Precise nuclear radii with muonic atoms

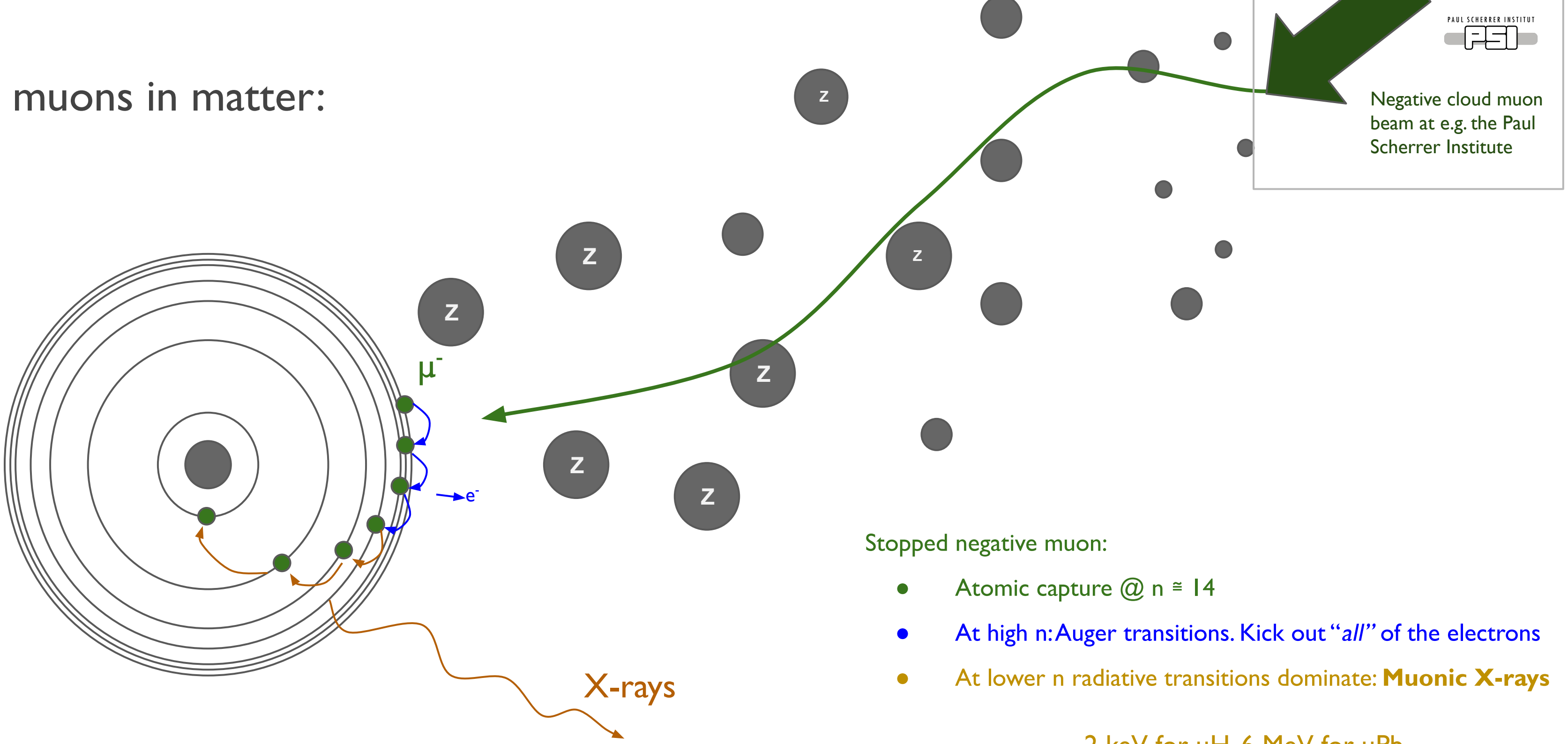
light and not so light nuclei

@ PSI

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

Muonic atoms: what is happening here?

Negative muons in matter:



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

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)

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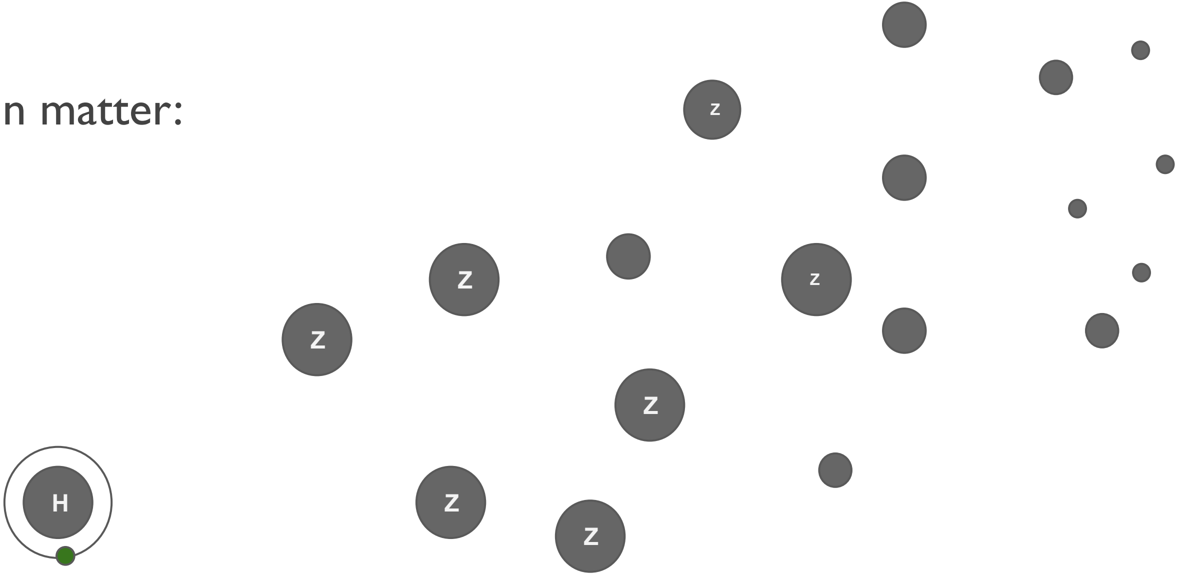

$$\mu p + p \rightarrow (p\mu p)^+$$
$$\mu p + d \rightarrow (p\mu d)^+ \rightarrow (He)^{2+} + \mu$$
$$\rightarrow (\mu^3He)^{2+} + \gamma_{5.5MeV}$$
$$\mu p + Z \rightarrow p + \mu Z$$

Stopped negative muon:

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- At high n: Auger transitions. Kick out "*all*" of the electrons
- At lower n radiative transitions dominate: **Muonic X-rays**
- **μH: neutral, molecular dynamics, transfer, catalyzed fusion**

Free energy?

… not so easy … new effort at PSI

US DMu/DT collaboration

Muonic atoms: what is happening here?

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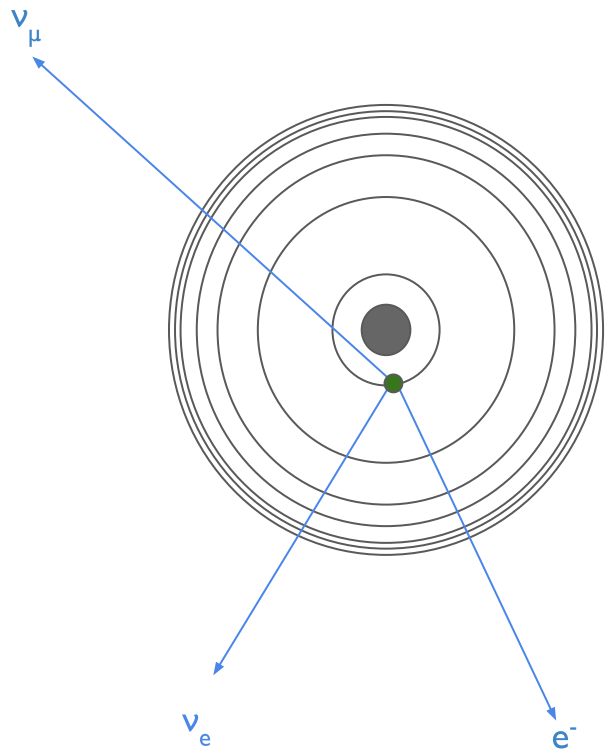

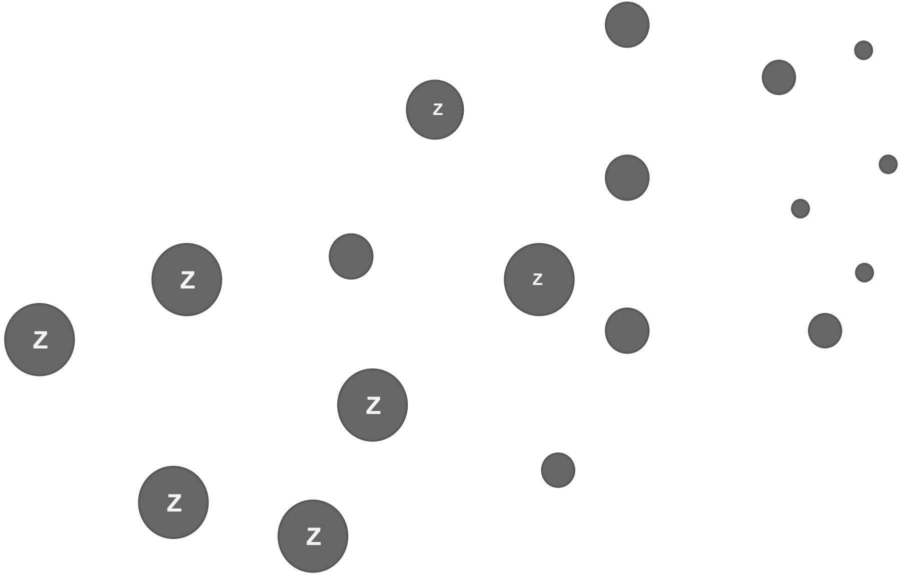

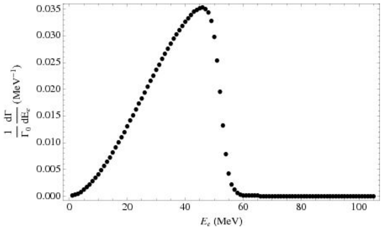

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- **Decay in orbit**

Mu2e and COMET experiments

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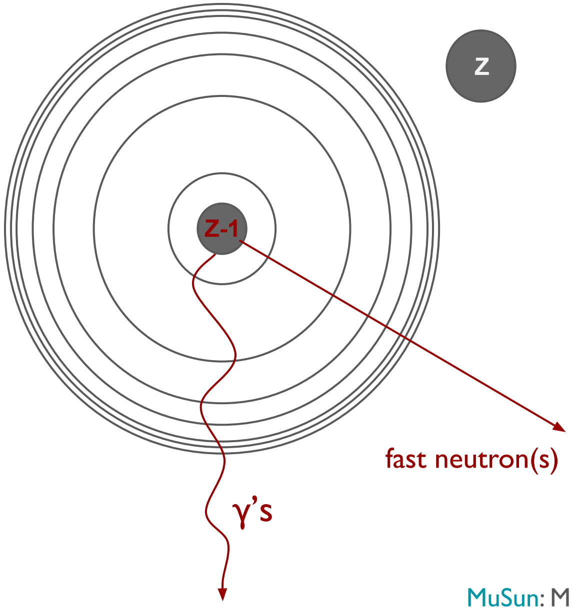

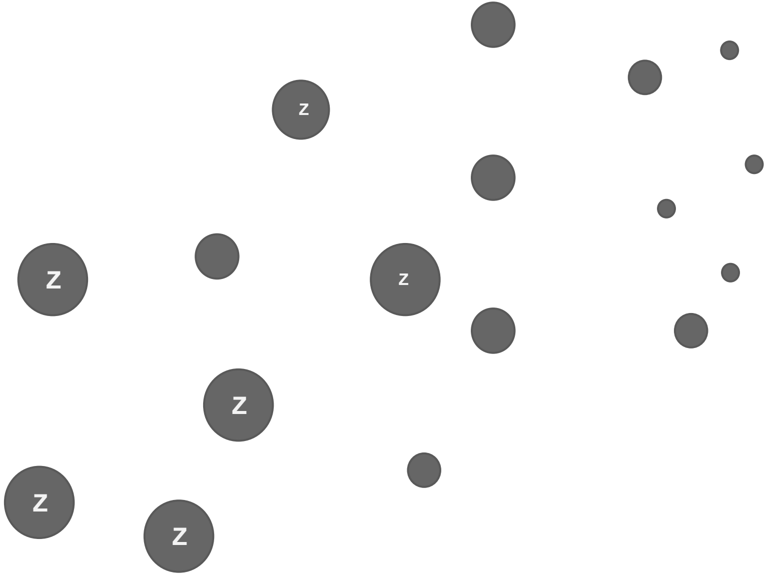

Stopped negative muon:

- Atomic capture @ n ≅ 14
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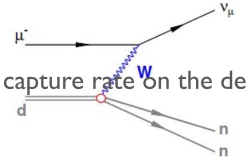
- **Decay in orbit**

or

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



MuSun: Muon capture rate on the deuteron

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 is happening here?

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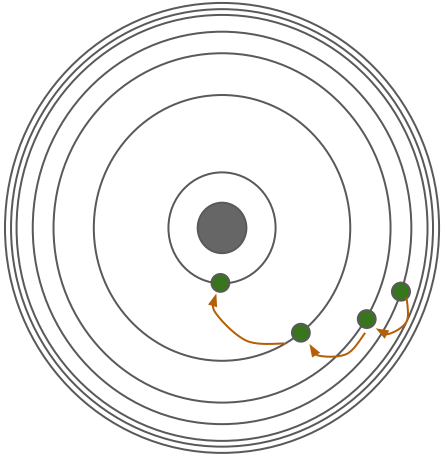


Very much like the H atom, but:

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

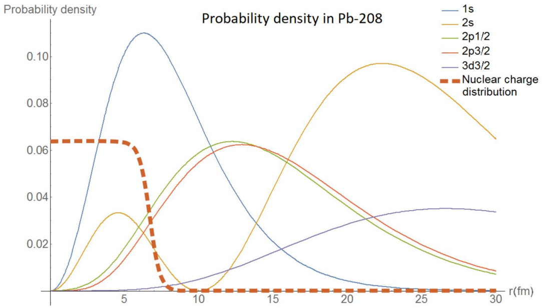
Radii 200 times smaller: significant overlap with the nucleus

The muon lives partially inside the nucleus

E_{1s}(Z=82)

→ 19 MeV (point nucleus)

→ 11 MeV (finite size)



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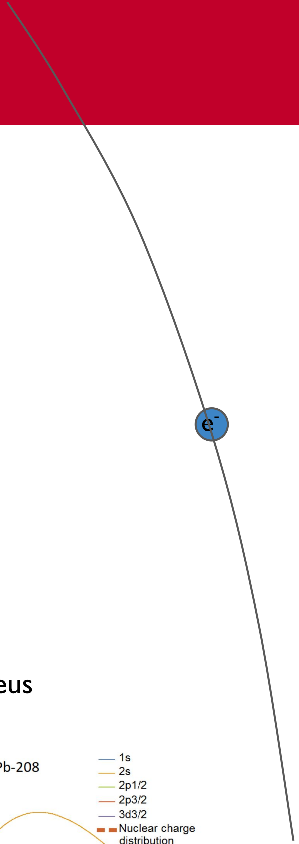

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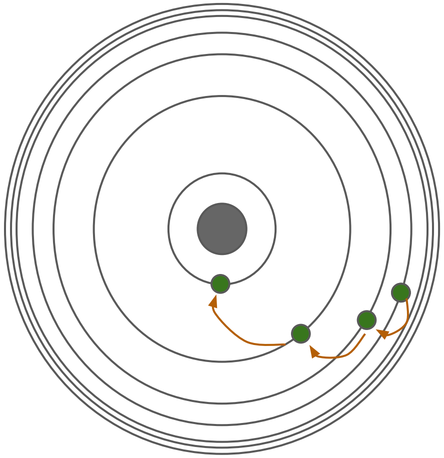

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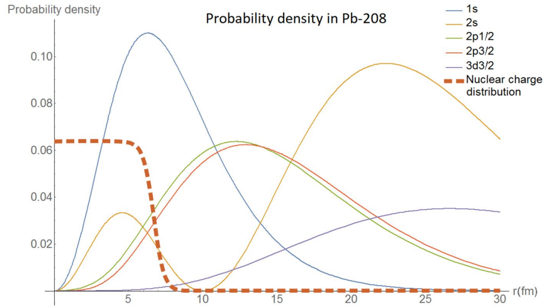
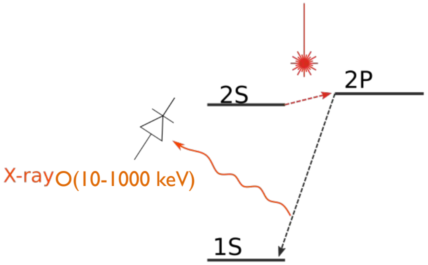


+ most $<r^2>$ of most stable nuclei in the tables

What to do with muonic atoms transitions?

Modern approach with
low Z muonic atoms



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

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Modern approach with
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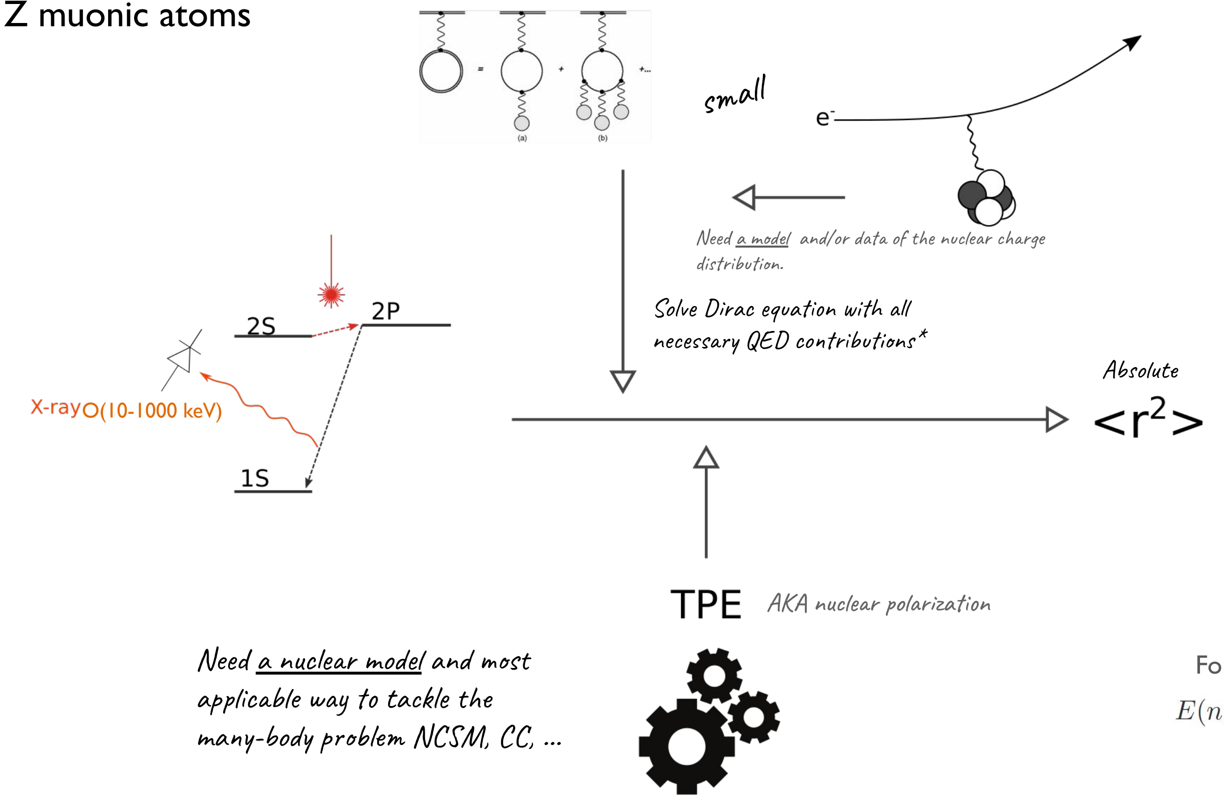


QED, R_∞, …

small

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

Solve Dirac equation with all necessary QED contributions*

Absolute

$<r^2>$

TPE *AKA nuclear polarization*

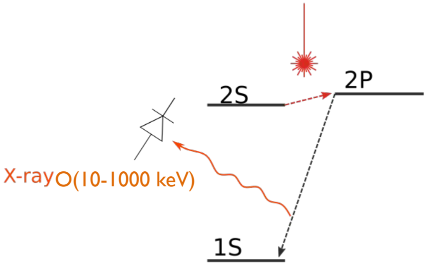
Need a nuclear model and most applicable way to tackle the many-body problem NCSM, CC, …

For Z=1,2 nuclei rigorous description in this RMP

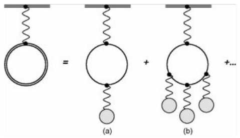
$$E(n,\ell,j)/h = -\frac{cR_\infty}{n^2}\frac{m_{\mathrm{red}}}{m_e} + \frac{E_{NS}}{n^3}\delta_{\ell 0} + \Delta(n,\ell,j)$$

What to do with muonic atoms transitions?

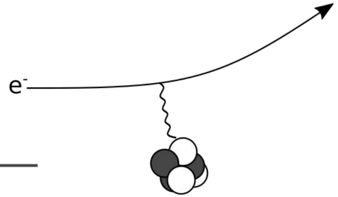
Modern approach with
low Z muonic atoms



QED, R_∞, …



small



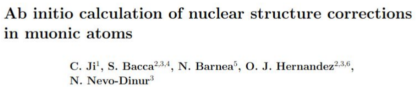
Need a model and/or data of the nuclear charge distribution.

*Solve Dirac equation with all necessary QED contributions**

Absolute

$<r^2>$

Put ab-initio nuclear theory to the test



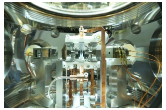
Ab initio calculation of nuclear structure corrections in muonic atoms

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

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

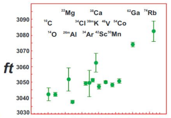
S. J. Novario, D. Lonardoni, S. Gandolfi, and G. Hagen
Phys. Rev. Lett. **130**, 032501 – Published 19 January 2023

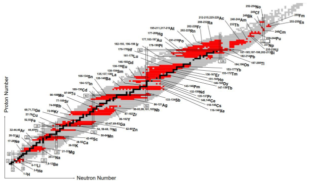
Combine with laser spectroscopy
→ fundamental constants R_∞, r_p



e.g. Thomas Udem @ MPI Munich

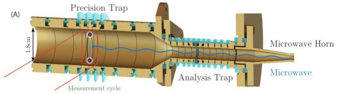
Input for $\delta\nu_i^{AA'} = \frac{A'-A}{AA'} M_i + F_i\,\delta\left\langle r^2\right\rangle^{AA'}$

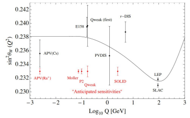




NFS input for precision physics experiments

g-factor measurements at MPI Heidelberg





APV with deformed nuclei

TPE *AKA nuclear polarization*

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

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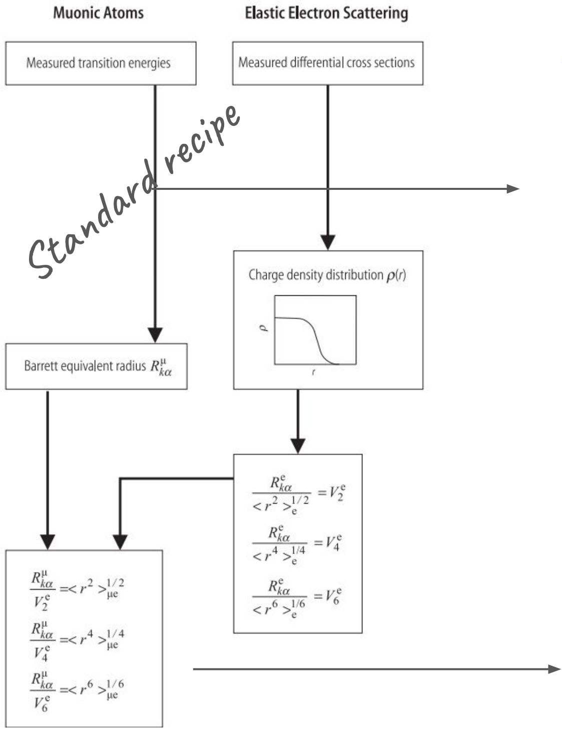
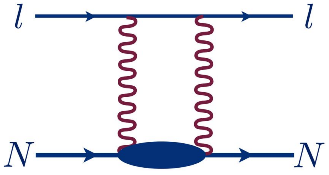
*P. Indelicato Phys. Rev. A 87, 022501

It’s not that simple …

Reference tables of (muonic) charge radii: Fricke & Heilig book, Fricke → Angeli tables



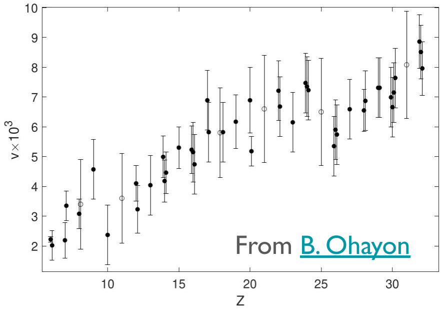


Two Photon exchange / Nuclear polarization recipe from Rinker & Speth (1978)
“we tentatively estimate that our overall results are accurate to within 20 % or 30 %”

Dominant uncertainty for Z>12
handle $\delta r/r < 10^{-3}$ from "the tables" with care

Perturbation theory, $\Delta E_{\rm if} = 4\pi \int \Delta\rho_{\rm c}(r)\left[V_\mu^{(\rm i)}(r) - V_\mu^{(\rm f)}(r)\right] r^2\,{\rm d}r$

Barrett moment → equivalent radius

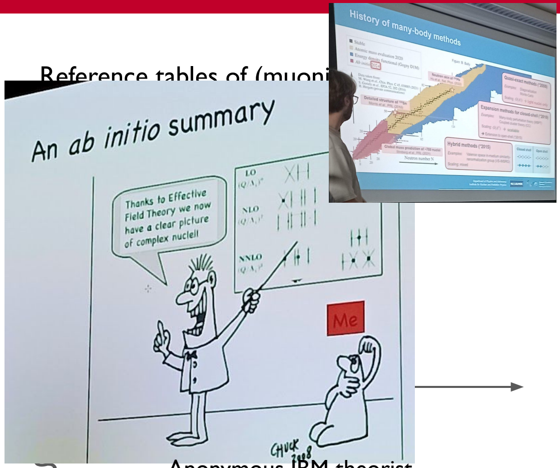


From B. Ohayon

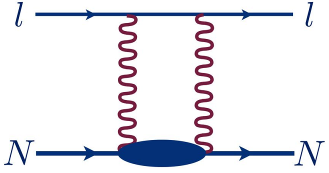
Approximated by Angeli $\delta R = v(Z)\sqrt{\frac{3}{5}}\delta R_{\rm B}, \quad v(Z) = 1 + 0.0035 \times \ln(0.22 \times Z + 1)$

It's not that simple …

Reference tables of (muoni



Anonymous IBM theorist



Two Photon exchange / Nuclear

"we tentatively estimate that our overall results are accu

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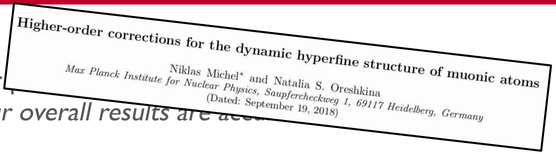
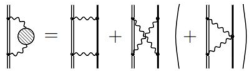


Higher-order corrections for the dynamic hyperfine structure of muonic atoms

Niklas Michel* and Natalia S. Oreshkina

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

(Dated: September 19, 2018)



Dominant uncertainty for $Z>12$

handle $\delta r/r < 10^{-3}$ from "the tables" with care

Perturba

Barrett

$r^2\,\mathrm{d}r$

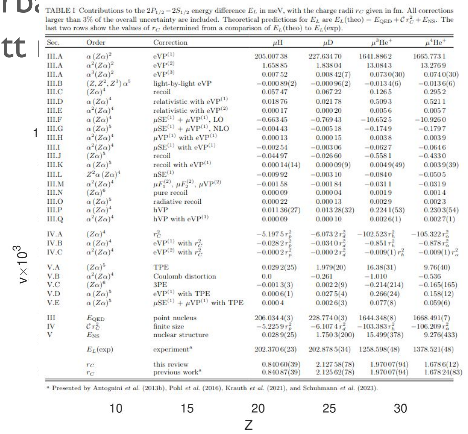
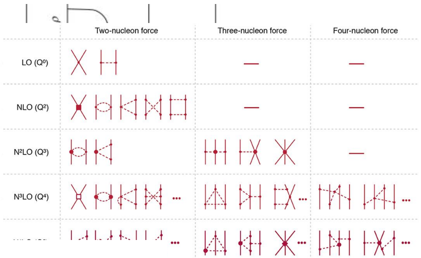


TABLE I Contributions to the $2P_{1/2}-2S_{1/2}$ energy difference E_L in meV, with the charge radii r_C given in fm. All corrections larger than 3% of the overall uncertainty are included. Theoretical predictions for E_L are $E_L(\text{theo}) = E_{\text{QED}} + \mathcal{C}\,r_C^2 + E_{\text{NS}}$. The last two rows show the values of r_C determined from a comparison of E_L(theo) to E_L(exp).

Sec.	Order	Correction	μH	μD	μ^3He$^+$	μ^4He$^+$
III.A	$\alpha(Z\alpha)^2$	eVP$^{(1)}$	205.007 38	227.634 70	1641.886 2	1665.773 1
III.A	$\alpha^2(Z\alpha)^2$	eVP$^{(2)}$	1.658 85	1.838 04	13.084 3	13.276 9
III.A	$\alpha^3(Z\alpha)^2$	eVP$^{(3)}$	0.007 52	0.008 42(7)	0.073 0(30)	0.074 0(30)
III.B	$(Z, Z^2, Z^3)\,\alpha^5$	light-by-light eVP	−0.000 89(2)	−0.000 96(2)	−0.013 4(6)	−0.013 6(6)
III.C	$(Z\alpha)^4$	recoil	0.057 47	0.067 22	0.126 5	0.295 2
III.D	$\alpha(Z\alpha)^4$	relativistic with eVP$^{(1)}$	0.018 76	0.021 78	0.509 3	0.521 1
III.E	$\alpha^2(Z\alpha)^4$	relativistic with eVP$^{(2)}$	0.000 17	0.000 20	0.005 6	0.005 7
III.F	$\alpha(Z\alpha)^4$	μSE$^{(1)}$ + μVP$^{(1)}$, LO	−0.663 45	−0.769 43	−10.652 5	−10.926 0
III.G	$\alpha(Z\alpha)^5$	μSE$^{(1)}$ + μVP$^{(1)}$, NLO	−0.004 43	−0.005 18	−0.174 9	−0.179 7
III.H	$\alpha^2(Z\alpha)^4$	μVP$^{(1)}$ with eVP$^{(1)}$	0.000 13	0.000 15	0.003 8	0.003 9
III.I	$\alpha^2(Z\alpha)^4$	μSE$^{(1)}$ with eVP$^{(1)}$	−0.002 54	−0.003 06	−0.062 7	−0.064 6
III.J	$(Z\alpha)^5$	recoil	−0.044 97	−0.026 60	−0.558 1	−0.433 0
III.K	$\alpha(Z\alpha)^5$	recoil with eVP$^{(1)}$	0.000 14(14)	0.000 09(9)	0.004 9(49)	0.003 9(39)
III.L	$Z^2\alpha(Z\alpha)^4$	nSE$^{(1)}$	−0.009 92	−0.003 10	−0.084 0	−0.050 5
III.M	$\alpha^2(Z\alpha)^4$	$\mu F_1^{(2)}$, $\mu F_2^{(2)}$, μVP$^{(2)}$	−0.001 58	−0.001 84	−0.031 1	−0.031 9
III.N	$(Z\alpha)^6$	pure recoil	0.000 09	0.000 04	0.001 9	0.001 4
III.O	$\alpha(Z\alpha)^5$	radiative recoil	0.000 22	0.000 13	0.002 9	0.002 3
III.P	$\alpha(Z\alpha)^4$	hVP	0.011 36(27)	0.013 28(32)	0.224 1(53)	0.230 3(54)
III.Q	$\alpha^2(Z\alpha)^4$	hVP with eVP$^{(1)}$	0.000 09	0.000 10	0.002 6(1)	0.002 7(1)
IV.A	$(Z\alpha)^4$	r_C^2	$-5.197\,5\,r_p^2$	$-6.073\,2\,r_d^2$	$-102.523\,r_h^2$	$-105.322\,r_\alpha^2$
IV.B	$\alpha(Z\alpha)^4$	eVP$^{(1)}$ with r_C^2	$-0.028\,2\,r_p^2$	$-0.034\,0\,r_d^2$	$-0.851\,r_h^2$	$-0.878\,r_\alpha^2$
IV.C	$\alpha^2(Z\alpha)^4$	eVP$^{(2)}$ with r_C^2	$-0.000\,2\,r_p^2$	$-0.000\,2\,r_d^2$	$-0.009(1)\,r_h^2$	$-0.009(1)\,r_\alpha^2$
V.A	$(Z\alpha)^5$	TPE	0.029 2(25)	1.979(20)	16.38(31)	9.76(40)
V.B	$\alpha^2(Z\alpha)^4$	Coulomb distortion	0.0	−0.261	−1.010	−0.536
V.C	$(Z\alpha)^6$	3PE	−0.001 3(3)	0.002 2(9)	−0.214(214)	−0.165(165)
V.D	$\alpha(Z\alpha)^5$	eVP$^{(1)}$ with TPE	0.000 6(1)	0.027 5(4)	0.266(24)	0.158(12)
V.E	$\alpha(Z\alpha)^5$	μSE$^{(1)}$ + μVP$^{(1)}$ with TPE	0.000 4	0.002 6(3)	0.077(8)	0.059(6)
III	E_{QED}	point nucleus	206.034 4(3)	228.774 0(3)	1644.348(8)	1668.491(7)
IV	$\mathcal{C}\,r_C^2$	finite size	$-5.225\,9\,r_p^2$	$-6.107\,4\,r_d^2$	$-103.383\,r_h^2$	$-106.209\,r_\alpha^2$
V	E_{NS}	nuclear structure	0.028 9(25)	1.750 3(200)	15.499(378)	9.276(433)
	E_L(exp)	experiment[a]	202.370 6(23)	202.878 5(34)	1258.598(48)	1378.521(48)
	r_C	this review	0.840 60(39)	2.127 58(78)	1.970 07(94)	1.678 6(12)
	r_C	previous work[a]	0.840 87(39)	2.125 62(78)	1.970 07(94)	1.678 24(83)

[a] Presented by Antognini *et al.* (2013b), Pohl *et al.* (2016), Krauth *et al.* (2021), and Schuhmann *et al.* (2023).

Barrett equivalent radius $R^{\mu}_{k\alpha}$



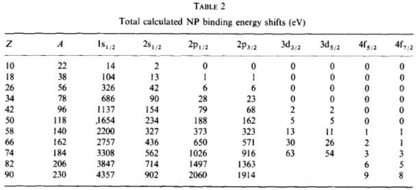


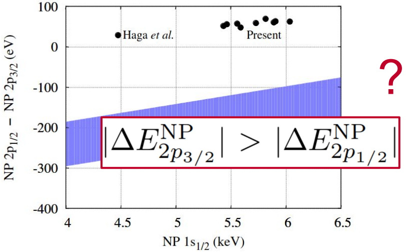
TABLE 2

Total calculated NP binding energy shifts (eV)

Z	A	$1s_{1/2}$	$2s_{1/2}$	$2p_{1/2}$	$2p_{3/2}$	$3d_{3/2}$	$3d_{5/2}$	$4f_{5/2}$	$4f_{7/2}$
10	22	14	2	0	0	0	0	0	0
18	38	104	13	1	1	0	0	0	0
26	56	326	42	6	6	0	0	0	0
34	78	686	90	28	23	0	0	0	0
42	96	1137	154	79	68	2	2	0	0
50	118	.1654	234	188	162	5	5	0	0
58	140	2200	327	373	323	13	11	1	1
66	162	2757	436	650	571	30	26	2	1
74	184	3308	562	1026	916	63	54	3	3
82	206	3847	714	1497	1363			6	5
90	230	4357	902	2060	1914			9	8

Fine structure **anomaly** in Pb, Zr, Sn

https://arxiv.org/abs/2201.09638



$$\left|\Delta E^{\mathrm{NP}}_{2p_{3/2}}\right| > \left|\Delta E^{\mathrm{NP}}_{2p_{1/2}}\right|$$

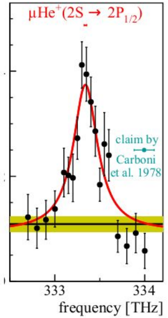
Different (nuclear) theory communities, different era's/methods of evaluation cooked up

$\times \ln(0.22 \times Z + 1)$

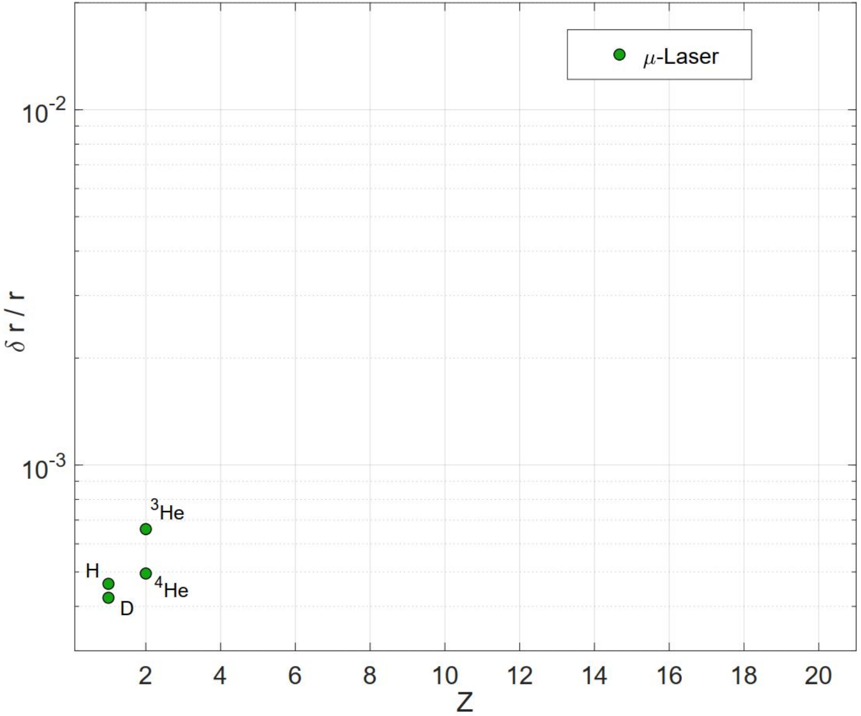
Experimental situation

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

See R. Pohl talk yesterday

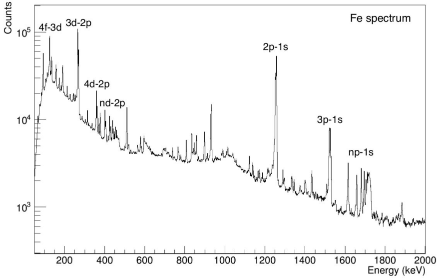


Ultimate precision, however limited the exotic atom transition in-range of lasers and meta-stable initial states



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

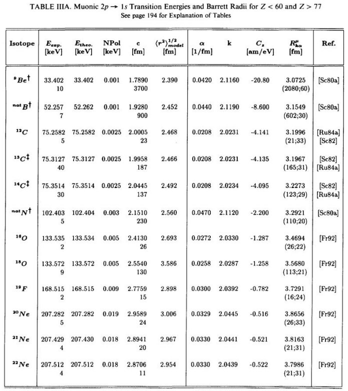
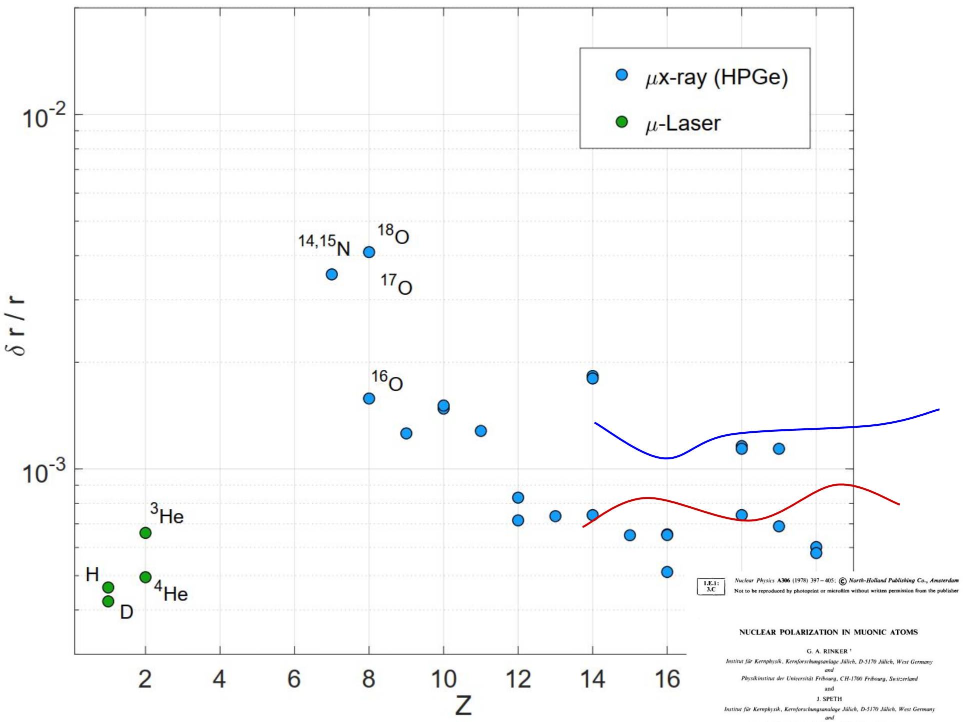


TABLE IIIA. Muonic $2p \rightarrow 1s$ Transition Energies and Barrett Radii for $Z < 60$ and $Z > 77$
See page 194 for Explanation of Tables

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*
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NUCLEAR POLARIZATION IN MUONIC ATOMS

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Physikinstitut der Universität Fribourg, CH-1700 Fribourg, Switzerland
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J. SPETH
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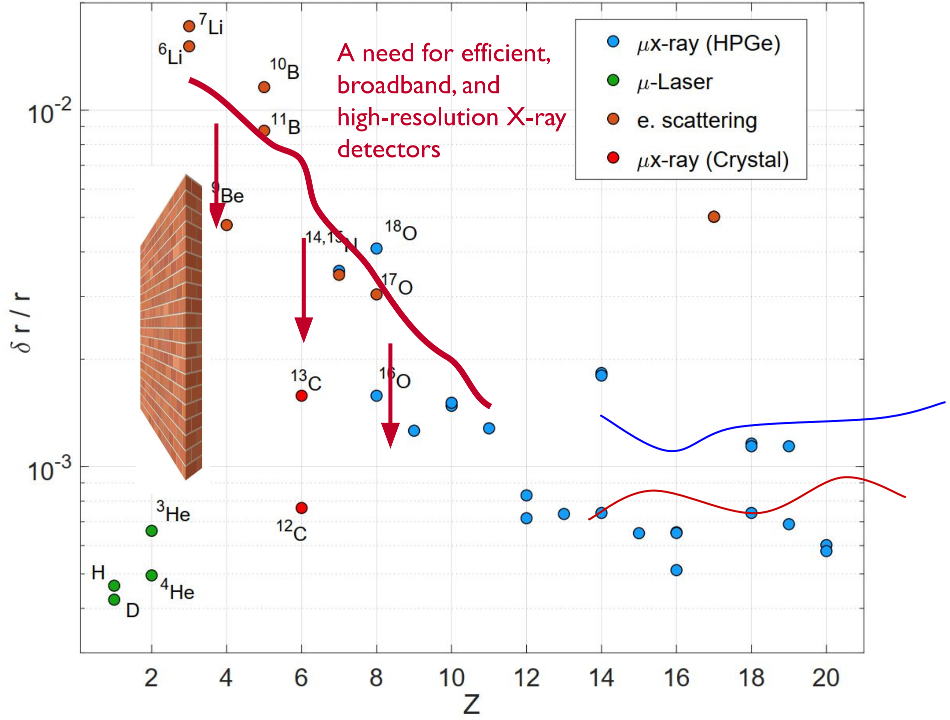
Institut für Physik, Universität Bonn, D-5300 Bonn, West Germany

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

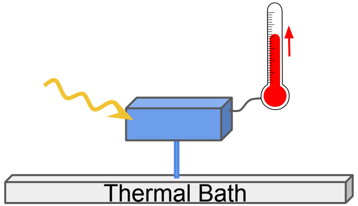
- ❑ Precision muonic atom data for Z=1,2
- ❑ Most of the stable nuclei have been measured with HPGe (70s / 80s)
    - ❑ Z>10 limited by Nuclear polarization / nuclear charge distribution
    - ❑ Z<10 limited by HPGe resolution
- ❑ ~1% precise radii from e-scattering to fill the gap
- ❑ Need for a 1-10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

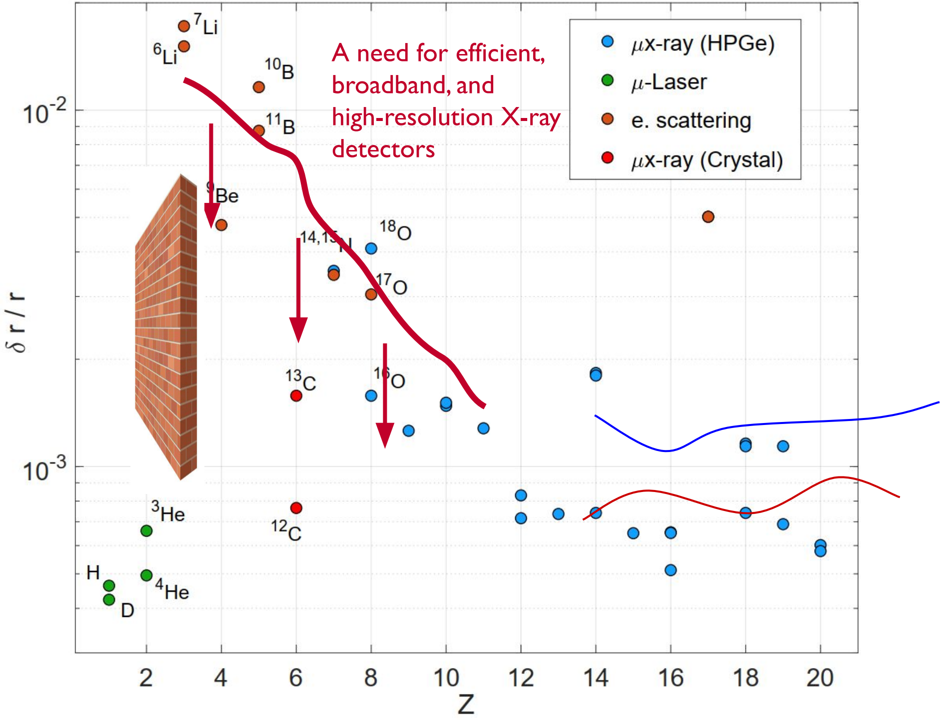
Limitations of solid state X-ray detectors:

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

Unit of heat ≪ Unit of Ionization:

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




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

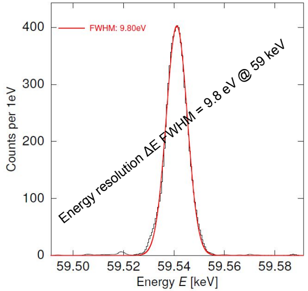
Experimental situation

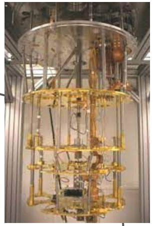
Unit of heat $\ll$ Unit of Ionization

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

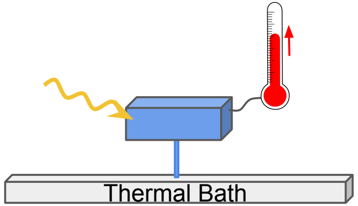
Metallic Magnetic Calorimeters → Unit of spin flip $\ll$ Unit of Ionization

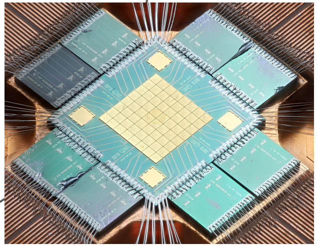
- ❏ Paramagnetic Au:Er Alloy
- ❏ $\Delta\Phi_S \cong \delta M/\delta T \, \Delta T = \delta M/\delta T \times E_{deposited} / C_{tot}$

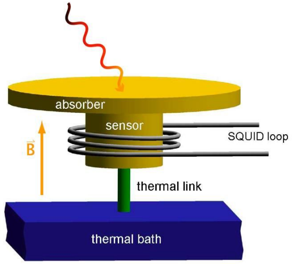


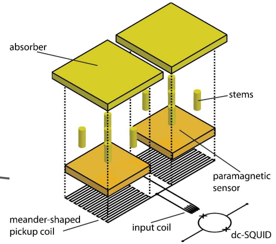


MaX*** sensors developed by HD-KIP for e.g. the ECHO experiment arXiv:2111.09945

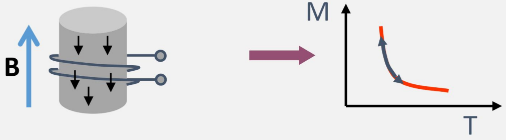








Magnetization of paramagnetic material, MMC

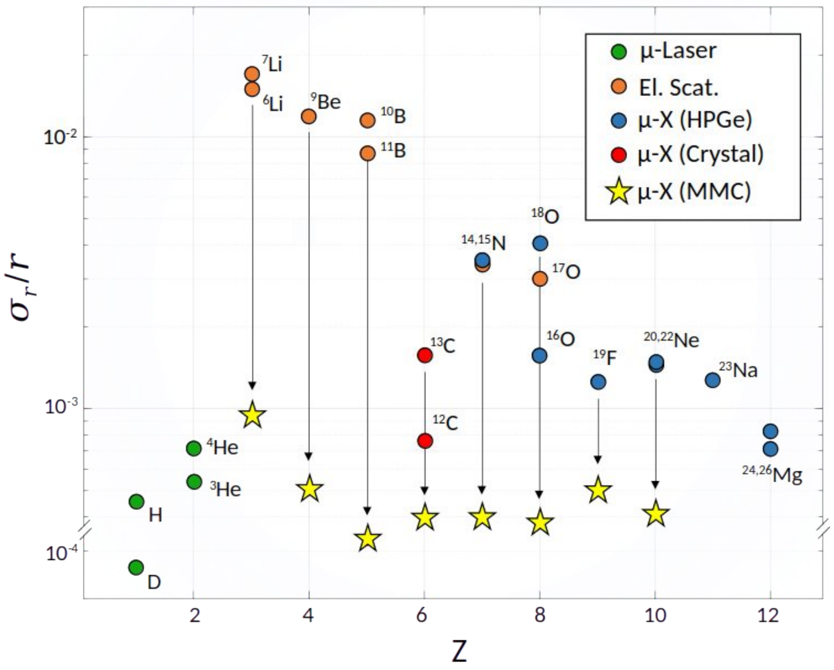


A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63
A.Fleischmann et al., AIP Conf. Proc. 1185 (2009) 571

Spectroscopy with MMCs

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

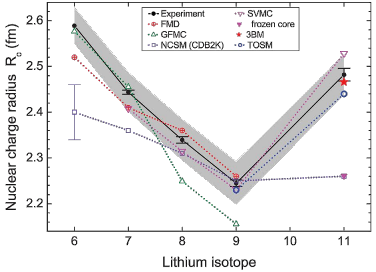
https://doi.org/10.1007/s10909-024-03141-x https://doi.org/10.3390/physics6010015

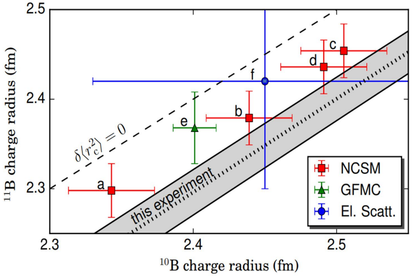


Spectroscopy with MMCs

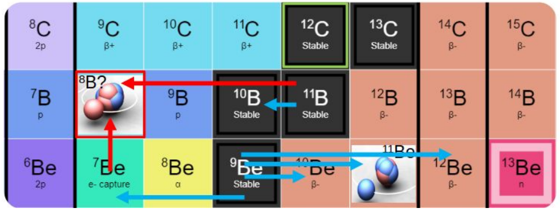
Quartet: interesting because

1. opportunity: big gain in experimental sensitivity 1% → 0.1% for light nuclei
2. few-body systems beyond helium
3. complement/reference existing and future laser spectroscopy data





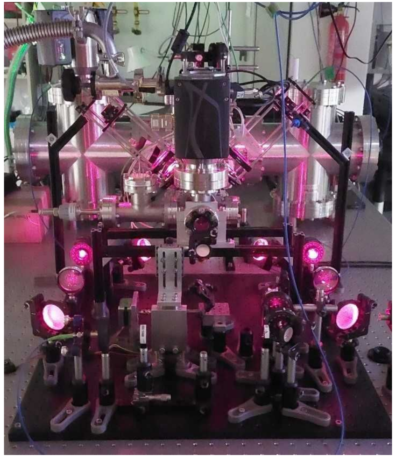
Isotope shifts by W. Nörterhäuser and Co



^{8}C 2p	^{9}C β+	^{10}C β+	^{11}C β+	^{12}C Stable	^{13}C Stable	^{14}C β-	^{15}C β-
^{7}B p	^{8}B?	^{9}B p	^{10}B Stable	^{11}B Stable	^{12}B β-	^{13}B β-	^{14}B β-
^{6}Be 2p	^{7}Be e- capture	^{8}Be α	^{9}Be Stable	^{10}Be β-	^{11}Be	^{12}Be β-	^{13}Be n

Muon can cross Z!

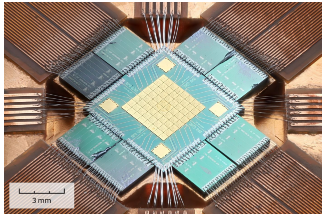
Lithium 2D MOT in Mainz

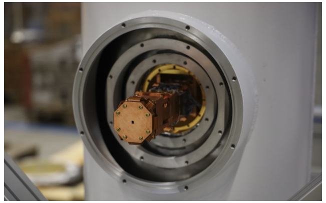


Spectroscopy with MMCs

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

⟶ 2023 test beam at PSI



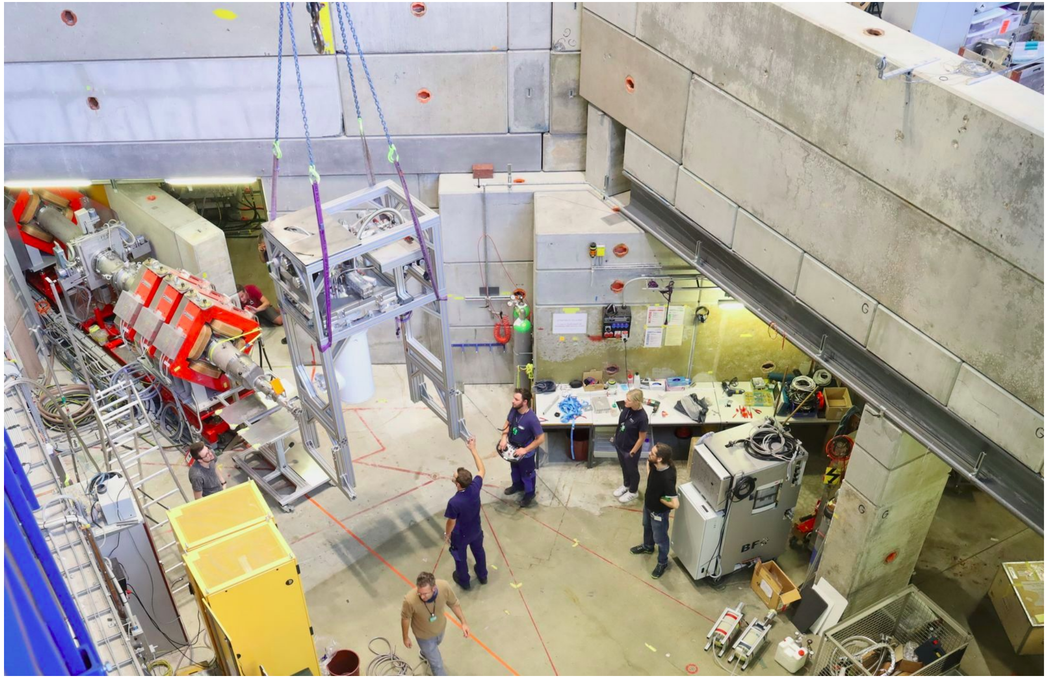


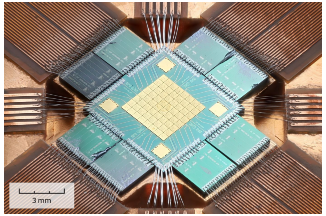
- ➢ Accelerator facility
- ➢ Beamline elements
- ➢ Neutron / electron / x-ray backgrounds (correlated and uncorrelated to the muon)
- ➢ Limited beamtime

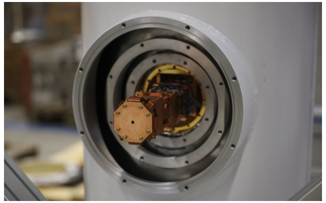
Spectroscopy with MMCs

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

→ 2023 test beam at PSI.







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Spectroscopy with MMCs

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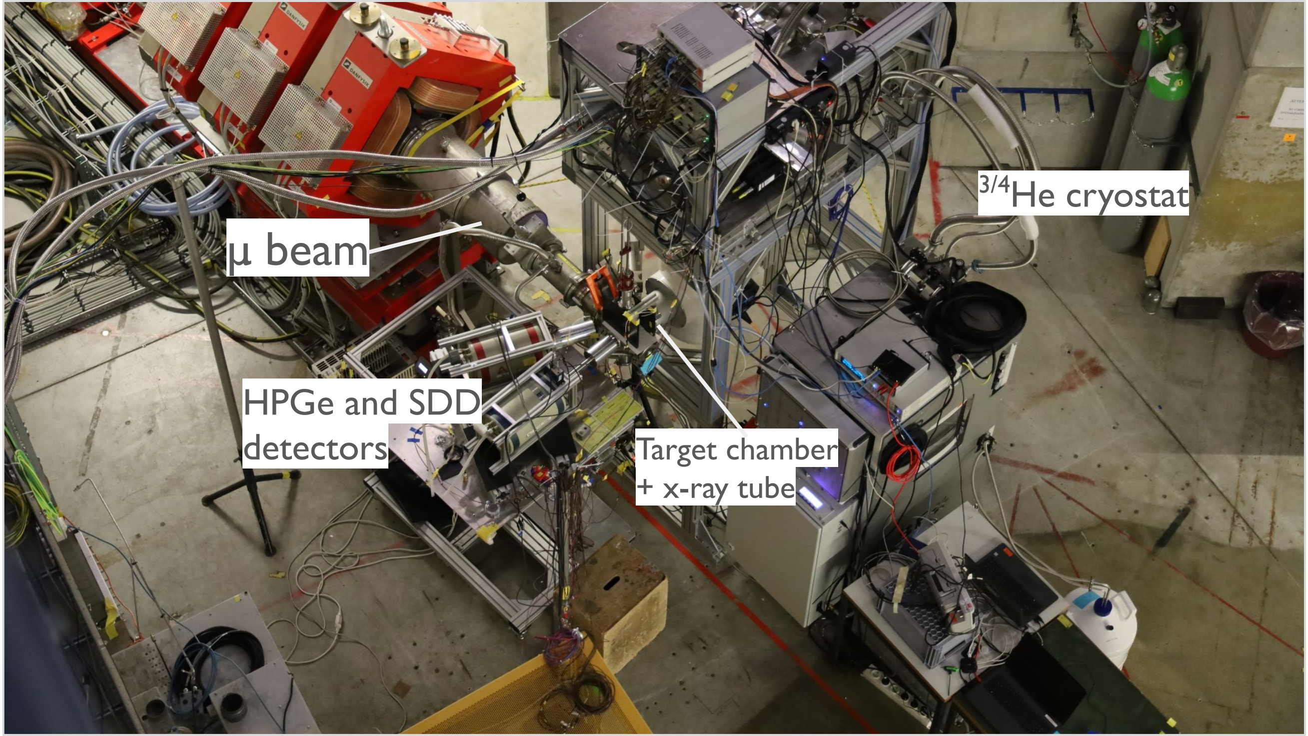

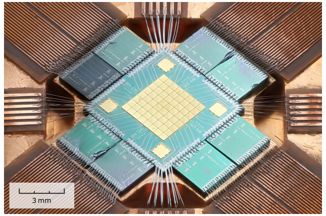

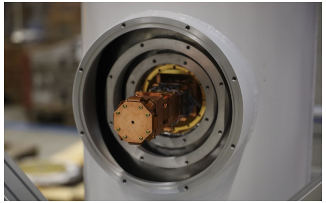

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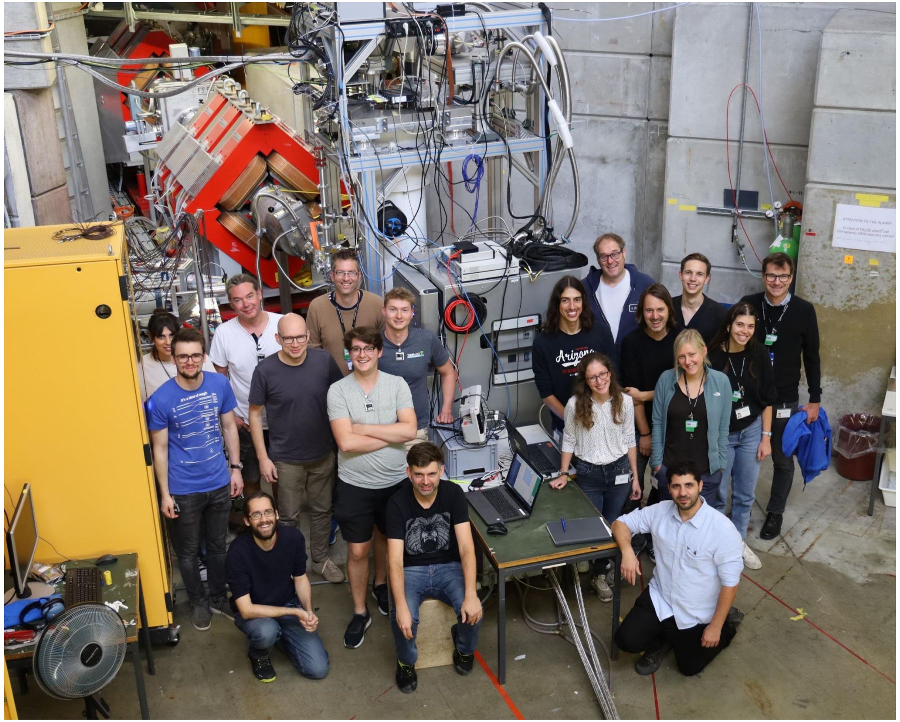

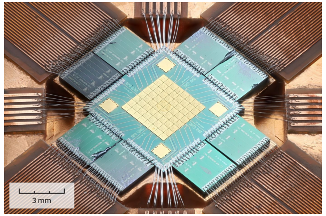

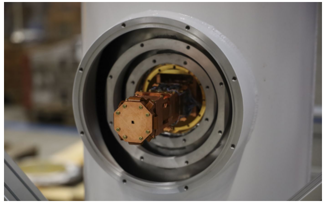

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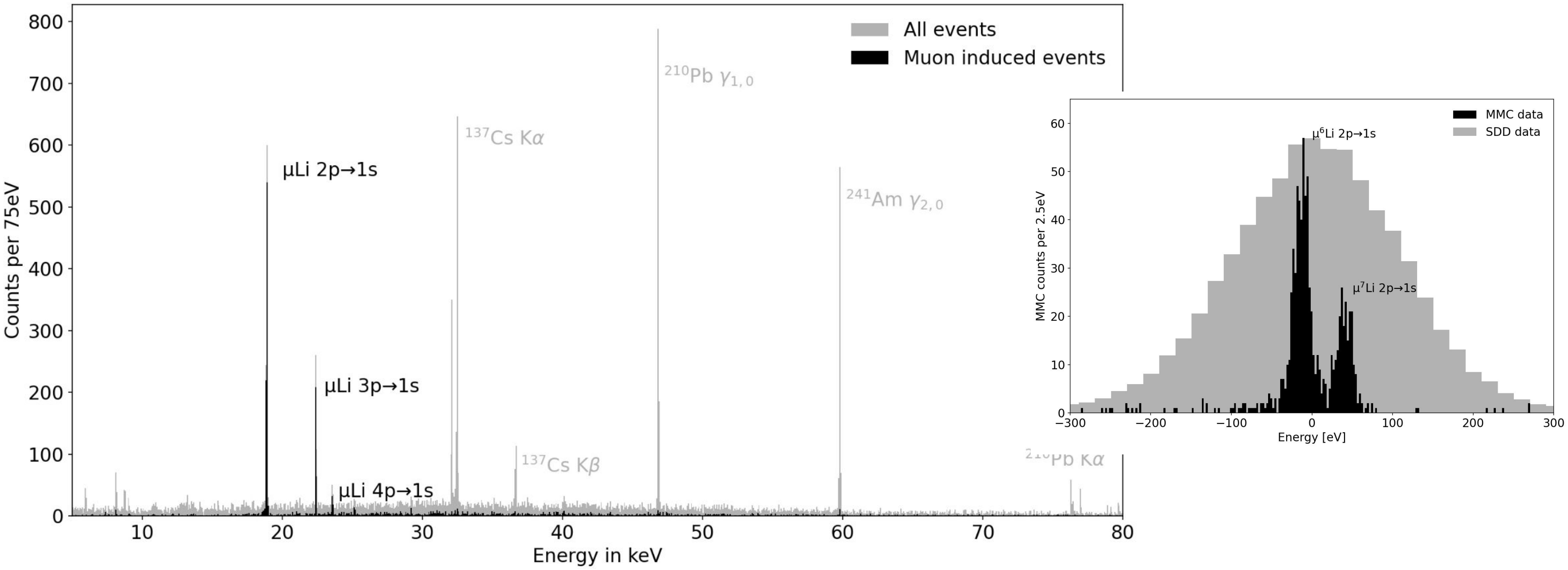
Spectroscopy with MMCs

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

⟶ 2023 test beam at PSI.

⟶ First 6Li and 7Li measurements.



Spectroscopy with MMCs

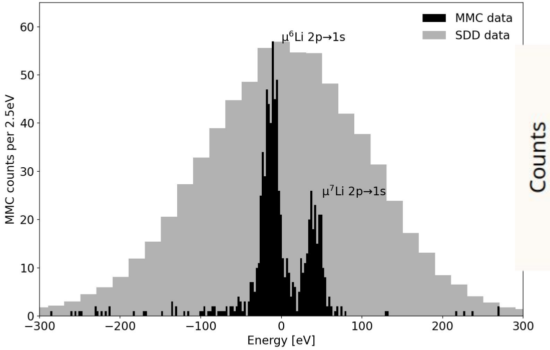
Quartet: MMC from the *basement* to an online experimental environment

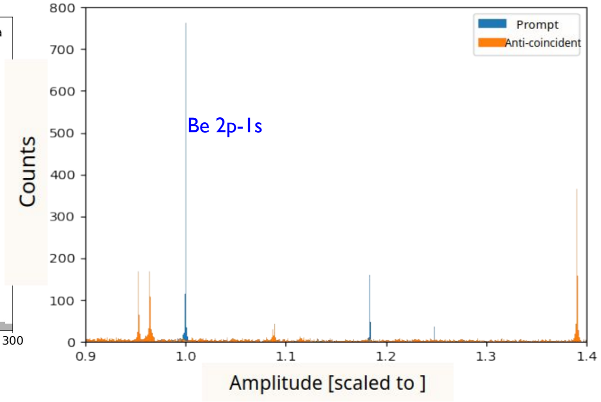
⟶ 2023 test beam at PSI.

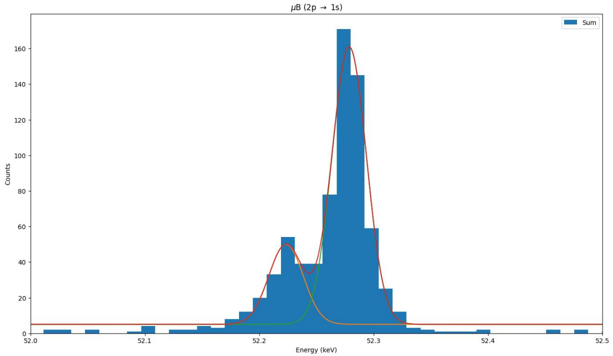
⟶ First 6Li and 7Li measurements.

⟶ Also did some Be & B.

Energy resolutions achieved of 15 eV @ 18-50 keV !







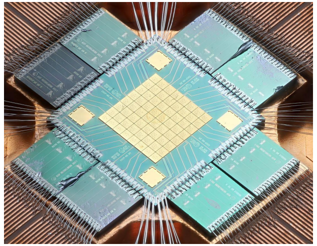
MMCs for muonic X-ray spectroscopy seems to work!

Spectroscopy with MMCs

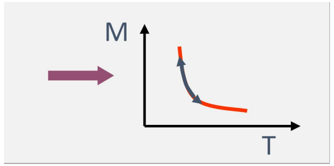
Quartet: MMC from the *basement* to an online experimental environment

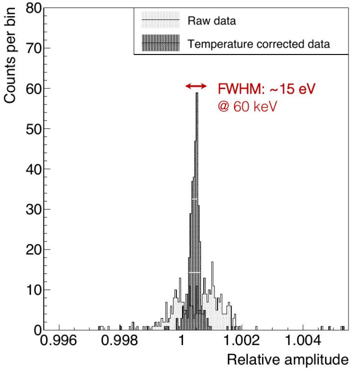
→ 2023 test beam at PSI with Li/B/Be

→ Applying a new technology: it's not that simple

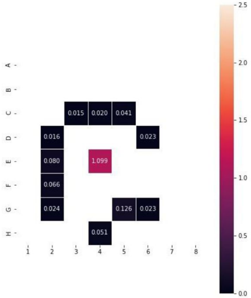


64 pixels thus detectors.
Each with a slightly different
working point/non linearity/…

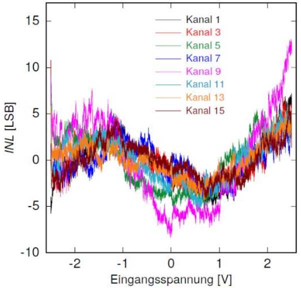




50 MeV *Michel* electrons
light (aka heat) up the entire
detector



At the single-bit limit of our
16-bit ADCs



Spectroscopy with MMCs

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

⟶ 2023 test beam at PSI with Li/B/Be

⟶ Status and prospects with the current proposal

	2p-1s energy	2023 statistical reach	Quartet σ aim **0.1 - 0.3 fm**	NP effect
$^{6/7}$Li	19 keV	0.1 eV	~ 0.05 eV	0.1-0.2
^{9}Be (^{10}Be)	33 keV	0.6 eV	~ 0.1 eV	0.7-0.8
$^{10/11}$B	52 keV	2 eV	~ 0.2 eV	1
$^{12/13}$C	75 keV		~ 0.4 eV	~3
$^{14/15}$N	102 keV		~ 0.5 eV	~5
$^{16/18}$O	134 keV		~ 0.5 eV	~5
^{19}F	169 keV		~ 0.6 eV	~9
$^{20/22}$Ne	207 keV		~ 0.7 eV	~20

New detector needed with thicker absorber

Muli, Poggiallini, Bacca 2020

Drake & Bye 1985

Rinker 1978

Spectroscopy with MMCs

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^{19}F				
$^{20/22}$Ne	207 keV		~ 0.7 eV	~20

Muli, Poggiallini, Bacca 2020

Drake & Bye 1985

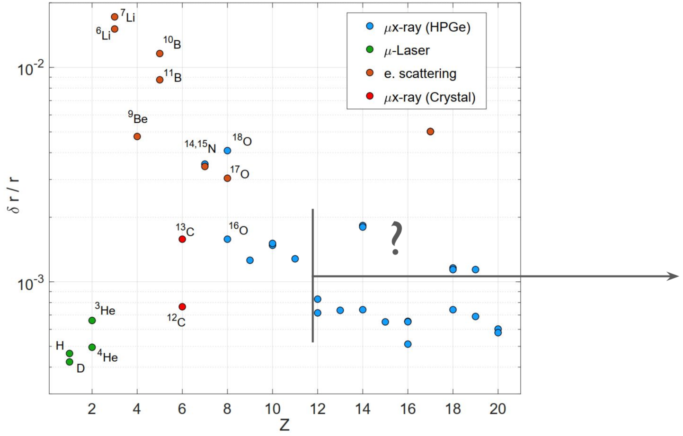
Rinker 1978

New detector needed with thicker absorber

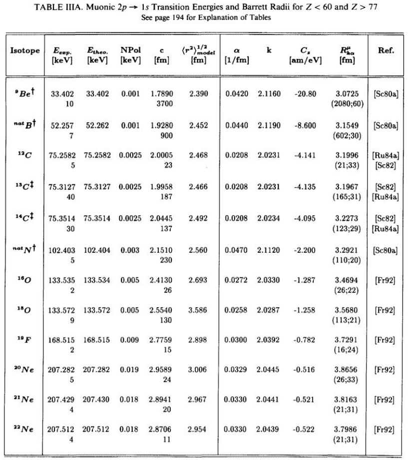
- ☐ New accurate radii of light nuclei coming soon (next beamtime next week)
- ☐ Need reliable/modern/accurate NP input (but not the most precise)

Spectroscopy with MMCs

And Z>10 → reference radii



But *everything* has been done already, and is *input* (NP/distribution) limited



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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]

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

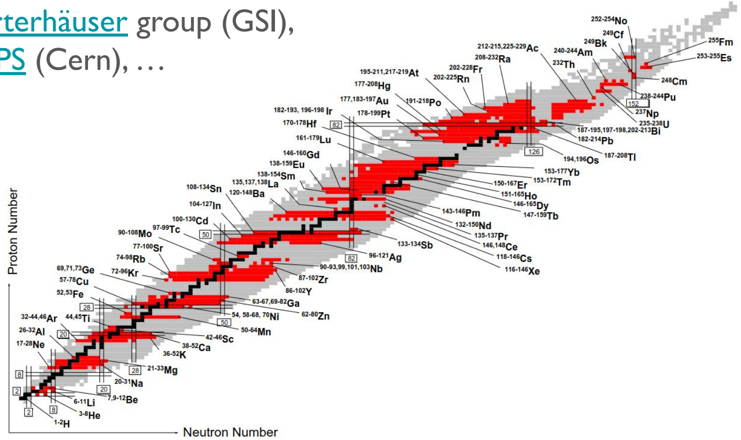
Spectroscopy with MMCs

And Z>10 → reference radii

$$R_{\mathrm{c}}(A) = \sqrt{\underbrace{R_{\mathrm{c}}^2(A_{\mathrm{ref}})} + \delta\langle r_{\mathrm{c}}^2\rangle^{A_{\mathrm{ref}},A}}$$

Need one accurate reference point to anchor the isotopic chain

See Nörterhäuser group (GSI), COLLAPS (Cern), …



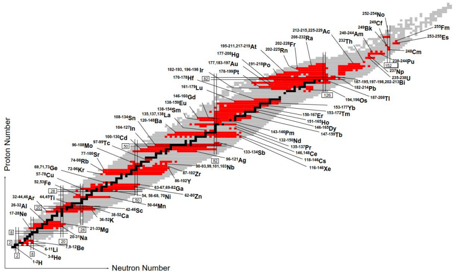
$$\delta\nu_{\mathrm{IS}}^{AA'} \approx K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + F\ \delta\left\langle r_{\mathrm{c}}^2\right\rangle^{AA'}$$

Two more differences experimentally constrain the Mass and Field shift for King plot analysis

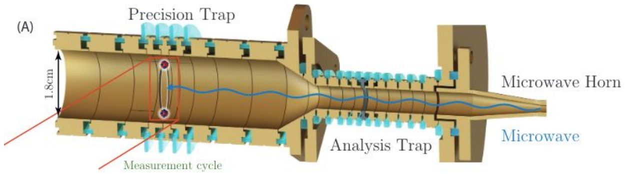
Spectroscopy with MMCs

And Z>10 → reference radii:

- ➢ Generic motivation to support the vast amount of laser spectroscopy data. (Nuclear model tests, nuclear astrophysics input, …)
- ➢ Nuclear physics data → NFS effects of precision experiments



Bound g-factor measurements at MPI Heidelberg



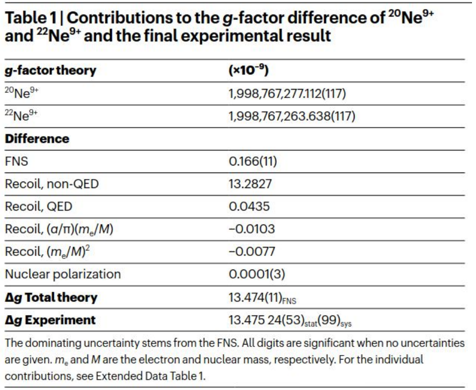
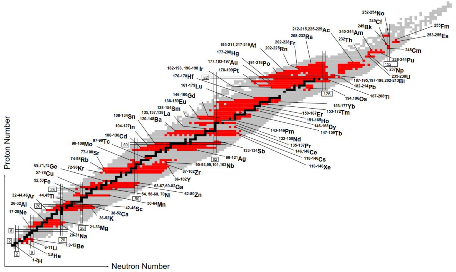


Table 1 | Contributions to the *g*-factor difference of $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$ and the final experimental result

g-factor theory	**(×10⁻⁹)**
$^{20}Ne^{9+}$	1,998,767,277.112(117)
$^{22}Ne^{9+}$	1,998,767,263.638(117)
Difference	
FNS	0.166(11)
Recoil, non-QED	13.2827
Recoil, QED	0.0435
Recoil, $(\alpha/\pi)(m_e/M)$	−0.0103
Recoil, $(m_e/M)^2$	−0.0077
Nuclear polarization	0.0001(3)
Δg Total theory	$13.474(11)_{FNS}$
Δg Experiment	$13.475\,24(53)_{stat}(99)_{sys}$

The dominating uncertainty stems from the FNS. All digits are significant when no uncertainties are given. m_e and M are the electron and nuclear mass, respectively. For the individual contributions, see Extended Data Table 1.

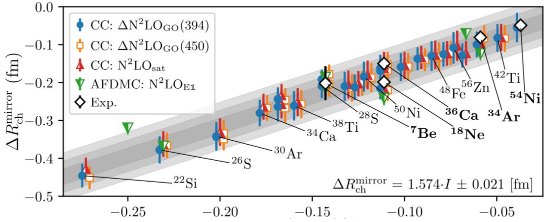
Spectroscopy with MMCs

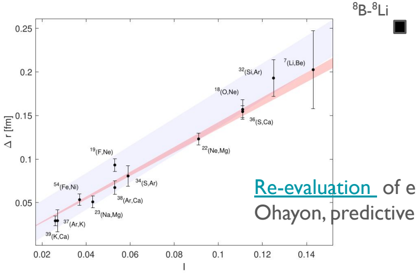


And Z>10 → reference radii:

- Generic motivation to support the vast amount of laser spectroscopy data. (Nuclear model tests, nuclear astrophysics input, …)
- Nuclear physics data → NFS effects of precision experiments
- Isospin difference, isospin triplets & Vud

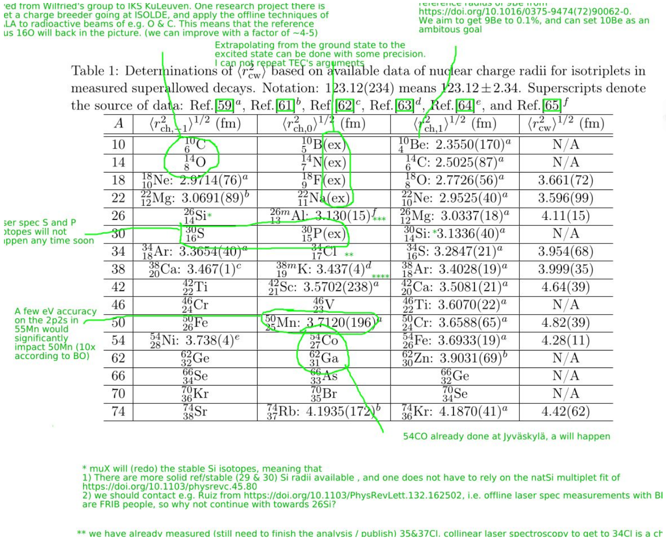
Correlation between ΔI and ΔR





Re-evaluation of experimental input by B. Ohayon, predictive power?

Misha & Seng Vud corrections



ed from Wilfried's group to IKS KuLeuven. One research project there is
et a charge breeder going at ISOLDE, and apply the offline techniques of
LA to radioactive beams of e.g. O & C. This means that the reference
us 16O will back in the picture. (we can improve with a factor of ~4-5)

reference radius of 9Be from
https://doi.org/10.1016/0375-9474(72)90062-0.
We aim to get 9Be to 0.1%, and can set 10Be as an ambitous goal

Extrapolating from the ground state to the excited state can be done with some precision. I can not repeat TEC's arguments

Table 1: Determinations of $\langle r^2_{\mathrm{cw}} \rangle$ based on available data of nuclear charge radii for isotriplets in measured superallowed decays. Notation: 123.12(234) means 123.12 ± 2.34. Superscripts denote the source of data: Ref. [59]^a, Ref. [61]^b, Ref. [62]^c, Ref. [63]^d, Ref. [64]^e, and Ref. [65]^f

A	$\langle r^2_{\mathrm{ch},-1} \rangle^{1/2}$ (fm)	$\langle r^2_{\mathrm{ch},0} \rangle^{1/2}$ (fm)	$\langle r^2_{\mathrm{ch},1} \rangle^{1/2}$ (fm)	$\langle r^2_{\mathrm{cw}} \rangle^{1/2}$ (fm)
10	$^{10}_{6}$C	$^{10}_{5}$B(ex)	$^{10}_{4}$Be: 2.3550(170)^a	N/A
14	$^{14}_{8}$O	$^{14}_{7}$N(ex)	$^{14}_{6}$C: 2.5025(87)^a	N/A
18	$^{18}_{10}$Ne: 2.9714(76)^a	$^{18}_{9}$F(ex)	$^{18}_{8}$O: 2.7726(56)^a	3.661(72)
22	$^{22}_{12}$Mg: 3.0691(89)^b	$^{22}_{11}$Na(ex)	$^{22}_{10}$Ne: 2.9525(40)^a	3.596(99)
26	$^{26}_{14}$Si*	$^{26m}_{13}$Al: 3.130(15)^f***	$^{26}_{12}$Mg: 3.0337(18)^a	4.11(15)
30	$^{30}_{16}$S	$^{30}_{15}$P(ex)	$^{30}_{14}$Si: *3.1336(40)^a	N/A
34	$^{34}_{18}$Ar: 3.3654(40)^a	$^{34}_{17}$Cl **	$^{34}_{16}$S: 3.2847(21)^a	3.954(68)
38	$^{38}_{20}$Ca: 3.467(1)^c	$^{38m}_{19}$K: 3.437(4)^d ****	$^{38}_{18}$Ar: 3.4028(19)^a	3.999(35)
42	$^{42}_{22}$Ti	$^{42}_{21}$Sc: 3.5702(238)^a	$^{42}_{20}$Ca: 3.5081(21)^a	4.64(39)
46	$^{46}_{24}$Cr	$^{46}_{23}$V	$^{46}_{22}$Ti: 3.6070(22)^a	N/A
50	$^{50}_{26}$Fe	$^{50}_{25}$Mn: 3.7120(196)^a	$^{50}_{24}$Cr: 3.6588(65)^a	4.82(39)
54	$^{54}_{28}$Ni: 3.738(4)^e	$^{54}_{27}$Co	$^{54}_{26}$Fe: 3.6933(19)^a	4.28(11)
62	$^{62}_{32}$Ge	$^{62}_{31}$Ga	$^{62}_{30}$Zn: 3.9031(69)^b	N/A
66	$^{66}_{34}$Se	$^{66}_{33}$As	$^{66}_{32}$Ge	N/A
70	$^{70}_{36}$Kr	$^{70}_{35}$Br	$^{70}_{34}$Se	N/A
74	$^{74}_{38}$Sr	$^{74}_{37}$Rb: 4.1935(172)^b	$^{74}_{36}$Kr: 4.1870(41)^a	4.42(62)

ser spec S and P
otopes will not
ppen any time soon

A few eV accuracy on the 2p2s in 55Mn would significantly impact 50Mn (10x according to BO)

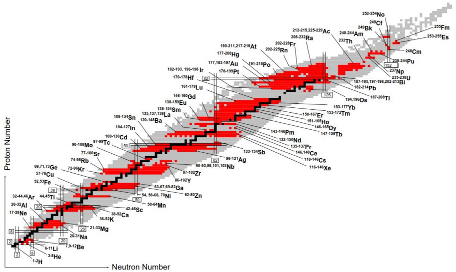
54CO already done at Jyväskylä, a will happen

* muX will (redo) the stable Si isotopes, meaning that
1) There are more solid ref/stable (29 & 30) Si radii available , and one does not have to rely on the natSi multiplet fit of https://doi.org/10.1103/physrevc.45.80
2) we should contact e.g. Ruiz from https://doi.org/10.1103/PhysRevLett.132.162502, i.e. offline laser spec measurements with Bl
are FRIB people, so why not continue with towards 26Si?

** we have already measured (still need to finish the analysis / publish) 35&37Cl. collinear laser spectroscopy to get to 34Cl is a ch

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

Spectroscopy with MMCs



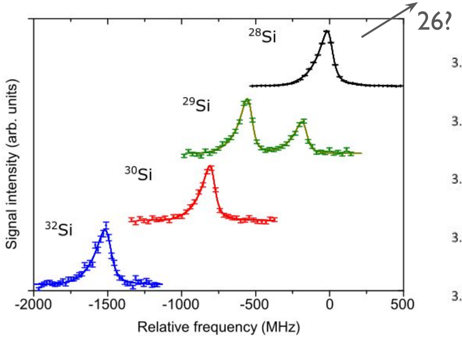
And Z>10 → reference radii:

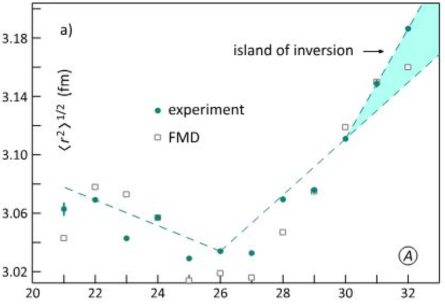
- ➢ Generic motivation to support the vast amount of laser spectroscopy data. (Nuclear model tests, nuclear astrophysics input, …)
- ➢ Nuclear physics data → NFS effects of precision experiments
- ➢ Isospin difference, isospin triplets & Vud

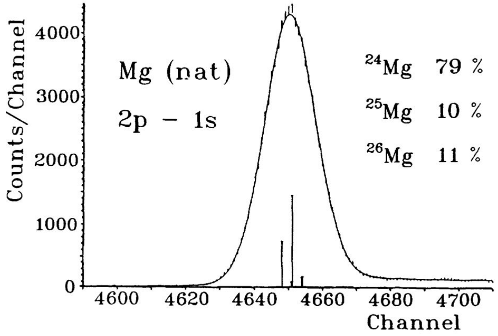
→ There is some low-hanging fruit,

e.g. laser spectroscopy on Si and Mg relying on natSi and natMg data

muX at PSI will measure with isotopically pure Si target this year (well, this week!)







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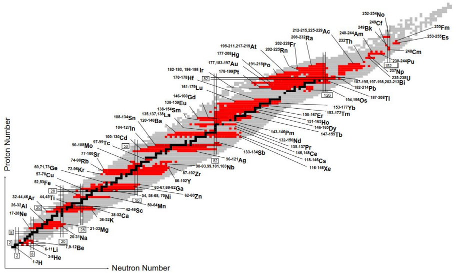
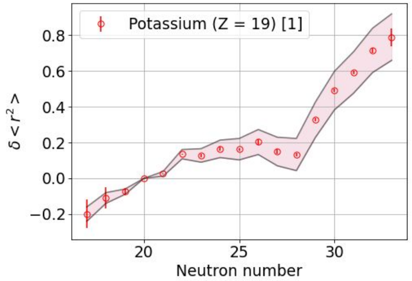


→ There is some low-hanging fruit,
e.g. laser spectroscopy on Si and Mg relying on natSi and natMg data
muX at PSI will measure with isotopically pure Si target this year (well, this week!)

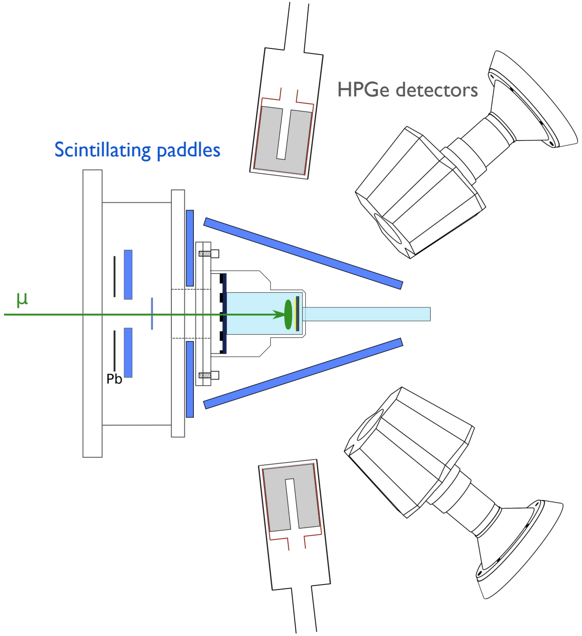
→ To make a significant impact on a chain, measure 3 isotopes with μZ, of which one is quite often not stable

Traditional muonic atom spectroscopy requires macroscopic targets → stable isotopes

What about long lived isotopes?

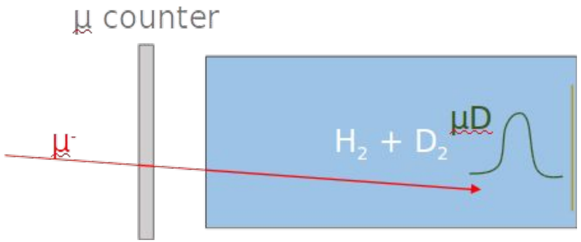


Radioactive targets



So we have:

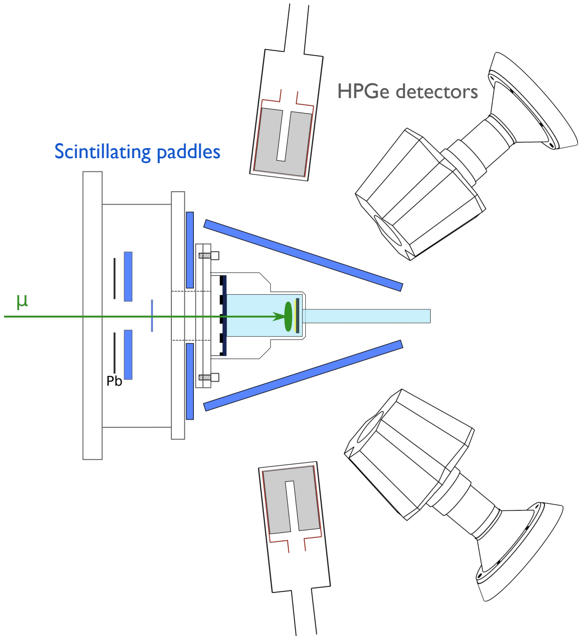
- ➢ μ-time → t=0
- ➢ Beam halo veto
- ➢ μ decay in orbit time
- ➢ X-ray time/energy/angle



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

Radioactive targets



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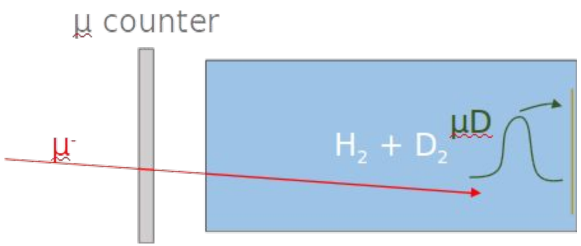

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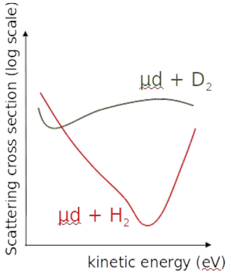
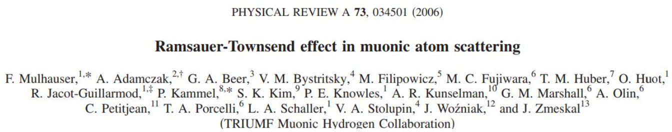
3. μD moves freely through H2 gas at ca. 5 eV

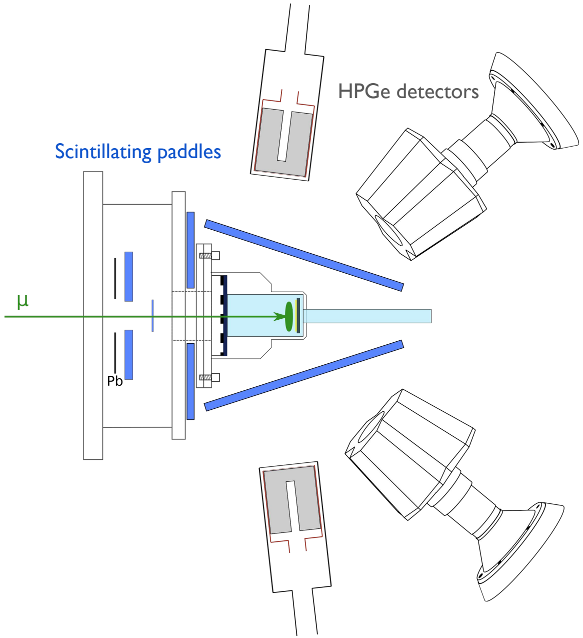



PHYSICAL REVIEW A **73**, 034501 (2006)

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



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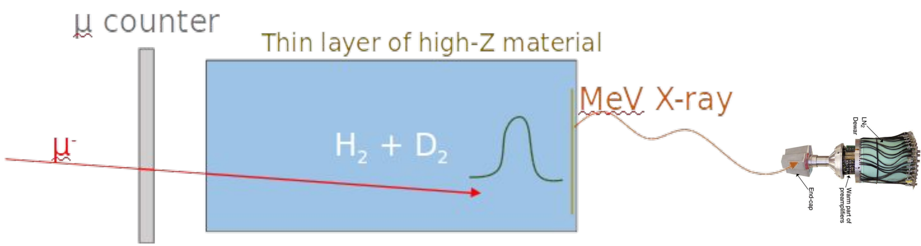

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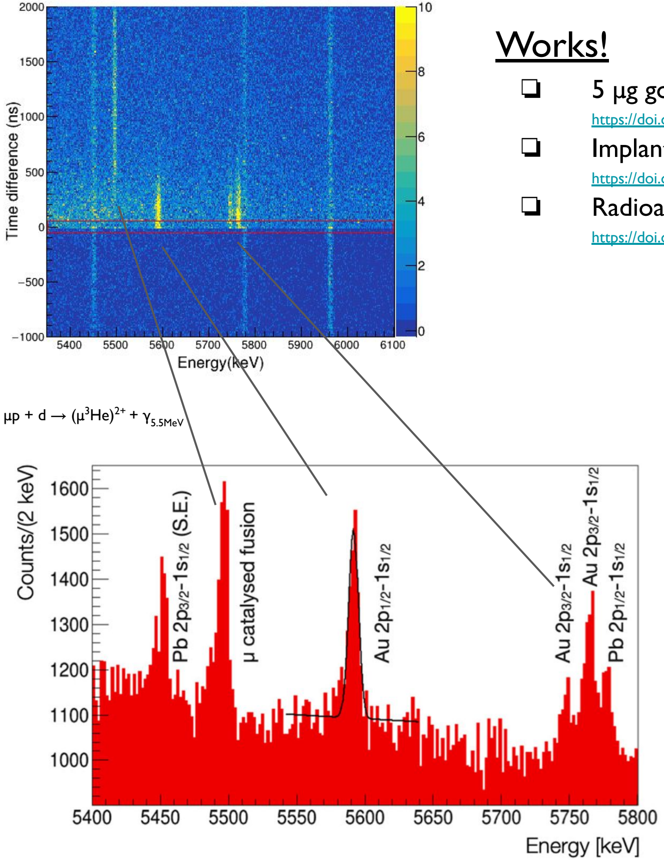
2. Transfer from μH to μD in ~100 ns + 45 eV of kinetic energy
3. μD moves freely through H2 gas at ca. 5 eV
4. Upon hitting the chamber walls: μD → μZ transfer

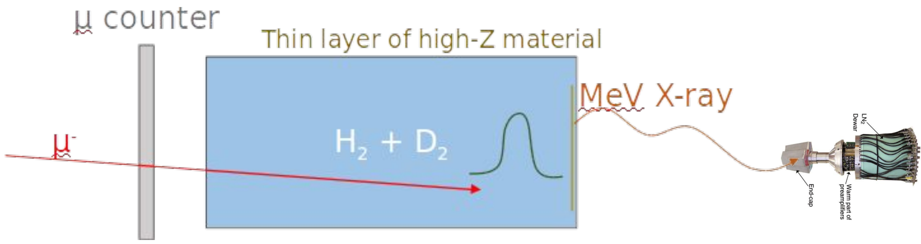
Radioactive targets

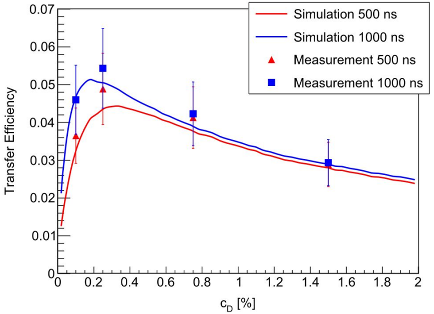


$\mu p + d \rightarrow (\mu^3He)^{2+} + \gamma_{5.5MeV}$

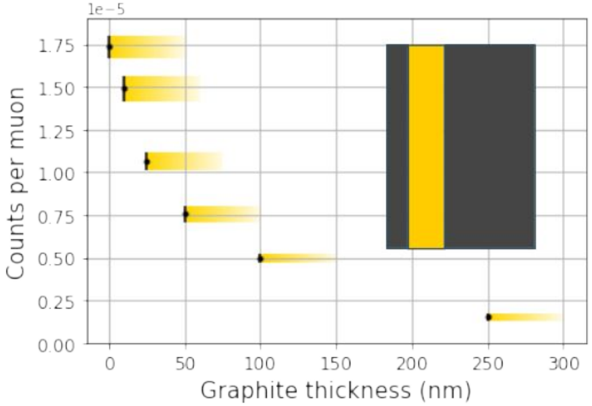
Works!

- ❑ 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



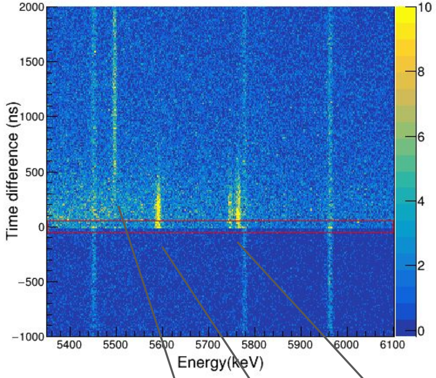


We need *surface* targets, but can get away with a shallow implantatio



Radioactive targets

Since 2017 muX has been running a decent size HPGe array + transfer targ



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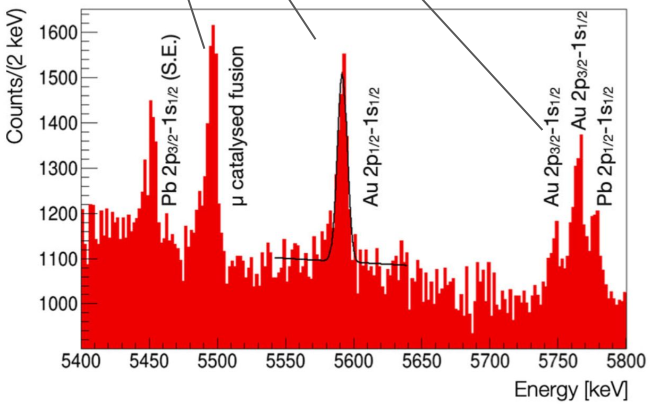

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  https://doi.org/10.1140/epja/s10050-023-00930-y
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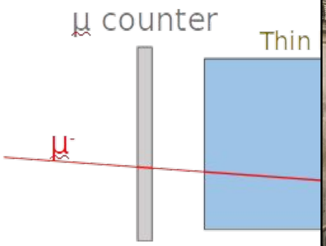
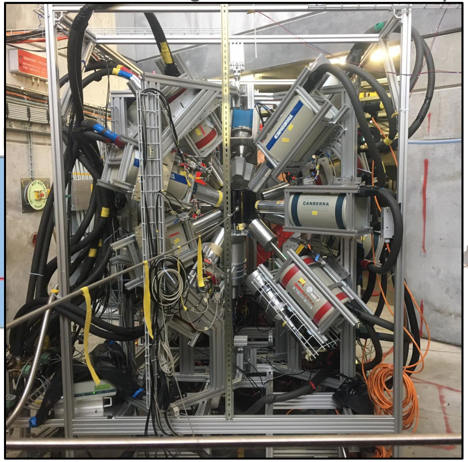
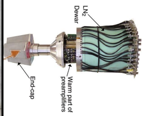
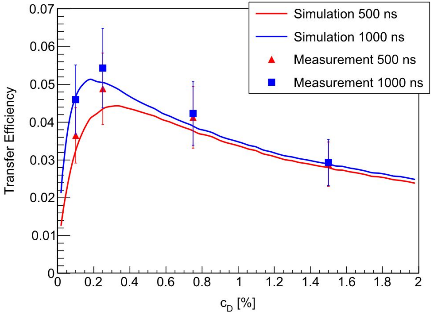
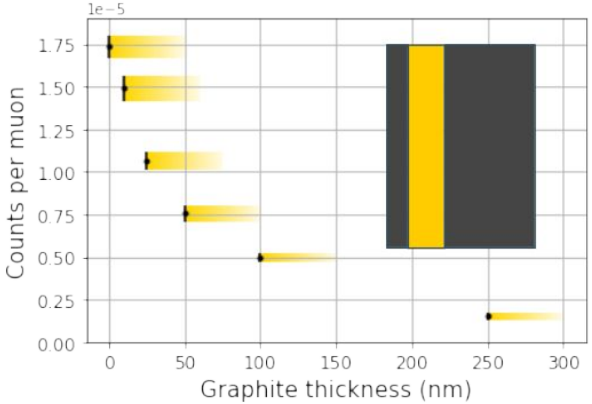






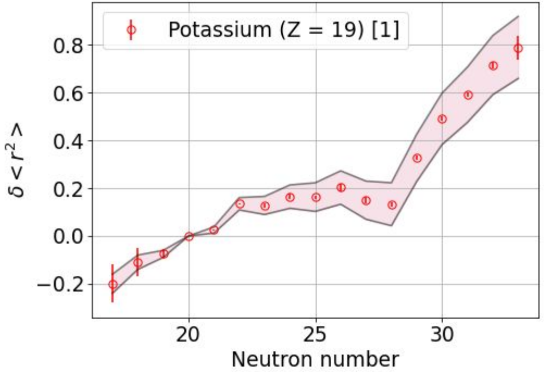


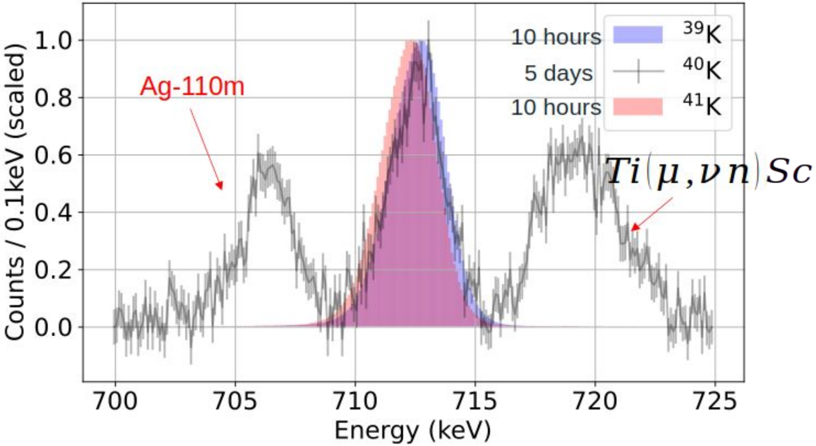


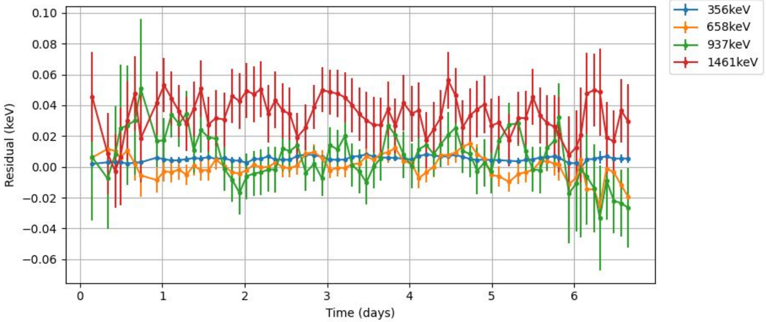
Radioactive targets

And Z>10 → reference radii:

- First data with $^{39/40/41}$K
- With a <r^2> sensitivity of ~0.1% / 100 eV, We control the HPGe detectors to a few 10 eV (< 20 ppm!)



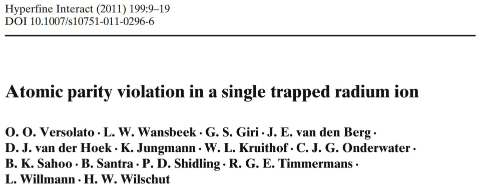




Heavy nuclei

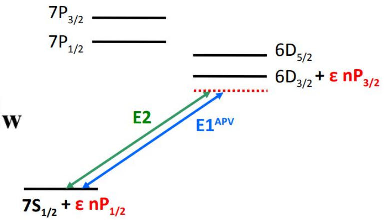
Why heavy nuclei? → *our* main target is 226Ra because of APV

- Unstable nuclei


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

Atomic parity violation in a single trapped radium ion

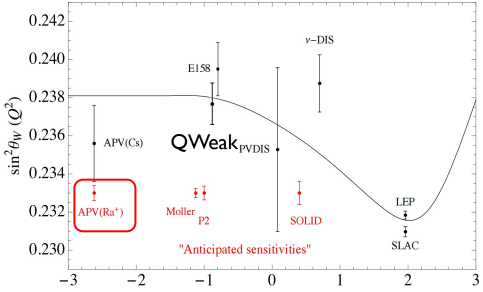
O. O. Versolato · L. W. Wansbeek · G. S. Giri · J. E. van den Berg ·
D. J. van der Hoek · K. Jungmann · W. L. Kruithof · C. J. G. Onderwater ·
B. K. Sahoo · B. Santra · P. D. Shidling · R. G. E. Timmermans ·
L. Willmann · H. W. Wilschut



muX @ PSI 2016 ←

$$E1_{PNC} = \boxed{K_r}\, Z^3\, Q_W$$

Limited progress in the last 10 years, some Ba+ spectroscopy, some ….



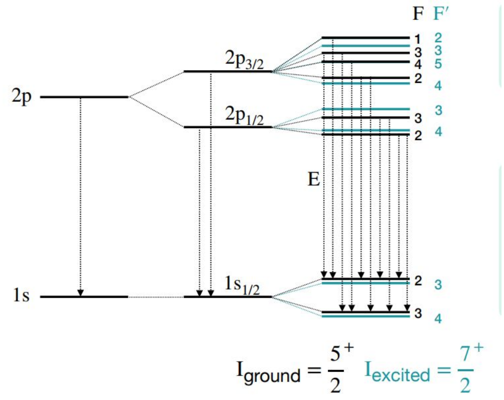
Heavy nuclei

Why heavy nuclei? → *our* main target is 226Ra because of APV

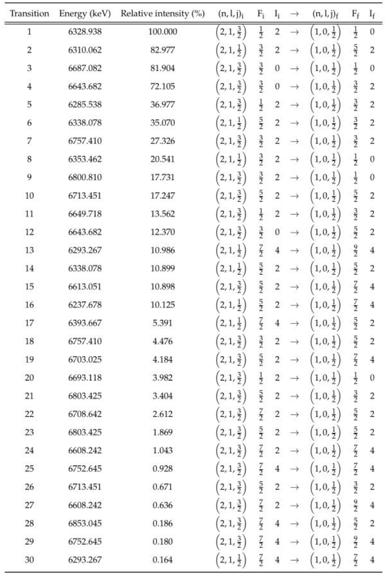
- Unstable nuclei
- Complicated hyperfine structure and nuclear charge distribution

Fine splitting (FS): $\vec{J} = \vec{l} + \vec{s}$

Static hyperfine splitting (HFS): $\vec{F} = \vec{I} + \vec{J}$



- Significant quadrupole and dipole shifts
- Hyperfine splitting from ground **and** excited states (I=0 nuclei don't save you)
- Ph.D. Thesis Stella vogiatzi and work by N. Oreshkina (nuclear wave functions from skyrme interactions for NP)



Transition	Energy (keV)	Relative intensity (%)	$(n,l,j)_i$	F_i	I_i	→	$(n,l,j)_f$	F_f	I_f
1	6328.938	100.000	$\left(2,1,\frac{3}{2}\right)$	$\frac{1}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{1}{2}$	0
2	6310.062	82.977	$\left(2,1,\frac{1}{2}\right)$	$\frac{3}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
3	6687.082	81.904	$\left(2,1,\frac{3}{2}\right)$	$\frac{3}{2}$	0	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{1}{2}$	0
4	6643.682	72.105	$\left(2,1,\frac{3}{2}\right)$	$\frac{3}{2}$	0	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
5	6285.538	36.977	$\left(2,1,\frac{3}{2}\right)$	$\frac{1}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
6	6338.078	35.070	$\left(2,1,\frac{1}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
7	6757.410	27.326	$\left(2,1,\frac{3}{2}\right)$	$\frac{3}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
8	6353.462	20.541	$\left(2,1,\frac{1}{2}\right)$	$\frac{3}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{1}{2}$	0
9	6800.810	17.731	$\left(2,1,\frac{3}{2}\right)$	$\frac{3}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{1}{2}$	0
10	6713.451	17.247	$\left(2,1,\frac{3}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
11	6649.718	13.562	$\left(2,1,\frac{3}{2}\right)$	$\frac{1}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
12	6643.682	12.370	$\left(2,1,\frac{3}{2}\right)$	$\frac{3}{2}$	0	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
13	6293.267	10.986	$\left(2,1,\frac{1}{2}\right)$	$\frac{7}{2}$	4	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{9}{2}$	4
14	6338.078	10.899	$\left(2,1,\frac{1}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
15	6613.051	10.898	$\left(2,1,\frac{3}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{7}{2}$	4
16	6237.678	10.125	$\left(2,1,\frac{1}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{7}{2}$	4
17	6393.667	5.391	$\left(2,1,\frac{1}{2}\right)$	$\frac{7}{2}$	4	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
18	6757.410	4.476	$\left(2,1,\frac{3}{2}\right)$	$\frac{3}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
19	6703.025	4.184	$\left(2,1,\frac{3}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{7}{2}$	4
20	6693.118	3.982	$\left(2,1,\frac{3}{2}\right)$	$\frac{1}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{1}{2}$	0
21	6803.425	3.404	$\left(2,1,\frac{3}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
22	6708.642	2.612	$\left(2,1,\frac{3}{2}\right)$	$\frac{7}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
23	6803.425	1.869	$\left(2,1,\frac{3}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
24	6608.242	1.043	$\left(2,1,\frac{3}{2}\right)$	$\frac{7}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{7}{2}$	4
25	6752.645	0.928	$\left(2,1,\frac{3}{2}\right)$	$\frac{7}{2}$	4	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{7}{2}$	4
26	6713.451	0.671	$\left(2,1,\frac{3}{2}\right)$	$\frac{5}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{3}{2}$	2
27	6608.242	0.636	$\left(2,1,\frac{3}{2}\right)$	$\frac{7}{2}$	2	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{9}{2}$	4
28	6853.045	0.186	$\left(2,1,\frac{3}{2}\right)$	$\frac{7}{2}$	4	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{5}{2}$	2
29	6752.645	0.180	$\left(2,1,\frac{3}{2}\right)$	$\frac{7}{2}$	4	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{9}{2}$	4
30	6293.267	0.164	$\left(2,1,\frac{1}{2}\right)$	$\frac{7}{2}$	4	→	$\left(1,0,\frac{1}{2}\right)$	$\frac{7}{2}$	4

Heavy nuclei

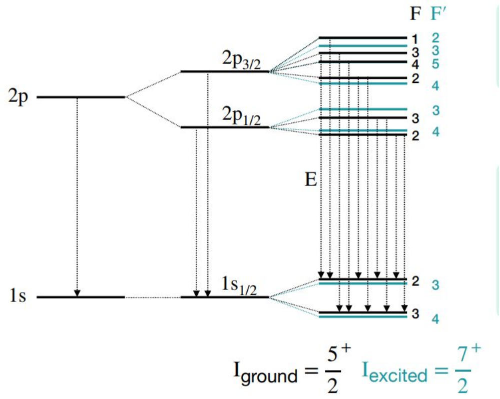
Why heavy nuclei? → *our* main target is 226Ra because of APV

- ➢ Unstable nuclei
- ➢ Complicated hyperfine structure and nuclear charge distribution
- ➢ Persisting fine splitting anomaly (From Bergem et. al. 1988 data persistent to Oreshkina 2022)

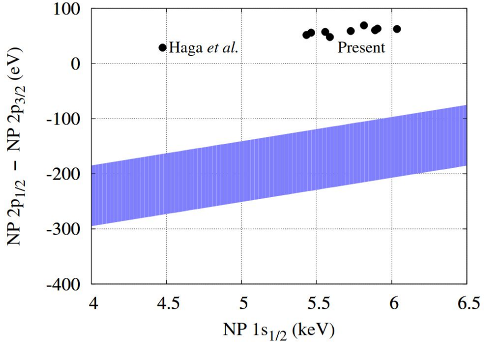
Fine splitting (FS): $\vec{J} = \vec{I} + \vec{s}$

Static hyperfine splitting (HFS): $\vec{F} = \vec{I} + \vec{J}$

µPb measurement to determine the NP, and then then it has not event the correct sign



- ❑ Significant quadrupola and dipole shifts
- ❑ Hyperfine splitting from ground **and** excited states (I=0 nuclei don't save you)
- ❑ Ph.D. Thesis Stella vogiatzi and work by N. Oreshkina (nuclear wave functions from skyrme interactions)

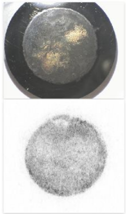


Heavy nuclei

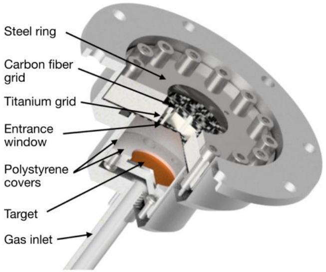
Why heavy nuclei? → *our* main target is 226Ra because of APV

- ➢ Unstable nuclei
- ➢ Complicated hyperfine structure and nuclear charge distribution
- ➢ First radioactive target measurement with 248Cm

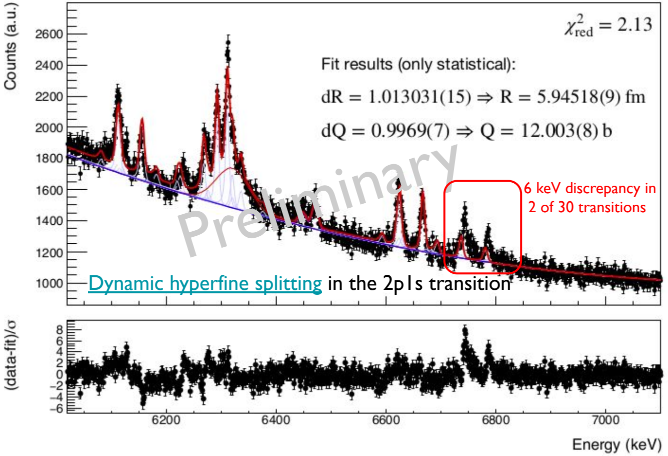
Target preparation at Mainz nuclear chemistry



15.5 µg ^{248}Cm target



248Cm muonic X-ray spectrum



6 keV discrepancy in 2 of 30 transitions

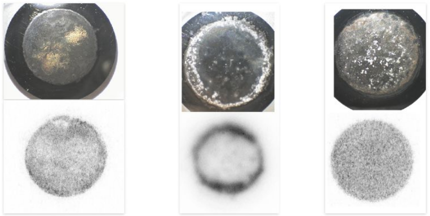
Dynamic hyperfine splitting in the 2p1s transition

Heavy nuclei

Why heavy nuclei? → *our* main target is 226Ra because of APV

- ➢ Unstable nuclei
- ➢ Complicated hyperfine structure and nuclear charge distribution
- ➢ First radioactive target measurement with [248Cm]
- ➢ 3 failed attempts with chemically prepared ^{226}Ra targets

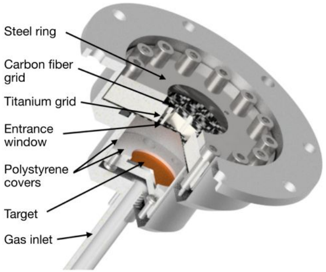
Target preparation at Mainz nuclear chemistry

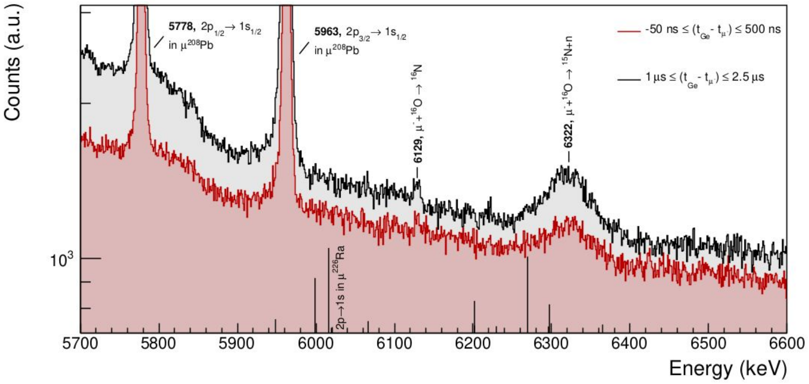


15.5 µg ^{248}Cm target

4.4 µg ^{226}Ra target

1.4 µg ^{226}Ra target

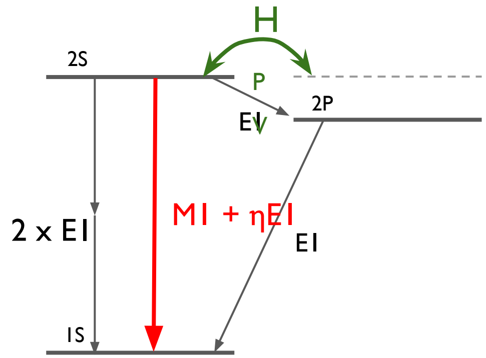


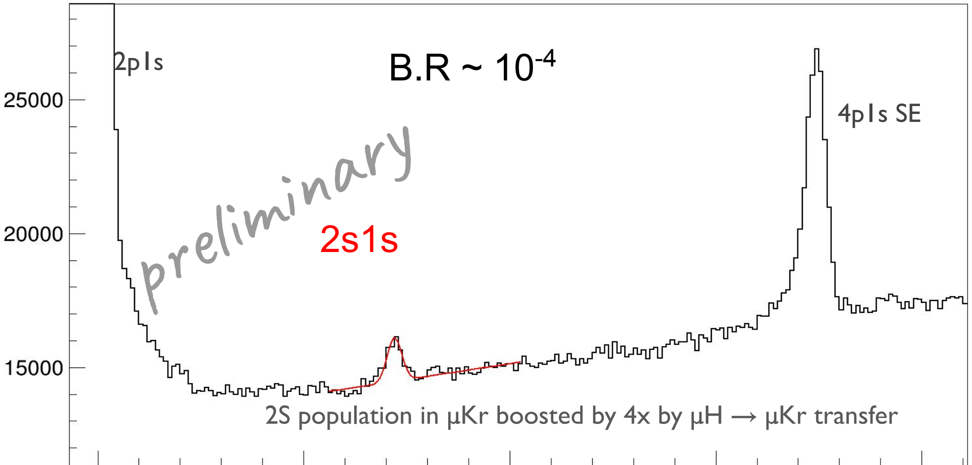


A teaser upon request

What about APV with muonic atoms?

- ➢ Long standing idea to measure APV with the 2s1s
  Missimer & Simons , Feinberg & Chen
- ➢ Large PNC amplitudes 10^{-2} @ Z=5 10^{-4} @ Z=30
  (circular polarization, e-γ or γ-**P** correlation)
- ➢ Challenging transition to observe
  → muX aimed to observe 2s1s for the first time





2S population in μKr boosted by 4x by μH → μKr transfer

Some (fun) references:

- ☐ J-PARC efforts: https://doi.org/10.1051/epjconf/202226201010
- ☐ Meta-stable 2S in Boron: https://doi.org/10.1103/PhysRevLett.78.4363
- ☐ D. Budker Gamma factories and highly charged ions
  https://doi.org/10.1002/andp.202100561
- ☐ HiMB physics case https://doi.org/10.48550/arXiv.2111.05788
- ☐ M. Pospelov ideas in the proton puzzle days
  https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.263401
  https://doi.org/10.1103/PhysRevLett.107.011803

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

Future:

- ☐ Li, B, Be, … Ca, K, Cl, Ag, … Re, U, Cm, … data under analysis
- ☐ Push MMC + muonic-rays to the limits
- ☐ Eying ^{7}Be-^{7}Li, ^{8}B-^{8}Li, ^{18}Ne-^{18}O, ^{19}F-^{19}Ne mirror pairs
- ☐ ^{10}Be combining MMC with transfer target
- ☐ measure $^{26/27}$Al, $^{28/29/30}$Si, ^{108m}Ag, … reference radii

Some challenges & needs:

- ☐ Need NP input to go from E to $<r^2>$ from A=6⟶226
- ☐ Understand all spectral features for the high Z nuclei
- ☐ Produce propper ^{226}Ra target (implant!) and measure
- ☐ Push MMC + muonic-rays to the limits

muX (A. Knecht & F.Wauters), QUARTET
(B. Ohayon, N. Paul), and Reference Radii
(T.E.Cocolios) collaborations

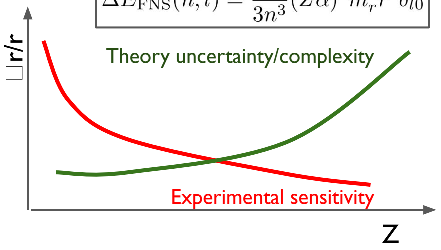
TECHNION Israel Institute of Technology
Laboratoire Kastler Brossel Physique quantique et applications
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
KU LEUVEN
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
NOVA UNIVERSIDADE NOVA DE LISBOA
ETH zürich
PSI

So why (re)measure muonic X-rays (with HPGe detectors)

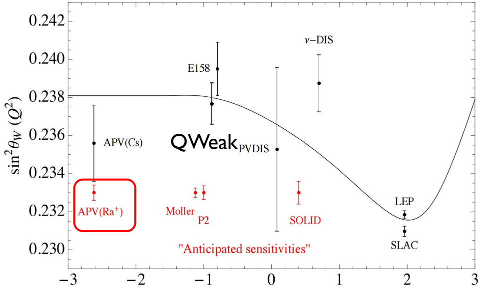
- ➢ Specific rare and/or heavy isotopes of interest
- ➢ Unstable isotopes?

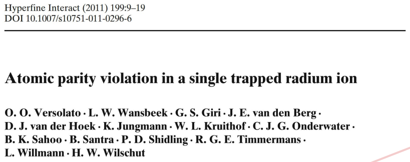
→ *muX project at PSI* https://arxiv.org/abs/2108.10765

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



Physics case: <u>Measuring 2P1S in 226Ra</u>
→ **Input** for a APV experiment on a single trapped Ra ion.





Hyperfine Interact (2011) 199:9–19
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Atomic parity violation in a single trapped radium ion

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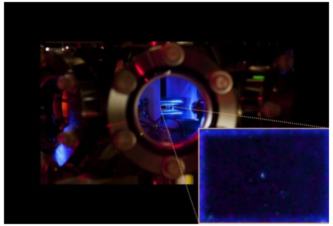
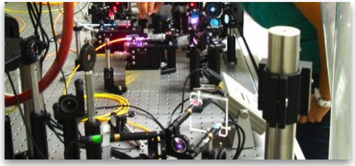
INPUT

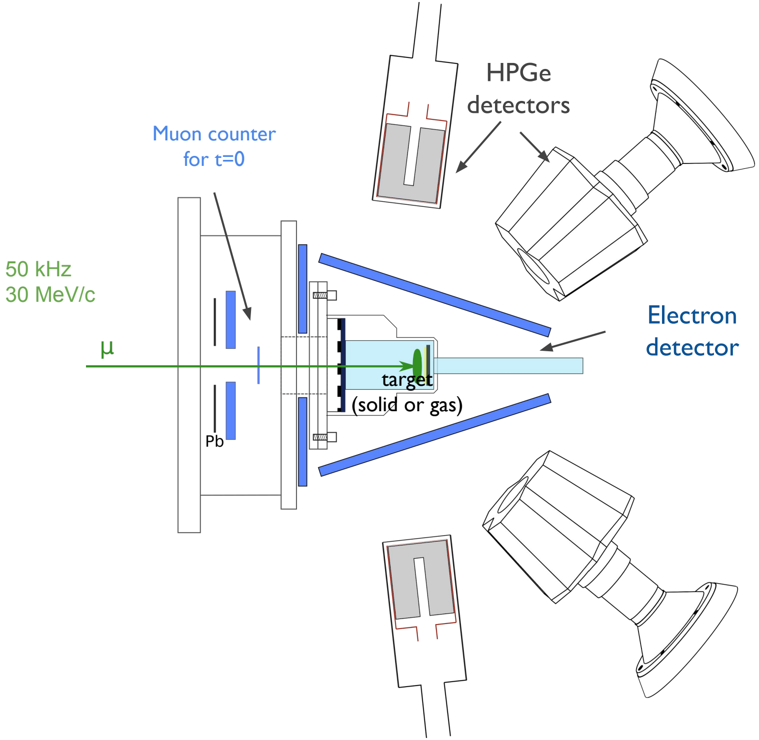
$$\mathbf{E1_{PNC} = \boxed{K_r}\, Z^3\, Q_w}$$



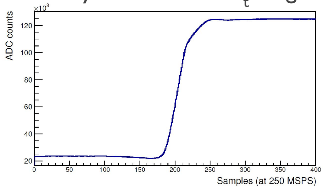


- ❑ Determine E(2P1S) < 10 keV to determine charge radius < 0.2% needed to calculate K_r
- ❑ But all Ra isotopes are radioactive! → **< 5 μg of 226Ra**

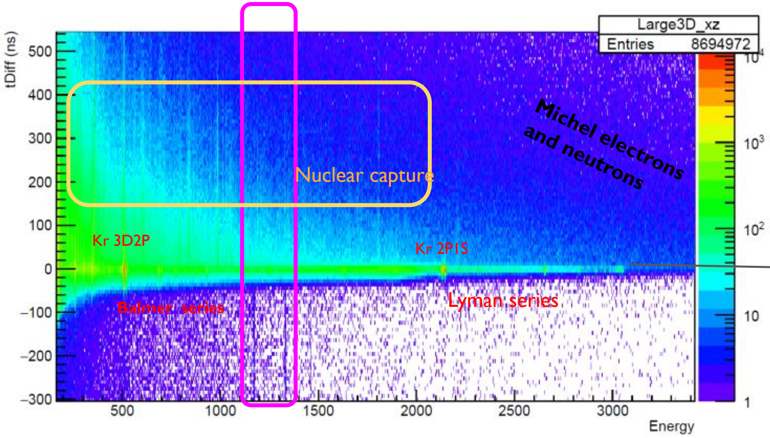
↔You need O(0.1 mm) of high-Z material to stop standard muon beam



Waveform analysis to achieve $\sigma_t \ll$ signal rise time



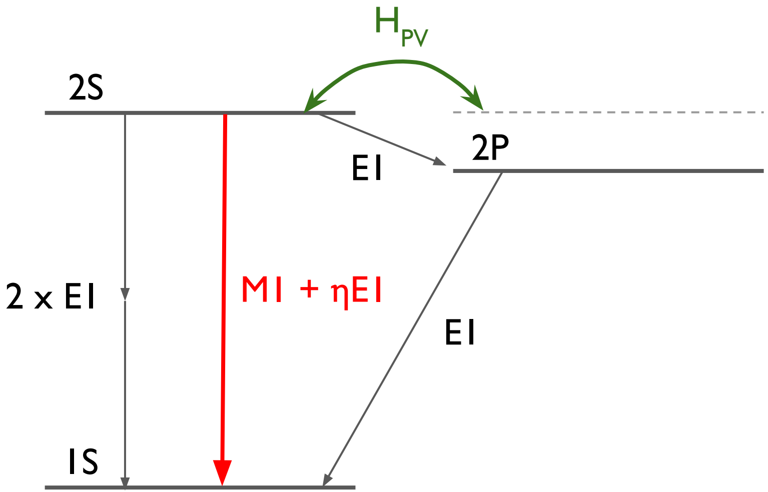
60Co calibration lines



Very busy physics events!

10 ns time resolution on HPGe detectors!

- Measure 2S1S for Z≈30 nuclei → measure APV with muons directly?
  - Motivation:
    1. Can we get $\sin^2(\theta_w)$?
    2. Is the muon special
    3. Neutral currents at low Q^2 have not yet been measured
  - **Goal of muX:**
    1. **Observe 2S1S transition**
    2. **Achieve good S/B for a 10^{-4} B.R. transition**



Is the muon special?


Extending theories on muon-specific interactions

Carl E. Carlson and Michael Freid
Phys. Rev. D **92**, 095024 – Published 23 November 2015

Constraints on muon-specific dark forces

Savely G. Karshenboim, David McKeen, and Maxim Pospelov
Phys. Rev. D **90**, 073004 – Published 13 October 2014; Erratum Phys. Rev. D **90**, 079905 (2014)

Testing Parity with Atomic Radiative Capture of μ^-

David McKeen and Maxim Pospelov
Phys. Rev. Lett. **108**, 263401 – Published 29 June 2012

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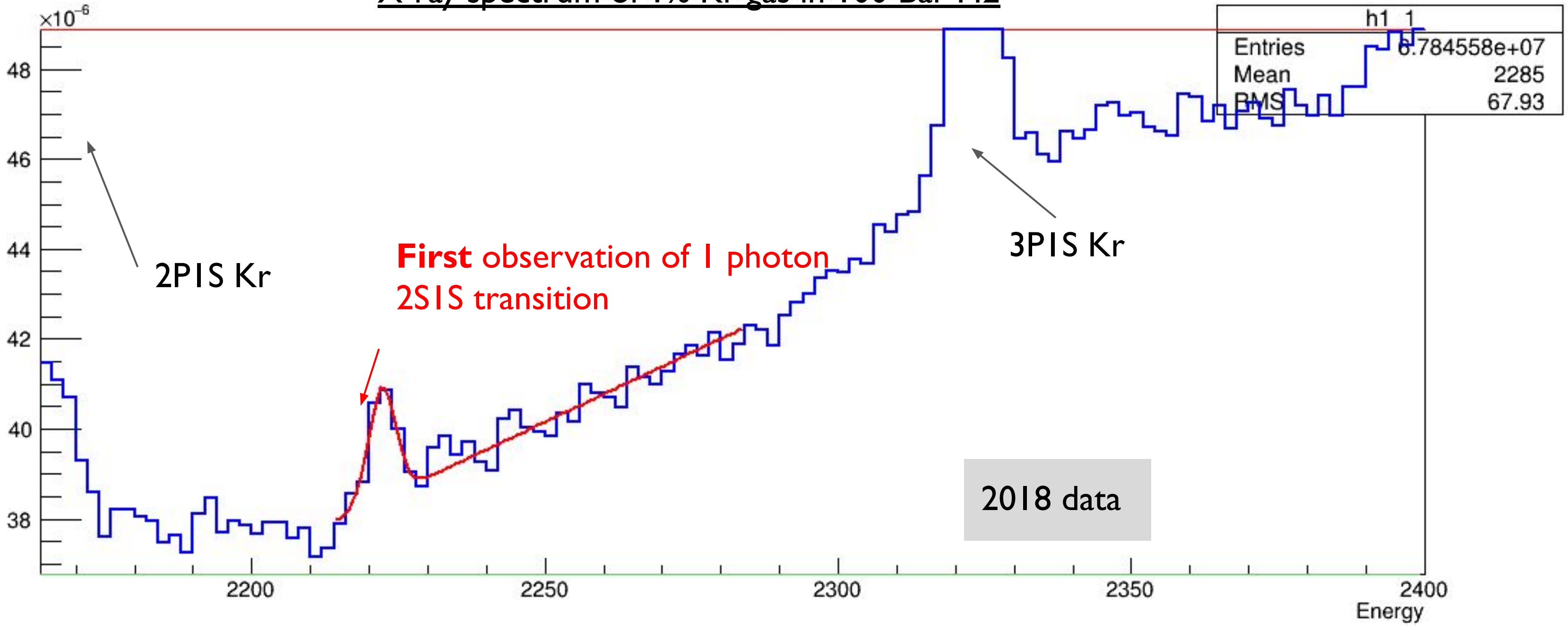
X-ray spectrum of 1% Kr gas in 100 Bar H2



2P1S Kr

First observation of 1 photon 2S1S transition

3P1S Kr

2018 data

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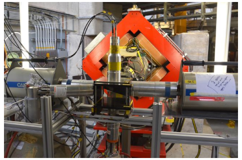
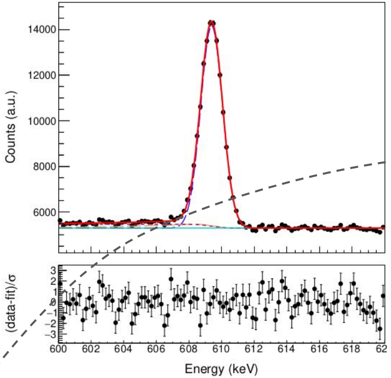


First we start *simple*

- ➢ Shoot directly on a rhenium target
- ➢ Two Germanium detectors



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

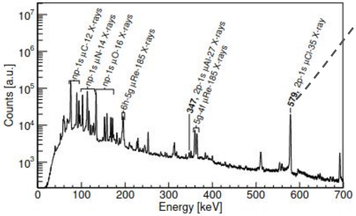
Niklas Michel and Natalia S. Oreshkina

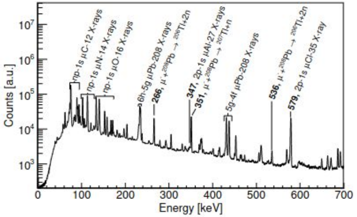
Phys. Rev. A 99, 042501 – Published 1 April 2019

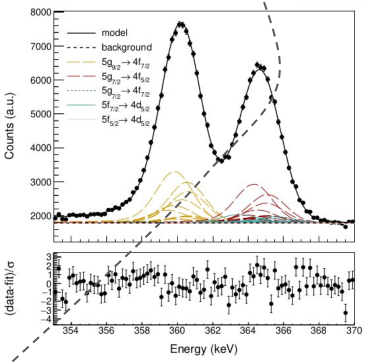
5→4 transitions to extract Q

1. Extract X-ray spectrum from data
2. Determine experimental line shape
3. Re-evaluate the (hyper)fine structure
4. Fit the multiplet
5. Extract Q

$$\Delta E^{if}(Q) = \Delta E_0^{if} + \Delta E_1^{if} Q + \Delta E_2^{if} Q^2,$$
$$I^{if}(Q) = I_0^{if} + I_1^{if} Q + I_2^{if} Q^2.$$







$$Q_{^{185}\mathrm{Re}} = (2.07 \pm 0.02\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}))\,\mathrm{b}$$
$$Q_{^{187}\mathrm{Re}} = (1.94 \pm 0.02\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}))\,\mathrm{b}$$

Published here:
https://doi.org/10.48550/arXiv.2003.02481