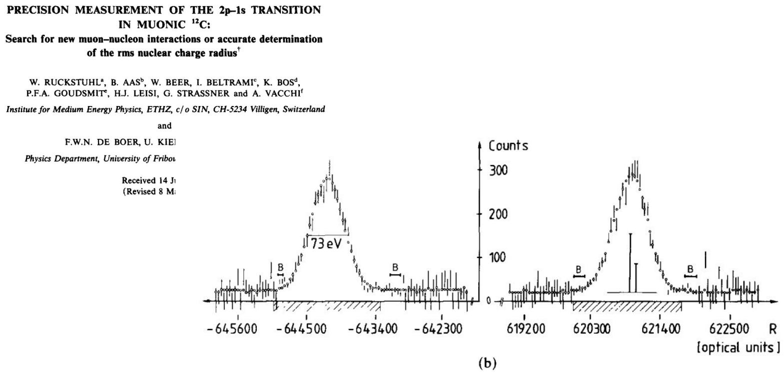
- What going on with carbon?
  - Accuracy and precision with a crystal spectrometer
  - > 10^{10} muons


PRECISION MEASUREMENT OF THE 2p–1s TRANSITION IN MUONIC ^{12}C:
Search for new muon–nucleon interactions or accurate determination of the rms nuclear charge radius

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Institute for Medium Energy Physics, ETHZ, c/o SIN, CH-5234 Villigen, Switzerland
and
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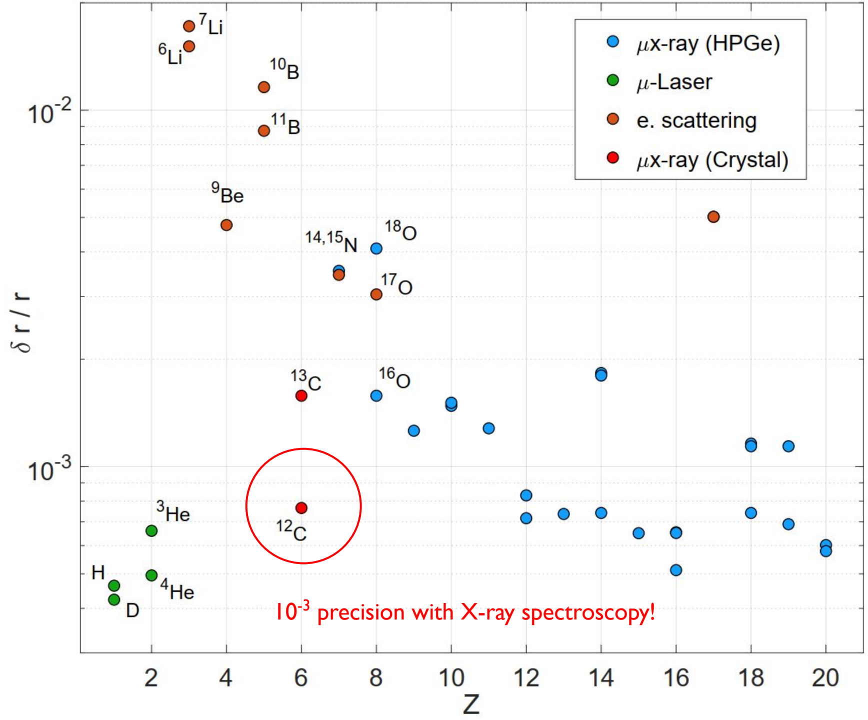
Physics Department, University of Fribo

Received 14 J
(Revised 8 M



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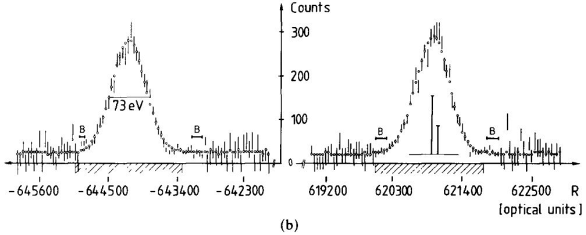
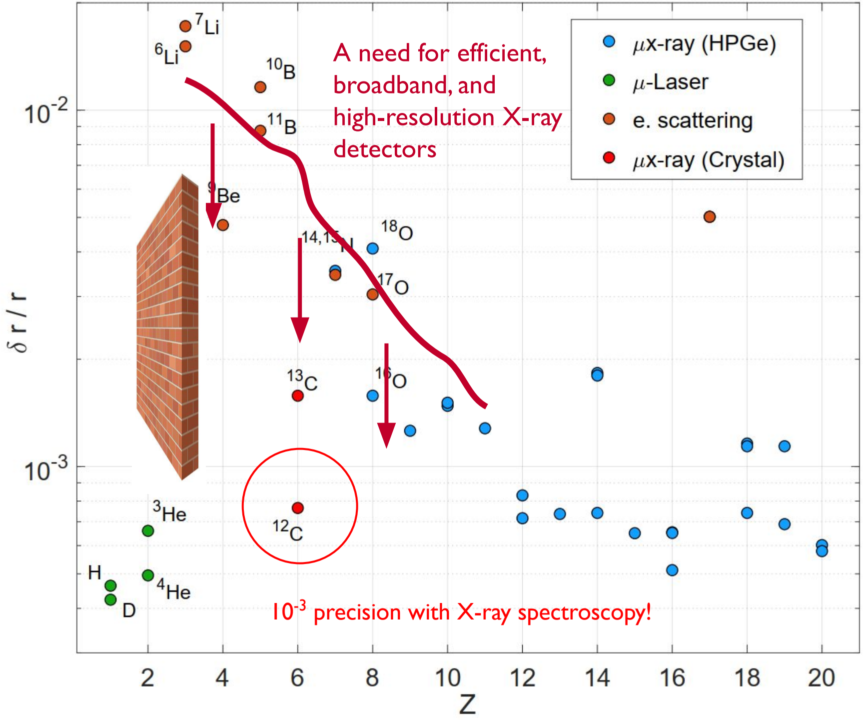




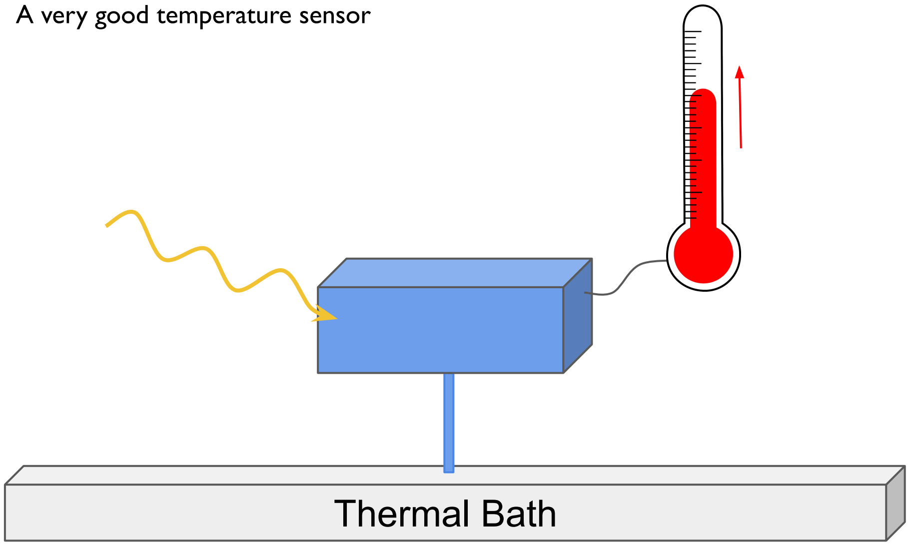
Precision X-ray spectroscopy

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



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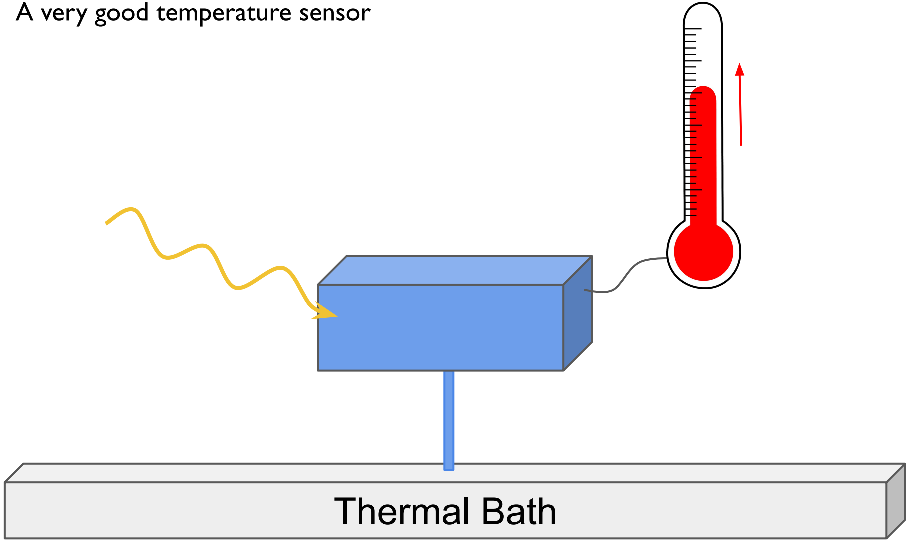

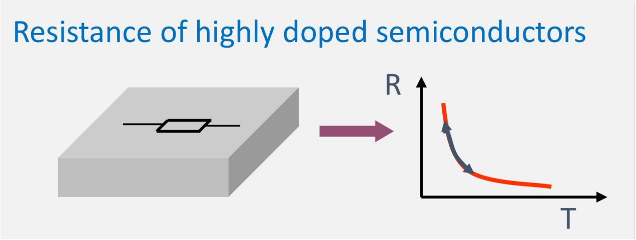

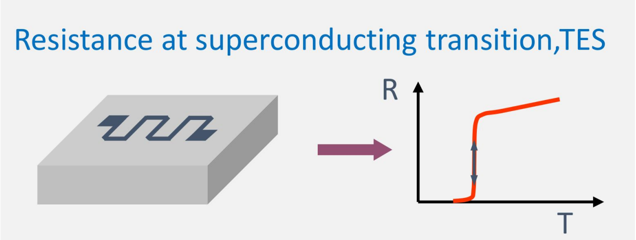

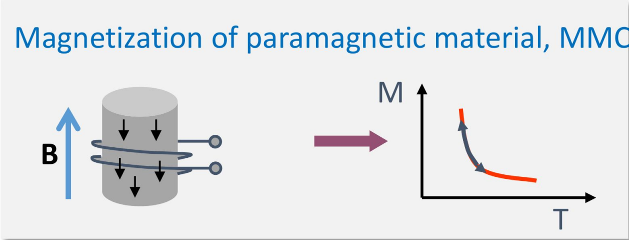

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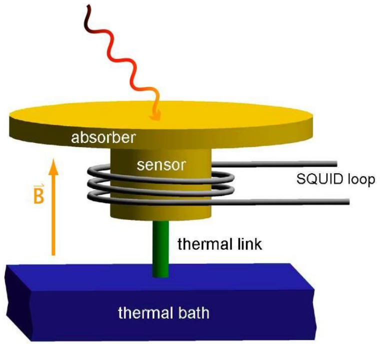
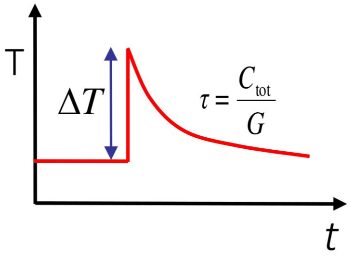
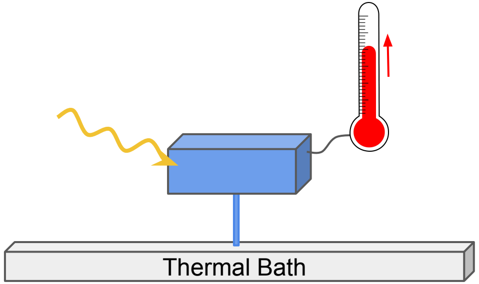
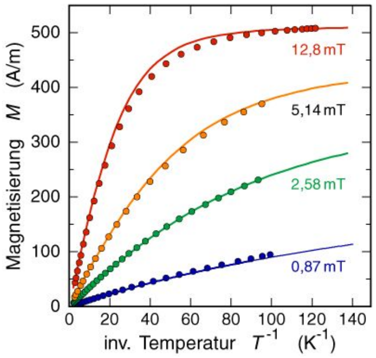
Metallic Magnetic Calorimeters → Unit of spin flip ≪ Unit of Ionization

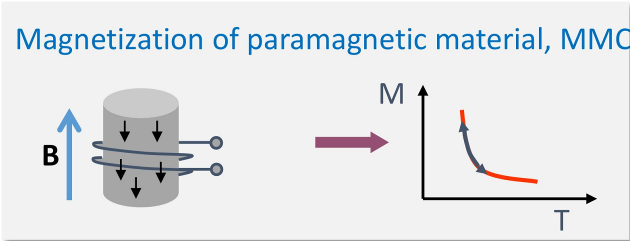
- Paramagnetic Au:Er Alloy
- $\Delta\Phi_S \cong \delta M/\delta T \, \Delta T = \delta M/\delta T \times E_{deposited} / C_{tot}$









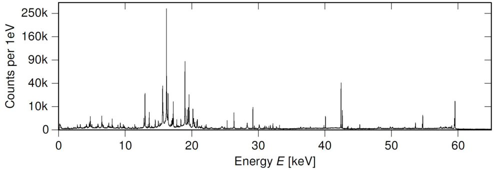


A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63
A.Fleischmann et al., AIP Conf. Proc. 1185 (2009) 571

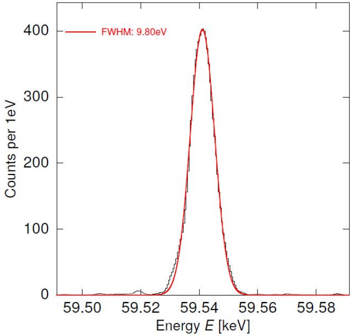
Precision X-ray spectroscopy

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

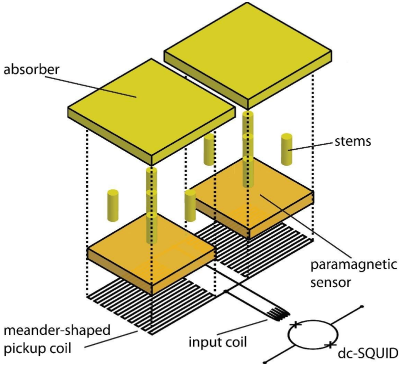


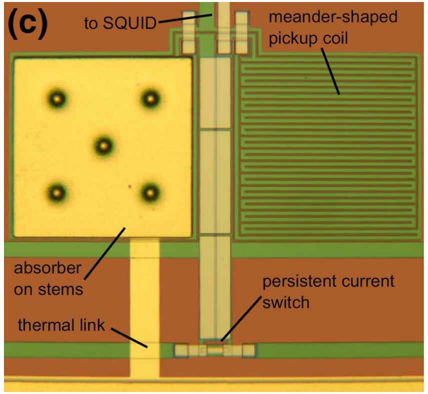
Energy resolution ΔE FWHM = 9.8 eV @ 59 keV

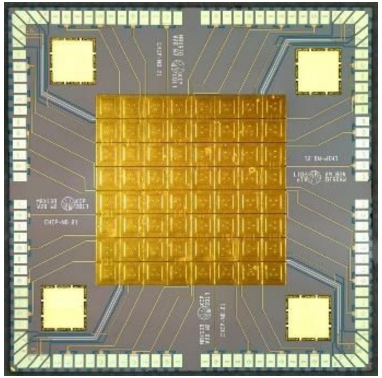


16 mm2 maXs-30 sensor

D. Unger *et al* 2021 *JINST* **16** P06006







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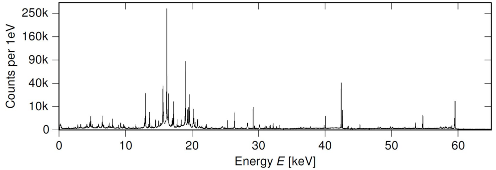

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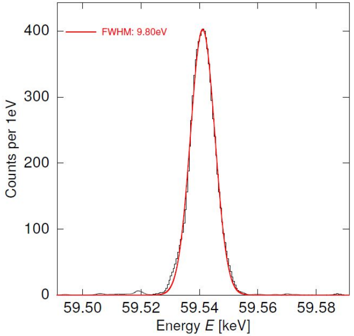
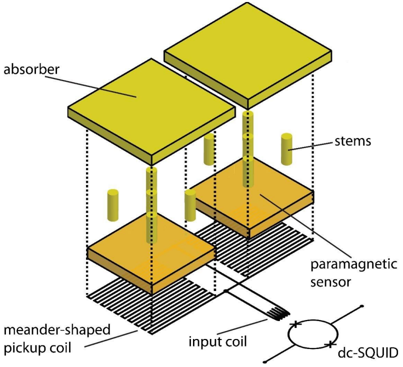
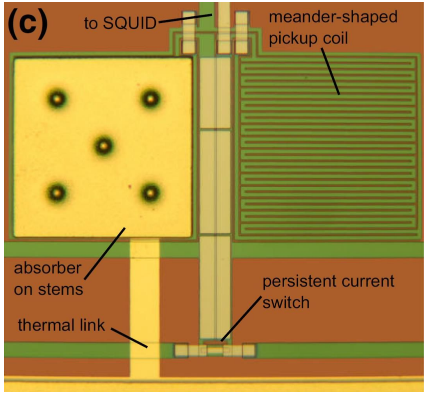
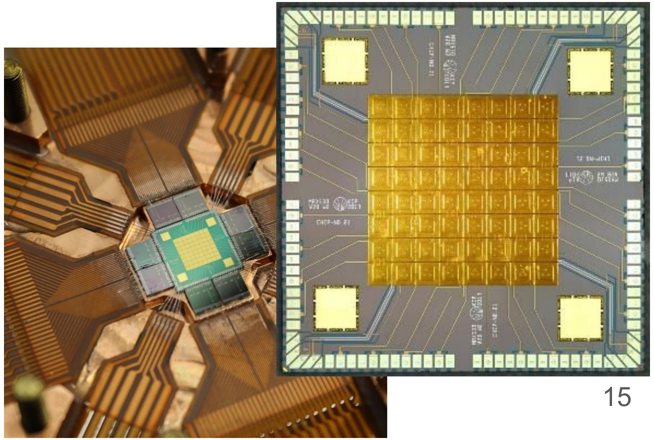


16 mm2 maXs-30 sensor

D. Unger *et al* 2021 *JINST* **16** P06006







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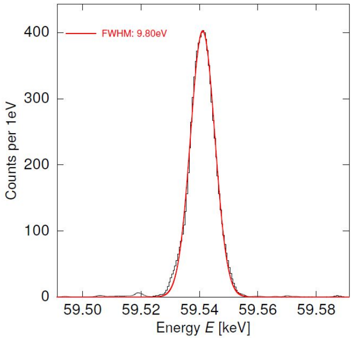

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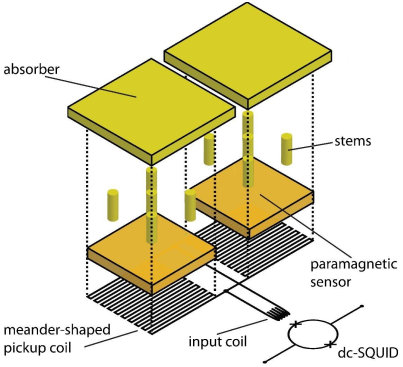

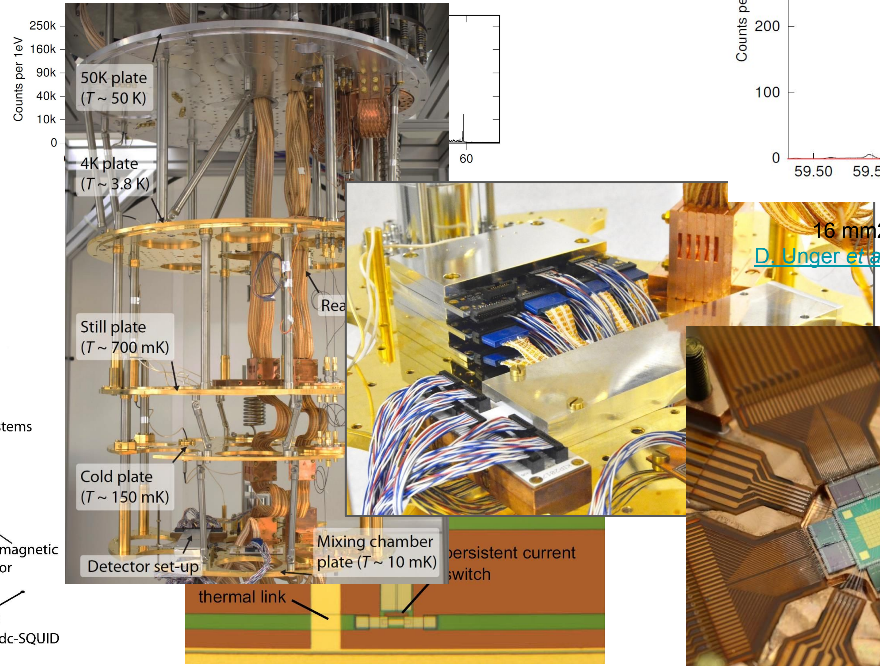

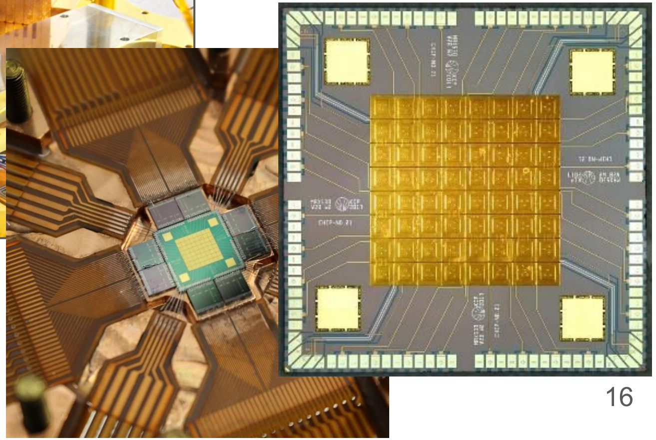

Multichannel read-out for arrays of metallic magnetic calorimeters arXiv:2102.11100

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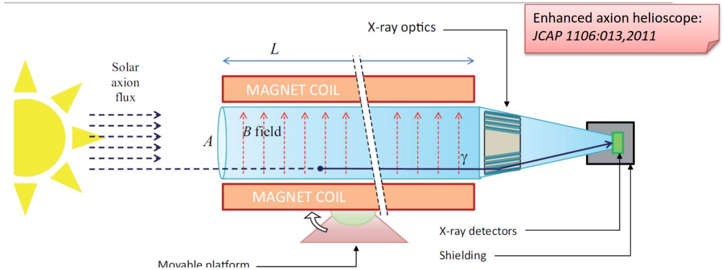
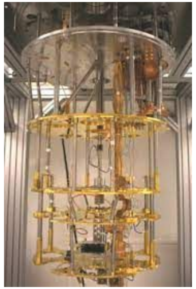
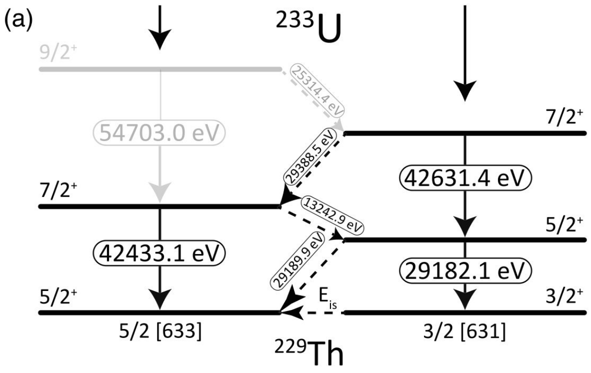
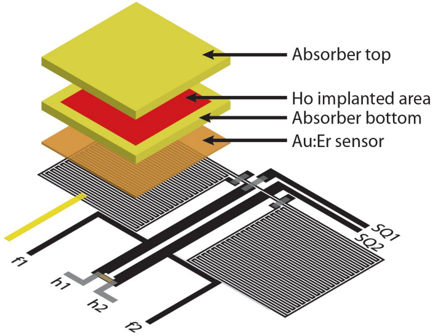
Used for a wide variety of (X-ray) spectroscopy experiments

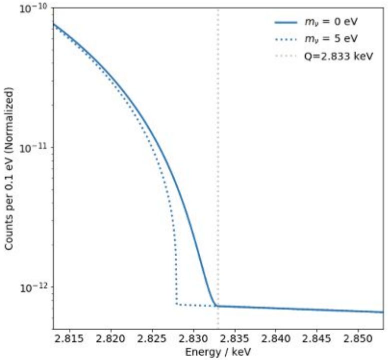
- IAXO arXiv:2010.15348
- ECHO arXiv:2111.09945
- Highly charged Ions https://doi.org/10.3390/atoms6040059
- Th isomer measurement arXiv:2005.13340







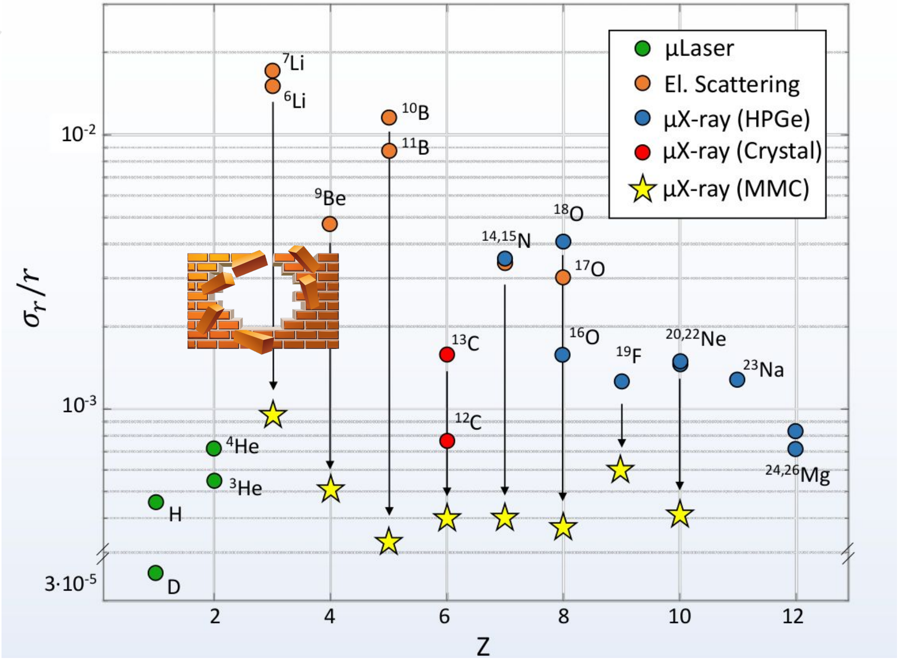




Precision X-ray spectroscopy with QUARTET

Quartet: Apply MMC to precision muonic atom X-ray spectroscopy

Motivated by opportunity



Precision X-ray spectroscopy with QUARTET

<u>Quartet:</u> Apply MMC to precision muonic atom X-ray spectroscopy

Lamb shift TPE x $(2/1)^3$

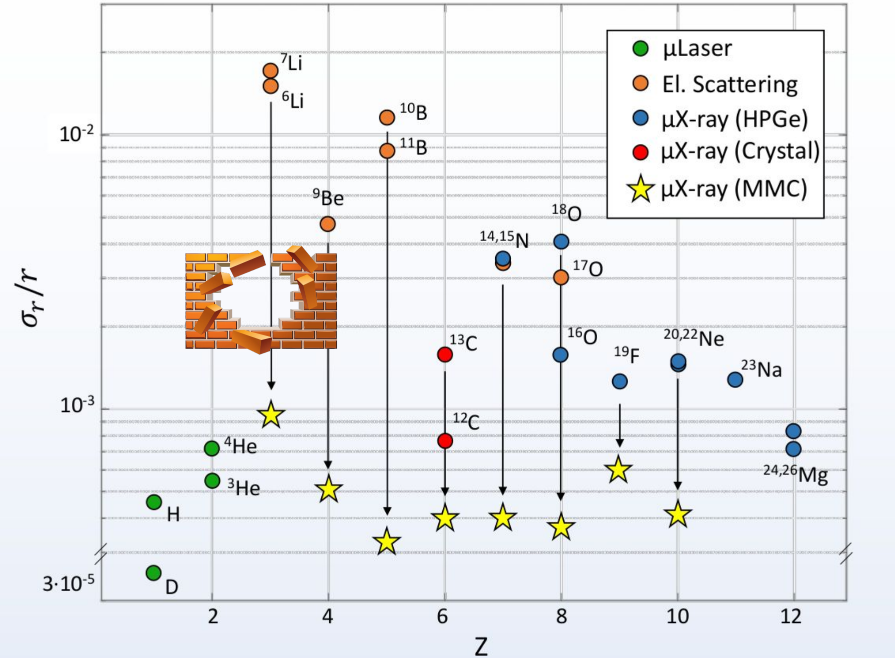
Detector

10^5 events

Needed/feasible

Isotopes	E_{2P-1S} [keV]	FWHM [eV]	σ_{stat} [eV]	σ_{TPE} [eV]	σ_r [am]
^{6,7}Li	19	4	0.01	0.02	2
^{9}Be	33	12	0.02	0.06	1
^{10,11}B	52	18	0.02	0.1	1
^{12,13}C	75	36	0.05	0.3	1
^{14,15}N	102	39	0.05	0.6	1
^{16,18}O	134	45	0.06	1	1
^{19}F	169	50	0.07	2	2
^{20,22}Ne	207	50	0.07	3	1

<u>Motivated by opportunity</u>



Precision X-ray spectroscopy with QUARTET

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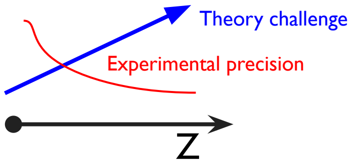

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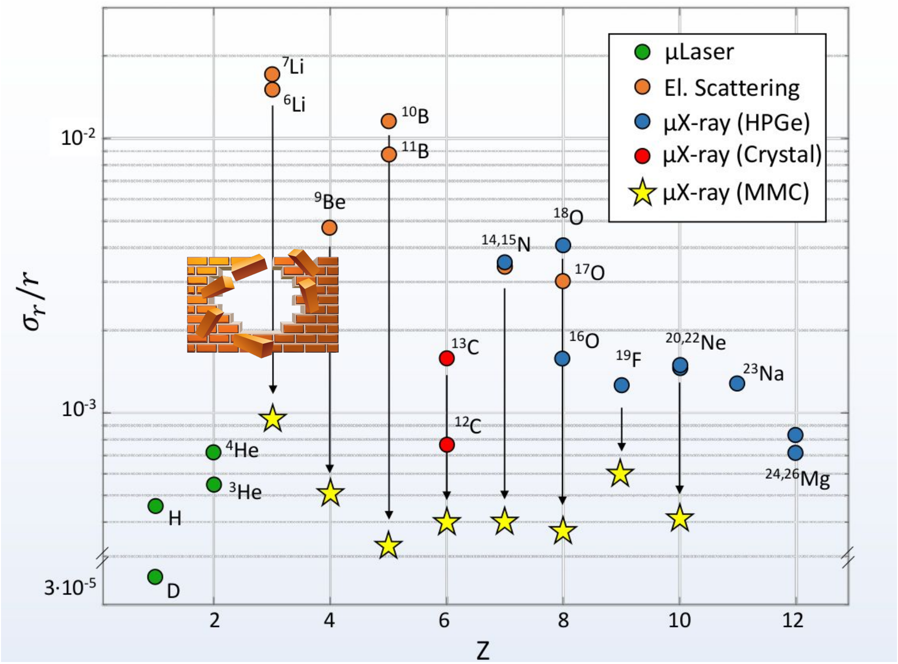

Precision X-ray spectroscopy with QUARTET

<u>What is interesting about Li, Be, & B</u>

- ❑ These <r^2> as ab-initio benchmarks
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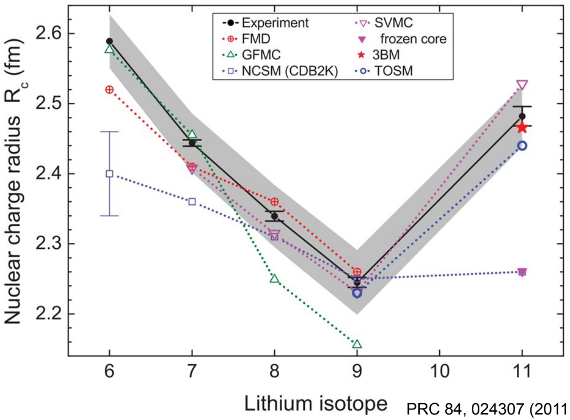
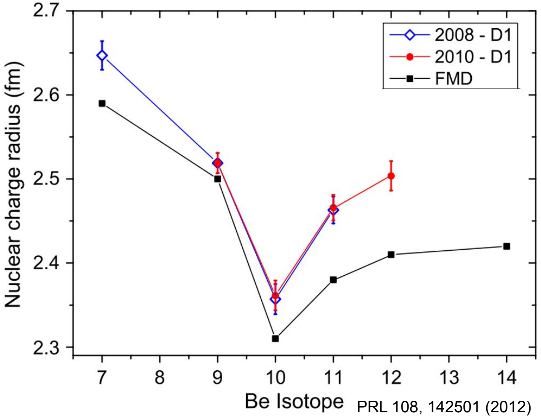
Ongoing collinear laser spectroscopy measurements at GSI (COALA) ISOLDE/CERN (CRIS), …

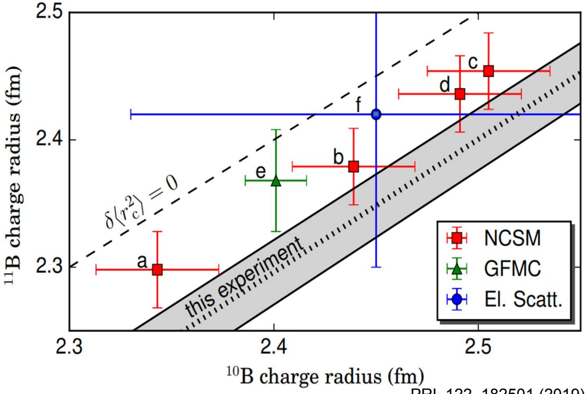
$$R_c(A) = \sqrt{R^2_{\text{ref}} + \delta\langle r^2_c\rangle^{A_{\text{ref}},A}}$$



PRC 84, 024307 (2011)



PRL 108, 142501 (2012)



PRL 122, 182501 (2019)

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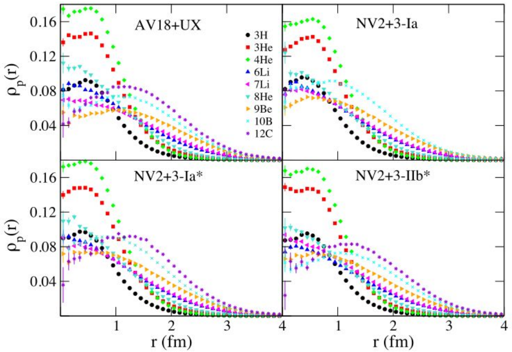
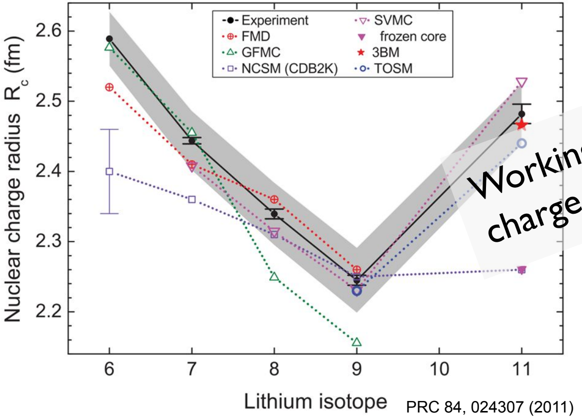
$$R_c(A) = \sqrt{R^2_{\mathrm{ref}} + \delta\langle r^2_c\rangle^{A_{\mathrm{ref}},A}}$$

From https://www.phy.anl.gov/theory/research/density/
(point radii)

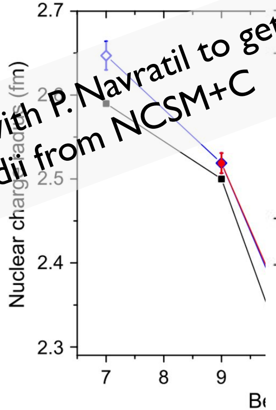
Isotope	AV18+UX	NV2+3-Ia	NV2+3-Ia*	NV2+3-Ib*	NV2+3-IIa*	NV2+3-IIb*
^{6}Li	2.4433	2.448	2.4426	2.5001	2.4503	2.4876
^{7}Li	2.2551	2.3062	2.3065	2.2532	2.2715	2.2475
^{9}Be	2.3583	2.3602	2.3344	2.3875	2.3394	2.3637

PHYSICAL REVIEW C **107**, 014314 (2023)





PRC 84, 024307 (2011)



Working with P.Navratil to get σ 10^{-3} charge radii from NCSM+C

^{9}Be	NCSM	NCSMC	Exp.	Refs.
$E_{3/2^-}$ [MeV]	−0.82	−1.52	−1.587	[47]
$E_{1/2^-}$ [MeV]	−0.49	−1.26	−1.157	[47]
r_{ch} [fm]	2.375	2.62	2.647(17)	[48]
Q [e fm^2]	−4.57	−6.14	–	
μ [μ_N]	−1.14	−1.16	−1.3995(5)	[48]
^{7}Li	NCSM	NCSMC	Exp.	Refs.
$E_{3/2^-}$ [MeV]	−1.79	−2.43	−2.467	[47]
$E_{1/2^-}$ [MeV]	−1.46	−2.15	−1.989	[47]
r_{ch} [fm]	2.21	2.42	2.39(3)	[49]
Q [e fm^2]	−2.67	−3.72	−4.00(3)	[50]
μ [μ_N]	3.00	3.02	3.256	[51]

Precision X-ray spectroscopy with QUARTET

<u>What is interesting about Li, Be, & B</u>

- ❑ These $<r^2>$ as ab-initio benchmarks
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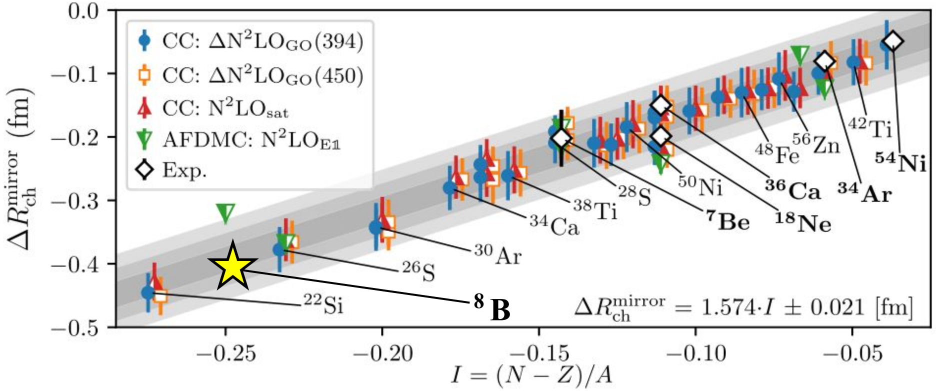
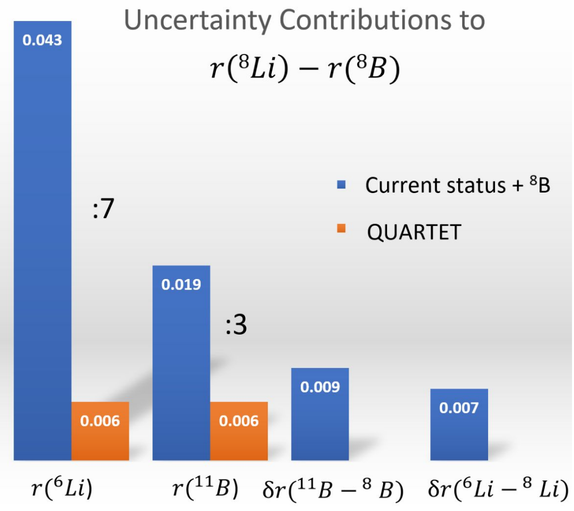
  Ongoing collinear laser spectroscopy measurements at GSI (COALA) ISOLDE/CERN (CRIS), …
- ❑ We (the μ's) can also do isotope shifts of different Z. Like mirror nuclei.

S. J. Novario, *et. al.*, PRL 130, 032501 (2023)



Golden case $I = 0.25$:



*Priv. Com. With W. Nörtershäuser

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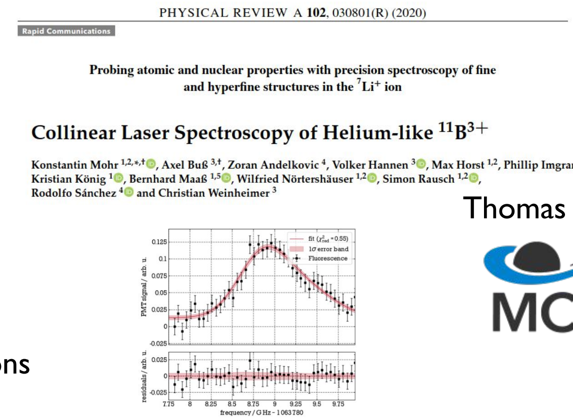
- ❑ We (the μ's) can also do isotope shifts of different Z. Like mirror nuclei.
- ❑ Targeted by next generation laser spectroscopy experiments, helium like ions
- ❑ Narrow search window for muonic atom laser spectroscopy


PHYSICAL REVIEW A 102, 030801(R) (2020)

Rapid Communications

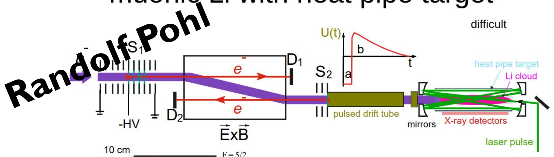
Probing atomic and nuclear properties with precision spectroscopy of fine and hyperfine structures in the $^7Li^+$ ion

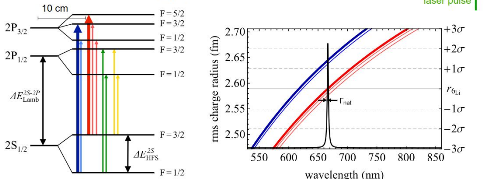
Collinear Laser Spectroscopy of Helium-like $^{11}B^{3+}$

Konstantin Mohr [1,2,*,†], Axel Buß [3,†], Zoran Andelkovic [4], Volker Hannen [3], Max Horst [1,2], Phillip Imgram [1], Kristian König [1], Bernhard Maaß [1,5], Wilfried Nörtershäuser [1,2], Simon Rausch [1,2], Rodolfo Sánchez [4] and Christian Weinheimer [3]

Thomas Udem @

muonic Li with heat pipe target

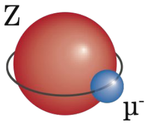




H, D, He, … (K. Eikema)

TPE test

QED, R_∞



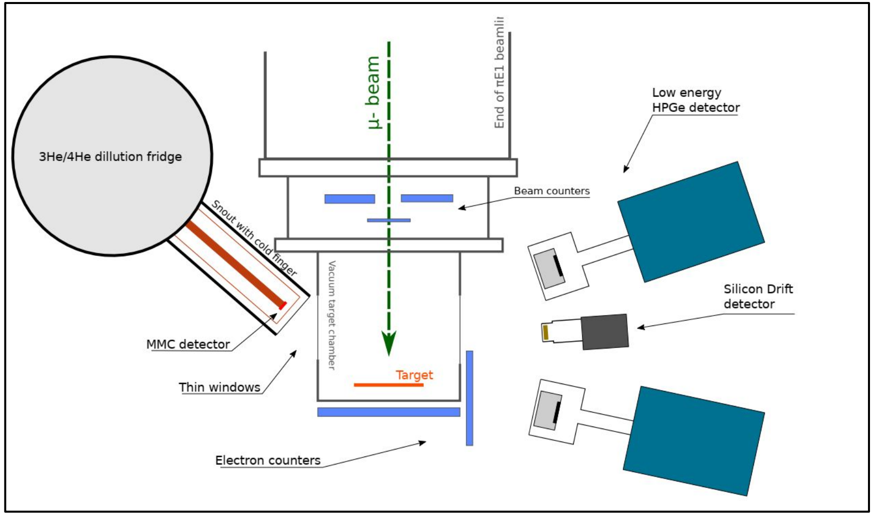
The next generation of laser spectroscopy experiments using light muonic atoms S Schmidt *et al* 2018 *J. Phys.: Conf. Ser.* 1138 012010

MMC spectroscopy @ PSI

<u>What is PSI?</u> □ Previous talk A Knecht

<u>What will we do?</u>

- ❑ Add MMC detector to muX setup



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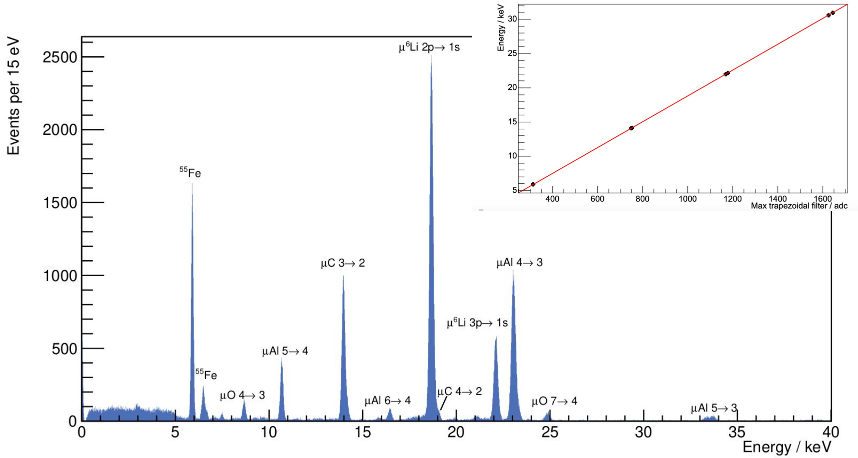
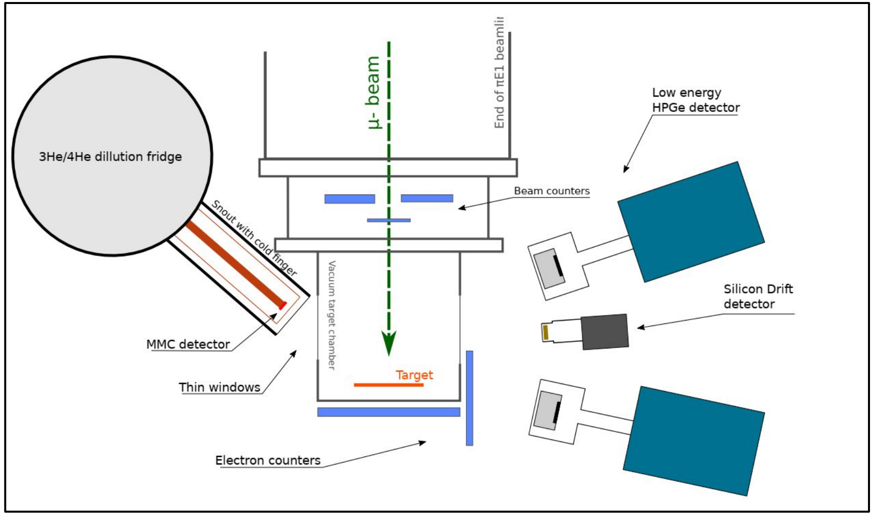
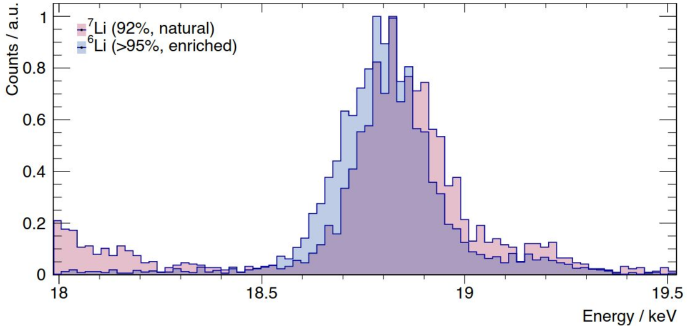




Preliminary measurements with Silicon Drift Detector (SDD):

- < 10 eV statistical precision
- Calibrated to a few eV
- Efficiency SDD ≅ Efficiency MMC
- Very little background

→ σ_{stat} < 0.1 eV after 1 day



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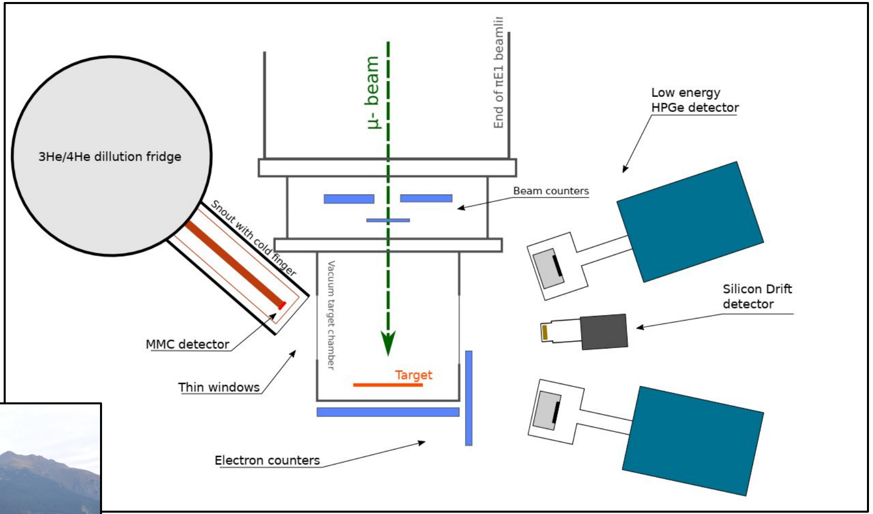
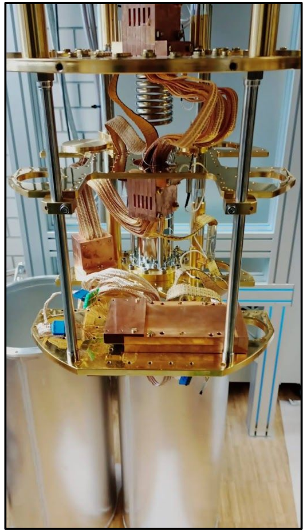
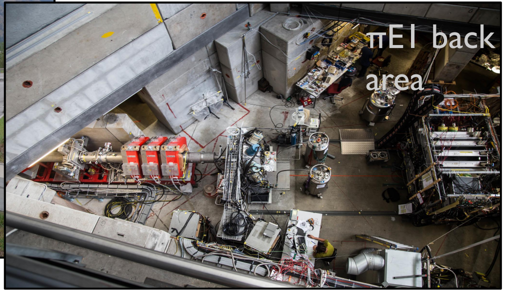
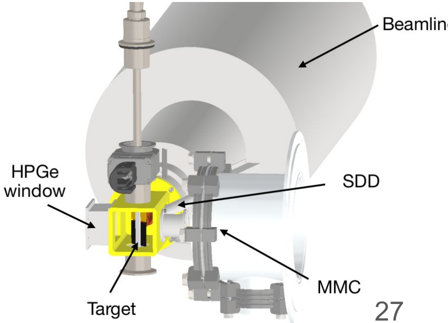
- Add MMC detector to muX setup
- Load MMC detector on a truck and see how much it likes a secondary muon beamline









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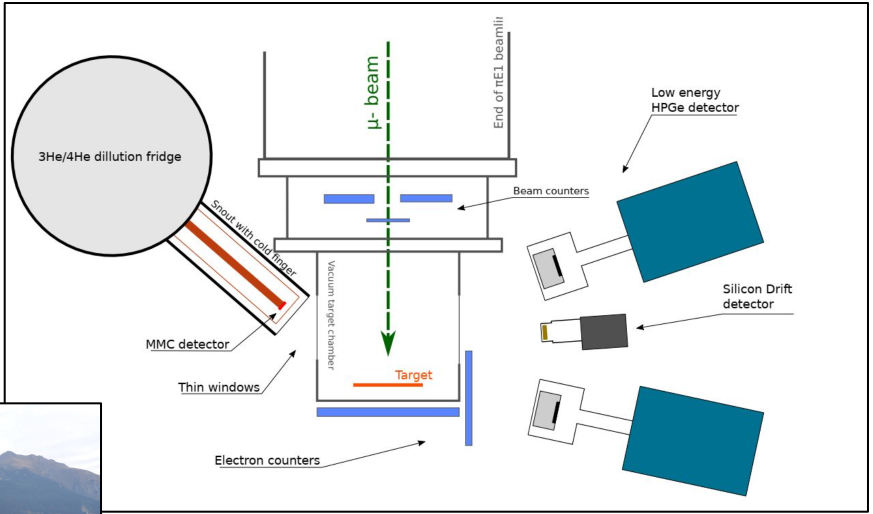
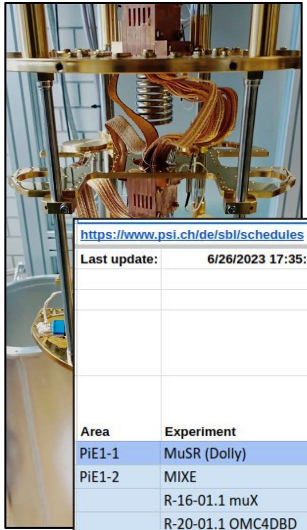
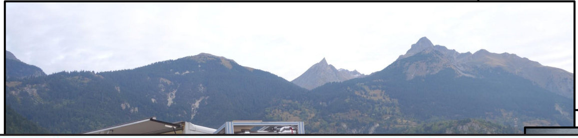
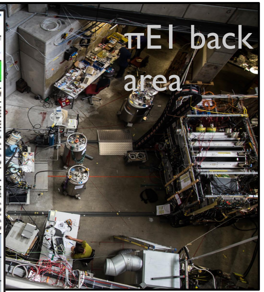
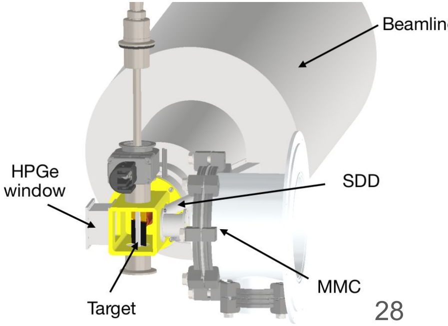






https://www.psi.ch/de/sbl/schedules		<stefan.ritt@psi.ch>	Month			August				September				October				November			
Last update:	6/26/2023 17:35:19		Week number	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	4
			Availability																		
			Days	4	4	7	7	6	7	3	7	7	6	7	3	7	7	6	7	3	7
			Start (Monday)	Jul/31/23	Aug/7/23	Aug/14/23	Aug/21/23	Aug/28/23	Sep/4/23	Sep/11/23	Sep/18/23	Sep/25/23	Oct/2/23	Oct/9/23	Oct/16/23	Oct/23/23	Oct/30/23	Nov/6/23	Nov/13/23	Nov/20/23	
Area	Experiment	PSI Contact	End (Sunday)	Aug/6/23	Aug/13/23	Aug/20/23	Aug/27/23	Sep/3/23	Sep/10/23	Sep/17/23	Sep/24/23	Oct/1/23	Oct/8/23	Oct/15/23	Oct/22/23	Oct/29/23	Nov/5/23	Nov/12/23	Nov/19/23	Nov/26/23	
PiE1-1	MuSR (Dolly)	Luetkens	Luetkens (coord.)																		
PiE1-2	MIXE	Amato	Amato/Knecht					wall													
	R-16-01.1 muX	Knecht	Knecht																		
	R-20-01.1 OMC4DBD	Knecht	Zinatulina																		
	R-23-02.1 QUARTET	Knecht	Ohayon																		
	R-23-03.1 ReferenceRadii	Knecht	Cocolios																		





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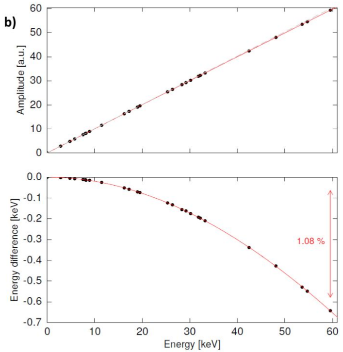
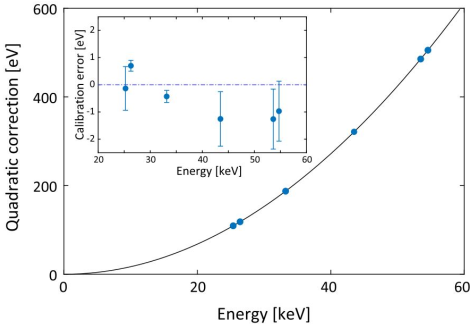
<u>What will we do?</u>

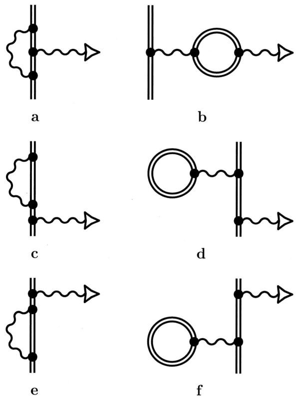
- ❑ Add MMC detector to muX setup
- ❑ Load MMC detector on a truck and
  see how much it likes a secondary muon beamline
- ❑ Will this work?
  - ❑ Statistics ✔
  - ❑ Background: *probably* OK, unless the sensor readout does not like neutrons, Michel electrons, dust & humidity, ….
  - ❑ QED. Fine, hyperfine (a few eV), and quadrupole (< 1eV) corrections calculated. ✔
  - ❑ e- screening & Coulomb explosion ✔
  - ❑ Calibration (γ-sources), calibration (X-ray), calibration (ADC), calibration (?)



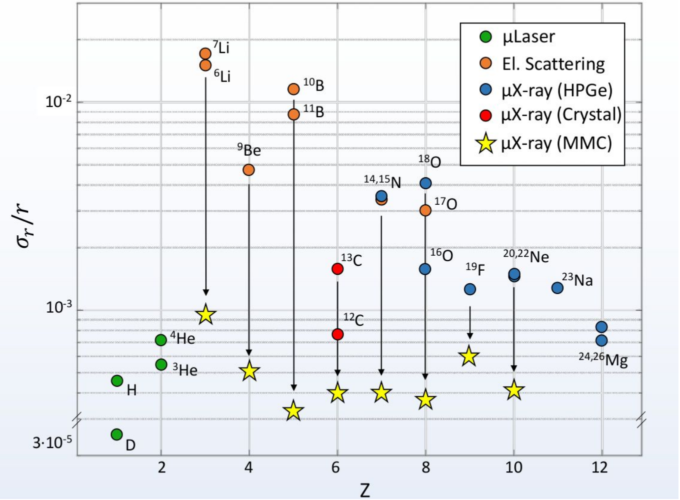


Paul Indelicato has the numbers

LKB



Precision X-ray spectroscopy with MMCs



Future

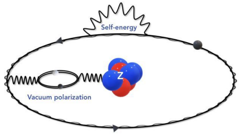
1. Improved charge radii of Li, Be, B
2. Improved charge radii of > C. Which ones make sense?
3. Other applications such as high-field BSQED on µZ

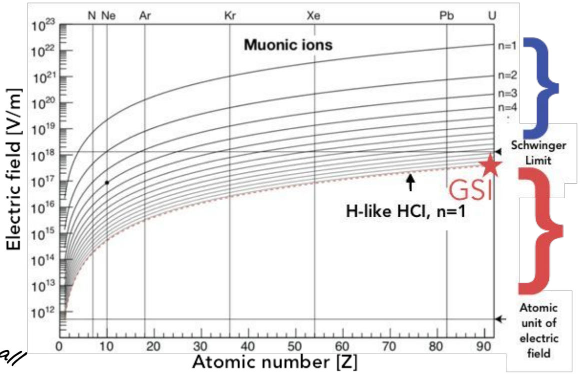
   [Phys. Rev. Lett. 126, 173001](#)

   ↔ hydrogen like high-Z @ GSI (SPARC/SPECTRAP)

In the present letter we have shown that measuring transitions between circular Rydberg states in exotic atoms allows to test BSQED much more accurately than in HCI, without uncertainties due to the nuclear effects, which currently limit BSQED tests. One can realize 1 to 2 orders of magnitude gains in sensitivity with these systems, opening for the first time the possibility of probing second-order QED effects across a broad range of Z. Using state-of-the-art microcalorimeters and high-precision, reference-free x-ray [104, 105] and γ-ray [106, 107] measurements for calibration, it is possible to reach a few ppm accuracy and to test the structure of the vacuum for systems in which the average field strength largely exceeds the Schwinger limit.

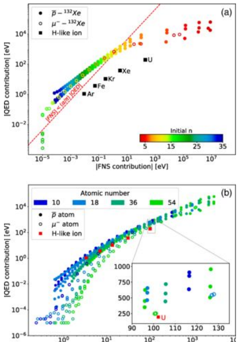
Go to a Rydberg state, so FNS effect is small
Nancy Paul & Paul Indelicato





Energy levels in muonic ions

Energy levels in HCI



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   [Phys. Rev. Lett. 126, 173001](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.173001)
   ↔ hydrogen like high-Z @ GSI (SPARC/SPECTRAP)
4. But first, 6/7Li ΔE_{2P1S} to < 1 eV

Muonic-Atom Spectroscopy and Impact on Nuclear Structure and Precision QED Theory

Aldo Antognini,[1,2,*] Sonia Bacca,[3,4] Andreas Fleischmann,[5] Loredana Gastaldo,[5] Franziska Hagelstein,[2,3,4,†] Paul Indelicato,[6] Andreas Knecht,[2] Vadim Lensky,[3] Ben Ohayon,[1,7,‡] Vladimir Pascalutsa,[3] Nancy Paul,[6] Randolf Pohl,[8,4] and Frederik Wauters[3,4]

[1]Institute for ... witzerland
[2]Laboratory for Particle Ph... lligen-PSI, Switzerland
[3]Institute of Nuclear Physics, ... z, 55099 Mainz, Germany
[4]PRISMA+ Cluster of Excellenc... inz, 55099 Mainz, Germany
[5]Universität Heidelberg ... 7, 69120 Heidelberg
[6]Laboratoir... , CNRS, ENS-PS... ance, Case ... nce
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Recent progress in laser and x-ray spectroscopy of muonic atoms offers promising long-term possibilities at the intersection of atomic, nuclear and particle physics. In muonic hydrogen, laser spectroscopy measurements will determine the ground-state hyperfine splitting (HFS) and additionally improve the Lamb shift by a factor of 5. Precision spectroscopy with cryogenic microcalorimeters has the potential to significantly improve the charge radii of the light nuclei in the $Z = 3 - 8$ range. Complementary progress in precision should be achieved on the theory of nucleon- and nuclear-structure effects. The impact of this muonic-atom spectroscopy program will be amplified by the upcoming results from H and He$^+$ spectroscopy, simple molecules such as HD$^+$ and Penning trap measurements. In this broader context, one can test ab-initio nuclear theories, bound-state QED for two- or three-body systems, and determine fundamental constants, such as the Rydberg (R_∞) and the fine- structure (α) constants.

https://arxiv.org/pdf/2210.16929.pdf

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Draft Proposal for a Collaborative Research Centre

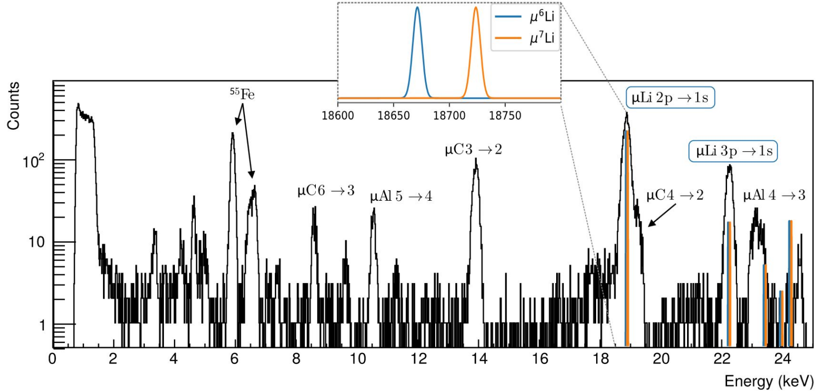
Hadrons and Nuclei as Discovery Tools

1st Funding Period: 2024 - 2027

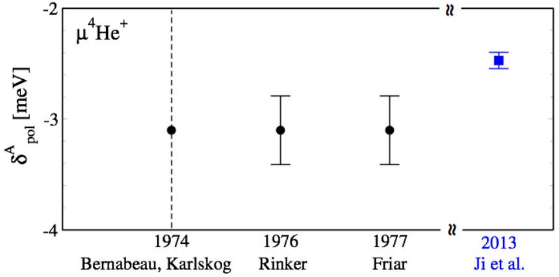
Spokespersons
Prof. Dr. Concettina Sfienti
Prof. Dr. Marc Vanderhaeghen

Research Area
Experimental and Theoretical
Hadron and Nuclear Physics

Institut für Kernphysik
Johannes Gutenberg-Universität Mainz

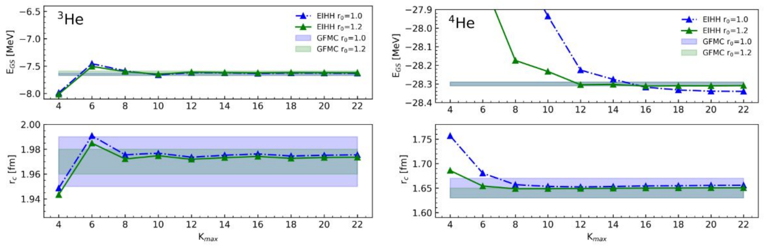


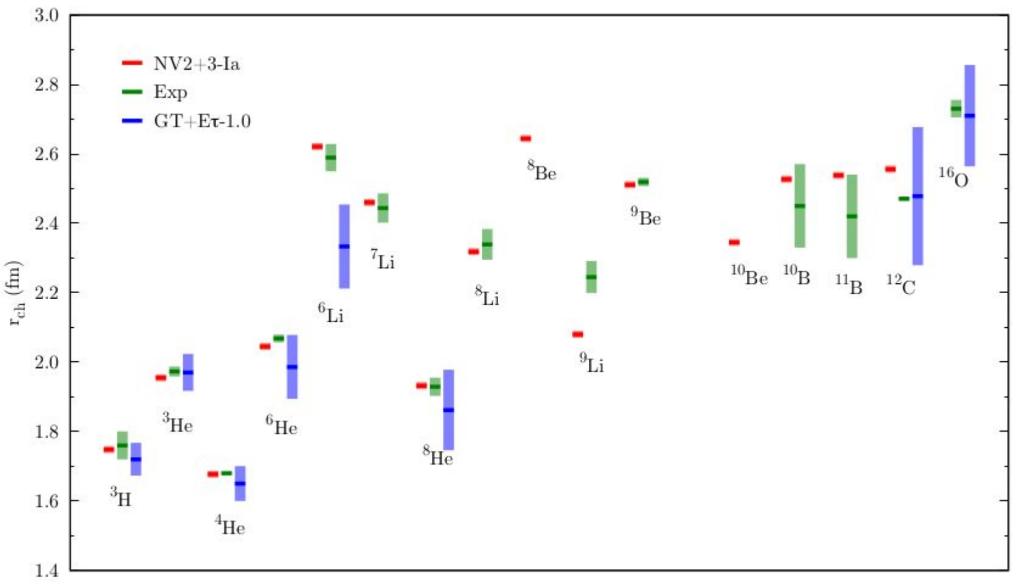
Extra



Benchmark tests

S.S. LM, S. Bacca , N. Barnea, Front. Phys. 9, 671869 (2021)





https://arxiv.org/abs/2001.01374

6Li

E(level)	J^π	$T_{1/2}$	XREF	Comments
0.0	$3/2^-$	stable	AB D FGHIJKLMN PQRS UVWXYZ	XREF: Others: AA T=1/2; μ=+3.2564268 *17* (1996FiZY); Q=−0.0406 *8*

7Li

E(level)	J^π	$T_{1/2}$	XREF	Comments
0.0	$3/2^-$	stable	AB D FGHIJKLMN PQRS UVWXYZ	XREF: Others: AA T=1/2; μ=+3.2564268 *17* (1996FiZY); Q=−0.0406 *8*

9Be

E(level)	J^π	$T_{1/2}$	XREF	Comments
0.0	$3/2^-$	stable	A C E GHI LMNOPQRSTUVWXYZ	XREF: Others: AA T=1/2; μ=−1.1778 *9*; Q=+0.05288 *38*

TABLE IV. Screening in muonic O (constant screening $V_0 = 510.4$ eV).

Transition	Transition energy (keV)	Screening correction (eV)
$4p_{3/2} \to 1s_{1/2}$	166.408	−2.4
$3p_{3/2} \to 1s_{1/2}$	157.714	−0.6
$2p_{3/2} \to 1s_{1/2}$	132.878	−0.1

Isotope	Transition	Linewidth (eV)	Recoil correction (eV)	Recoil previous transition (eV)
^{6}Li	2p1-1s	0.0067	-0.030	0.001
^{7}Li	2p1-1s	0.0068	-0.026	0.001
^{9}Be	2p1-1s	0.021	-0.065	0.002

TPE effect on lambshift according to S. Bacca: 11.8 meV. With n^3 scaling this gives **0.09 eV** for ^{6}Li

TPE effect on lambshift according to S. Bacca: 22.2 meV. With n^3 scaling this gives **0.18 eV** for ^{7}Li

The next generation of laser spectroscopy experiments using light muonic atoms

S Schmidt[1], M Willig[1], J Haack[1], R Horn[1], A Adamczak[2], M Abdou Ahmed[3], F D Amaro[4], P Amaro[5], F Biraben[6], P Carvalho[5] + Show full author list

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