Access to the Kaon Radius with Kaonic Atoms

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Max Planck Institute for Nuclear Physics, Heidelberg

Physics Opportunities with Gamma Factory
4.12.2020

MAX-PLANCK-GESELLSCHAFT

Atomic spectroscopy

- Atomic properties are important for other fields

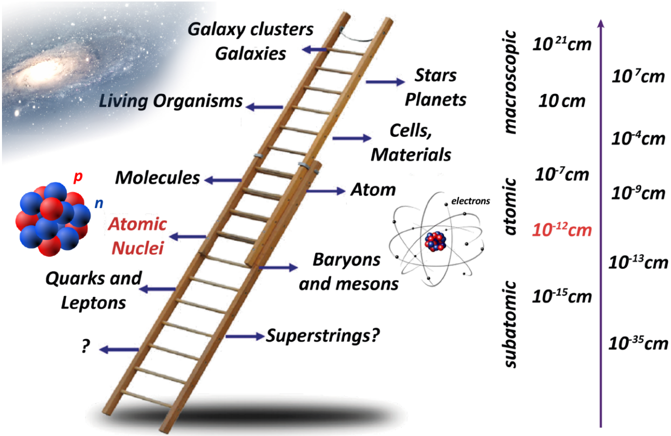


Figure courtesy: Liss V. Rodrigez

Atomic spectroscopy

- Atomic properties are important for other fields
- Gives access to nuclear and particle properties

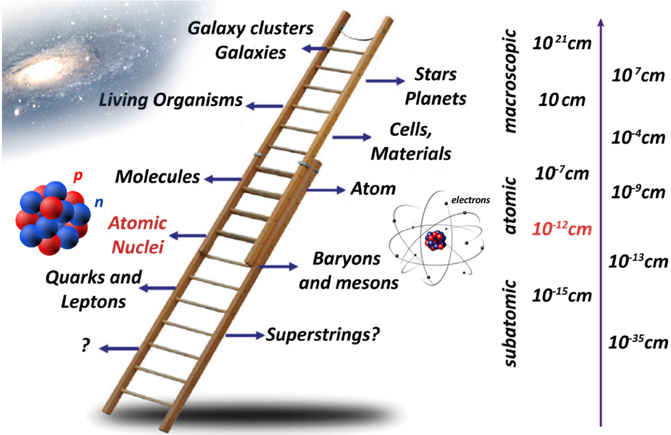


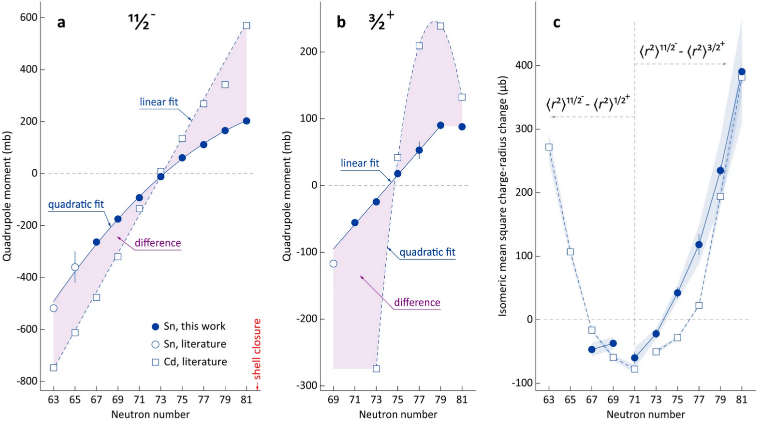
Figure courtesy: Liss V. Rodrigez

$^{117-131}$Sn spectroscopy at ISOLDE

$$B_{\mathrm{el}}[^1P_1^o] = 703 \pm 50\,\mathrm{M}Hz/b \qquad Q(^{119}\mathrm{Sn}) = -0.176(4)(12)\,\mathrm{b}$$

Fig. 3: Sn vs. Cd.

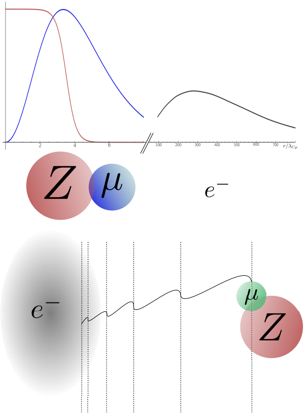
From: Structural trends in atomic nuclei from laser spectroscopy of tin



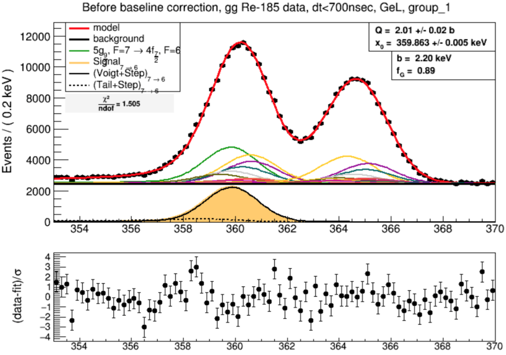
D. T. Yordanov *et al.*, Comm. Phys. 3, 107 (2020), Fig. 3

Muonic spectroscopy at PSI

Muon: heavy ($\approx \times 200$) and short-lived ($\approx 2\mu$s) copy of electron



Figures courtesy: Niklas Michel



A. Antognini *et al.*, Phys. Rev. C **101**, 054313 (2020)

$$Q[^{185}\mathrm{Re}] = 2.07(5)\,\mathrm{b};$$

$$Q[^{187}\mathrm{Re}] = 1.94(5)\,\mathrm{b}$$

What is a kaon

- Composite/hadron/meson
- K^+, K^0, $K^- = s\bar{u}$

Cute quarks figures source:

https://www.particlezoo.net/

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- lifetime $1.238(20) \times 10^{-8}$s: can form an exotic atom
- short-lived, therefore always H-like

Formalism: Klein-Gordon equation

As a spinless particle, a kaon is described by a stationary KGE:

$$\left[(E - V(\mathrm{r}))^2 + \Delta - m^2\right] \varphi(\mathrm{r}) = 0$$

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Spherically symmetric potential $\Rightarrow \varphi(\mathrm{r}) = \frac{R_l(r)}{r} \mathrm{Y}_{lm}(\vartheta, \varphi)$,
Infinite mass, point like nucleus with charge Z: $V = -\alpha Z / r$

$$\epsilon(\alpha Z, n, l) = \left(1 + \frac{(\alpha Z)^2}{n - l - 1/2 + \mu}\right)^{-1/2}$$

$$\mu = \sqrt{(l + 1/2)^2 - (\alpha Z)^2}$$

For 1s state, it breaks at $(\alpha Z)^2 = (1/2)^2$, or $Z = 69$.

Toy models

Finite nucleus: homogeneously charged sphere

$$\rho(r) = \frac{3Ze}{4\pi r_0^3}\theta(r_0 - r)$$

$$r_0 = \sqrt{\frac{5}{3}\langle r^2 \rangle}$$

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$$V(r) = \begin{cases} -\frac{Z\alpha}{2r_0}\left(3 - \frac{r^2}{r_0^2}\right), & \text{while } r \leq r_0, \\ -\frac{Z\alpha}{r}, & \text{while } r > r_0. \end{cases}$$

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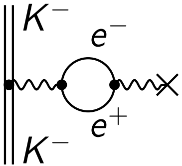
Finite kaon: two uniform spheres, kaon R_K and nucleus R_N

$$V(r) = \begin{cases} -V_0(C_0 - \rho^2) & \text{inside:} \quad 0 \le r \le R_N - R_K \\ -\frac{3}{8}\frac{V_0}{\lambda^3}\left(\frac{C_1}{\rho} + \sum_{k=0}^{5} C_{k+2}\rho^k\right) & \text{overlap:} \; R_N - R_K \le r \le R_N + R_K \\ -V_0/\rho & \text{outside:} \quad r \ge R_N + R_K \end{cases}$$

Leading QED: Uehling correction

- correction to Coulomb potential at small distances
- electronic loop less suppressed (smaller mass)



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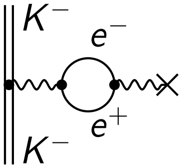

$$V_{\mathrm{Uehl}}(r) = -\frac{2\alpha(\alpha Z)}{3\pi}\int_0^\infty \mathrm{d}r' 4\pi\rho(r')\int_1^\infty \mathrm{d}t\left(1+\frac{1}{2t^2}\right) \times \frac{\sqrt{t^2-1}}{t^2}\,\frac{\exp(-2m_e|r-r'|t)-\exp(-2m_e(r+r')t)}{4m_e rt}$$

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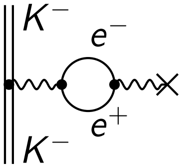

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Recoil: Important for light atoms, reduced-mass formalism

$$m_r = \frac{m_N m_K}{m_N + m_K}$$

Access to the parameters

$$V(r_K) = V_{\mathrm{FNS}}(r_K) + V_{\mathrm{FKS}}(r_K) + V_{\mathrm{Uehl}}(r_K)$$

Observables: energies of (circular) transitions
Sensitivities to the parameters:

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Nuclear radius

$$\frac{\Delta E}{E} = K_R \frac{\Delta R}{R}$$

Kaon mass

$$\frac{\Delta E}{E} = K_m \frac{\Delta m_K}{m_K}$$

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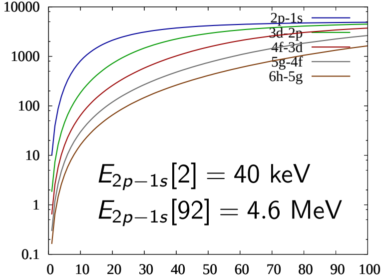
Kaon radius

$$\delta_{\mathrm{FKS}} = 1 - \frac{E_{nl}[V_{\mathrm{2spheres}}]}{E_{nl}[V_{\mathrm{sphere}}]}$$

Results


10000
1000
100
10
1
0.1
0 10 20 30 40 50 60 70 80 90 100
2p-1s
3d-2p
4f-3d
5g-4f
6h-5g
$E_{2p-1s}[2] = 40$ keV
$E_{2p-1s}[92] = 4.6$ MeV

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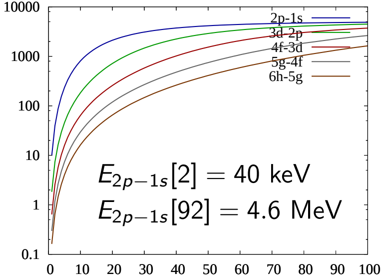
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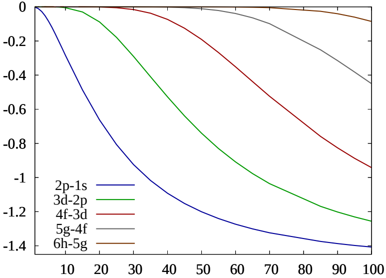
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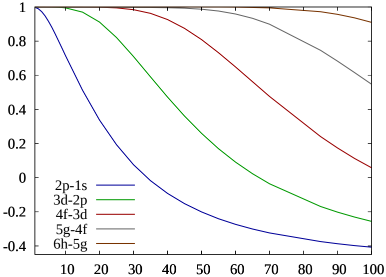
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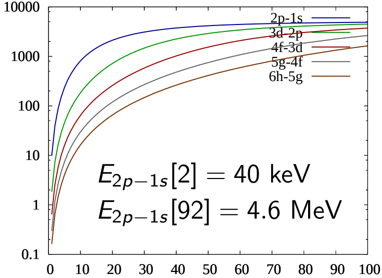
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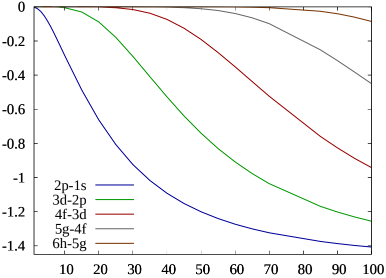
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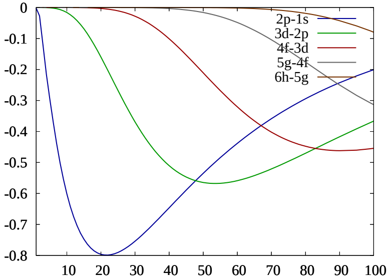
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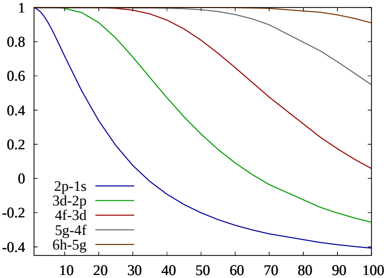
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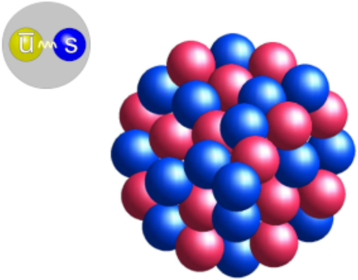
Hadronic contribution

- extremely important
- significantly change energies



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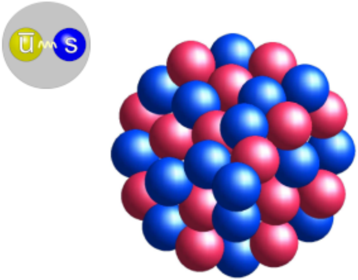

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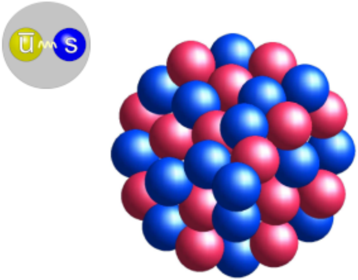

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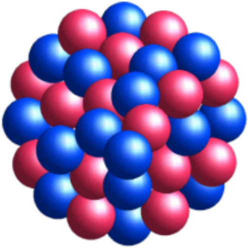

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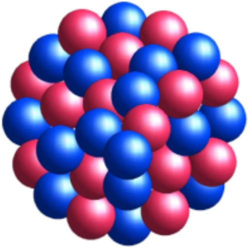
- main source of uncertainty



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What is done:

- order of magnitude estimate with a toy model
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Opportunities with Gamma Factory

- experimental accessibility to many isotopes
- high-precision measurements
- wide range of energies
- muonic atoms
- kaonic atoms

Acknowledgements

N. Michel, C. O. Curceanu, V. Debierre, Z. Harman

N. Michel, NSO, Access to the kaon radius with kaonic atoms,
https://arxiv.org/abs/2010.11602 (2020)

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Isoscalar and isovector kaon form factors from e^+e^- and τ data

Konstantin Beloborodov[1,2*], Vladimir Druzhinin[1,2] and Sergey Serednyakov[1,2]

APCTP Pre2019-012, LFTC-19-7/45

Electroweak properties of kaons in a nuclear medium

Parada T. P. Hutauruk[1,*] and K. Tsushima[2,1,†]

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- Form-factor and size
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Jhih-Ying Su, Jusak Tandean

EPJ Web of Conferences 212, 03006 (2019)
https://doi.org/10.1051/epjconf/201921203006

Isoscalar and isovector kaon form factors from e^+e^- and τ data

Konstantin Beloborodov[1,2*], Vladimir Druzhinin[1,2] and Sergey Serednyakov[1,2]

APCTP Pre2019-012, LFTC-19-7/45

Electroweak properties of kaons in a nuclear medium

Parada T. P. Hutauruk[1,*] and K. Tsushima[2,1,†]

1.E.8:6.C

Nuclear Physics **A254** (1975) 381–395; © **North-Holland Publishing Co., Amsterdam**

K^- MASS FROM KAONIC ATOMS†

S. C. CHENG, Y. ASANO††, M. Y. CHEN, G. DUGAN, E. HU, L. LIDOFSKY, W. PATTON and C. S. WU

VOLUME 60, NUMBER 3 — PHYSICAL REVIEW LETTERS — 18 JANUARY 1988

Precision Measurements of the K^- and Σ^- Masses

K. P. Gall, E. Austin, J. P. Miller, F. O'Brien,[(a)] B. L. Roberts, and D. R. Tieger[(b)]

Studies of kaons and kaonic atoms

- Experiments with kaonic atoms at DAΦNE
- Kaon physics at KLOE-2
- Dark matter
- CP violation and neutron EDM
- Kaon decays
- Form-factor and size
- Mass determination from kaonic atoms decay
- Further proposals

Physics Letters B
A new measurement of kaonic hydrogen X-rays
SIDDHARTA Collaboration

Physics Letters B
Kaonic helium-4 X-ray measurement in SIDDHARTA
SIDDHARTA Collaboration

EPJ Web of Conferences 212, 09001 (2019)
https://doi.org/10.1051/epjconf/201921209001
Recent results on Kaon Physics at KLOE-2
Alessandro Di Cicco[1,2*] on behalf of the KLOE-2 Collaboration

PHYSICAL REVIEW LETTERS **124**, 041802 (2020)
Probing Muonphilic Force Carriers and Dark Matter at Kaon Factories
Gordan Krnjaic,[1] Gustavo Marques-Tavares,[2,3] Diego Redigolo,[4,5,6] and Kohsaku Tobioka[7,8]

PHYSICAL REVIEW D **101**, 035036 (2020)
Kaon *CP* violation and neutron EDM in the minimal left-right symmetric model
Stefano Bertolini,[1,*] Alessio Maiezza,[2,†] and Fabrizio Nesti[3,‡]

arXiv.org > hep-ph > arXiv:2009.04494
High Energy Physics - Phenomenology
[Submitted on 9 Sep 2020]
Probing lepton number violating interactions in rare kaon decays
Frank F. Deppisch, Kåre Fridell, Julia Harz

arXiv.org > hep-ph > arXiv:2006.05985
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Nuclear Experiment
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Resonance photoproduction of pionic and kaonic atoms at the Gamma Factory
Victor V. Flambaum, Junlan Jin, Dmitry Budker

Next step: the choice of the most suitable system, based on

- sensitivities
- accuracy of theoretical predictions
- experimental accessibility
- the natural linewidths
- possibility to carry high-precision measurements