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Measurement of the magnetic moment of negative muon in the bound state in different atoms

T.N.Mamedov[1], D.Herlach[2], R.Scheuerman[2]
A.V.Stoykov[1,2], U.Zimmermann[2]

[1]The Joint Institute for Nuclear Research, Dubna, Russia
[2]Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

- In Dirac quantum theory g-factor of a free electron and muon are exactly equal to 2.

As it is well known due to interaction with the radiation field the free electron (muon) possesses an anomalous magnetic moment g_e (g_μ)

g_e^{free} = 2 ·1.001 159 652 193(10)

g_μ^{free} = 2· 1.001 165 923 0(84)

G.Breit //Nature, 122, 649 (1928)

- $g_e^{Breit} = 2[1 - (4/3)\int F^2\, dr] = (2/3)\,[1 + 2\sqrt{(1-(Z\alpha)^2)}\,] \approx 2[1-(Z\alpha)^2/3]$

- H.Grotch et.al., //Phys.Rev. A, 4, 59 (1971)
- H.Persson et.al., //Phys.Rev. A, 56, R2499 (1997)

S.G.Karshenboim et.al., //JETP 93, 477 (2001)

A.P.Martunenko, R.N.Faustov //JETP 93, 471 (2001)

$$g_e^{1S} = 2(1 + a_e^{free} + a_e^{BS} + a_e^{rel})$$

$$a_e^{rel} = -2\,[1 - \sqrt{1-(\alpha Z)^2}\,]/3 \approx -(\alpha Z)^2/3$$

$$a_e^{BS}\,(QED) \approx (\alpha Z)^2\, \alpha/(4\pi)$$

Experiment:

- $\underline{e^-}$ H, He^{1+} , C^{5+}, N^{6+}

H

J.S.Tiedman et.al. //PRL 39(10), 602-604 (1977)

$$g_e^{1S}(H) / g_e^{free} = 1.- 17.709(13) \cdot 10^{-6}$$

C^{5+}

N.Hermanspahn et.al. //Phys.Rev.Lett., 84, 427 (2000).

$$g_e^{1S} (C^{5+}) = 2.001\ 042(2)$$

H.Haffner et.al., //Phys.Rev.Lett., 84, 427 (2000).

$$g_e^{1S} (C^{5+}) = 2.001\ 041\ 596(5)$$

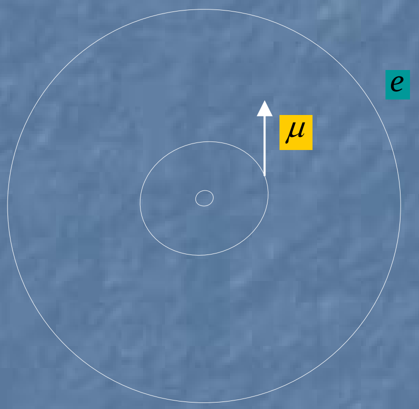
- T.Beier et.al. Phys.Rev. A, 62, 032510 (2000)

$$g_e^{1S} (C^{5+}) = 2.001\ 041\ 590(7)$$

$$g_e^{1S} (C^{5+})^{BS} = 0.000\ 000\ 844$$

K.W.Ford, J.G.Wills //Nucl.Phys., **35**, 295 (1962)
K.Ford, V.W.Hughes, J.G.Wills //Phys.Rev., **129**, 194 (1963)

$$g_\mu^{1S} = 2\left(1 + \sum a_\mu^{(i)}\right)$$



- $a_\mu^{(1)}$ – radiative correction for free muon;
  $a_\mu^{(2)}$ - binding correction to radiative correction;
  $a_\mu^{(3)}$ - direct binding (relativistic & Breit) correction;
  $a_\mu^{(4)}$ - nuclear polarization correction;
  $a_\mu^{(5)}$ - center-of –mass correction (finite mass);

- $a_\mu^{(6)}$ - electronic diamagnetic shielding correction;
- $a_\mu^{(7)}$ - electronic polarization correction (Knight shift: from experimental data in alloys) ;

Results of numeral calculation for muon bounded in atom

	$a_\mu^{(2)}$	$a_\mu^{(3)}$	$a_\mu^{(4)}$	$a_\mu^{(6)}$
C	-0.000 008	-0.000 629(0)	+0.000 004	-0.000 19
O	-0.000 013	-0.001 104(1)	+0.000 012	-0.000 32
Mg	-0.000 029	-0.002 379(6)	+0.000 053	-0.000 62
Si	-0.000 040	-0.003 172(10)	+0.000 090	-0.000 79
S	-0.000 051	-0.004 035(15)	+0.000 140	-0.000 96
Zn	-0.000 153	-0.011 26(10)	+0.000 89	-0.002 38
Cd	-0.000 449	-0.026 59(44)	+0.004 0	-0.006 9
Pb	-0.000 605	-0.032 48(62)	+0.004 6	-0.009 8

$$a_\mu^{(1)} = 0.001\ 165\ 923\ 0(84)$$

D.P.Hutchinson et.al. //Phys.Rev. 119, 1362 (1963).

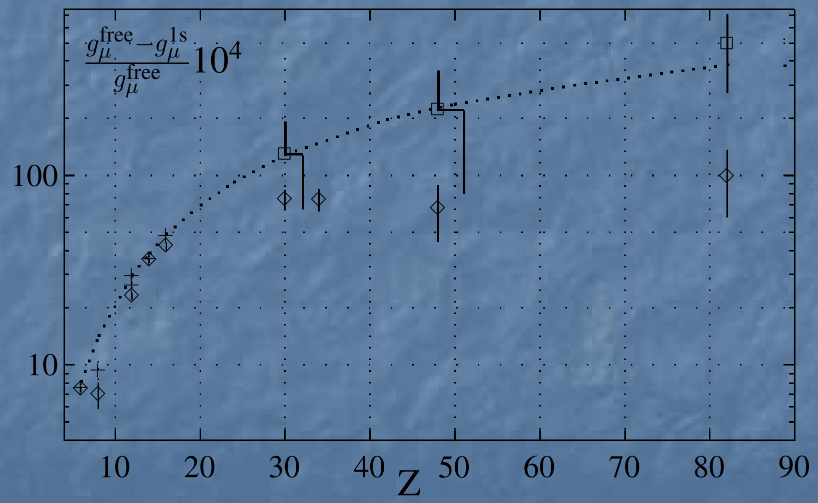
C, O(H2O), Mg, Si, S

T.Yamazaki et.al., //Phys.Lett. 53B, 117 (1974).

Zn, Cd, Pb (1.20±0.62; 2.01± 1.40; 4.68±2.20)·10^{-2}

T.N.Mamedov et al. //JETP 93, 941 (2001), JETP letter 76,821 (2002)

C, O(H20), Mg, Si, S, Zn, Ge, Cd, (Pb)



Sample	$10^4 \cdot (g_\mu^{free} - g_\mu^{1s})/g_\mu^{free}$				
	our exp. (2000 -2003)	exp. [1] (2005)	exp. [2] (1963)	exp. [3] (1974)	theor. [4]
C(graphite)	7.5±0.2	7.18 ±0.23	7.6±0.3 7.1±0.6 8.0±0.5		8.2±0.1
O, in H_2O	6.8±0.9	11.2±0.42	9.4±1.0		14.3±0.2
Mg, metal. Mg, in MgH_2	22.6±0.8	23.48±0.25	26.4±0.7 29.6±0.7		29.8±0.6
Si, crystal.	35.8±0.8	33.63±0.34	36.3±1.1		39.1±1.0
S, amorphous	42.4±2.1	42.62±0.36	48.2±1.6		49.1±1.5
Ca, metal		51.55±2.5			
Ti, metal		67.9±2.4			
Zn, metal	75.3±8.3	115.0±2.6		120±62	129.0 ($\geq$ 122)
Ge, crystal	75±10				
Cd, metal	67±22	214.8^{+17}_{-21}		201±140	218 ($\geq$ 175)
Pb, metal	98±38	260.1^{+22}_{-23}		468±220	383

References

[1] J.H.Brewer,.A.M.Froese, B.A.Fryer, K.Ghandi, Phys.Rev. **A 72**, 022504 (2005).

[2] D.P.Hutchinson, J.Menes, G.Shapiro, A.M.Patlach, Phys. Rev. **131**, 1362 (1963).

[3] T.Yamazaki, S.Nagamiya, O.Hashimoto et.al., Phys.Lett. **53B**, 117 (1974).

[4] K.W.Ford, V.W.Hughes, J.G.Wills, Phys.Rev. **129**, 194 (1963).

25.02.2005

Measurement

- The measurement of g-factor of negative muon bounded in 1S-state of a atom based to fact that in external magnetic field the muon spin precess with the Larmor frequency

$$\omega = g_\mu \cdot \frac{e}{2m_\mu c} H$$

$$\frac{g_\mu^{free} - g_\mu^{1S}}{g_\mu^{free}} = \frac{\omega^{free} - \omega^{1S}}{\omega^{free}}$$

- A.Schenck //Helv.Phys.Acta, 54, 471 (1981)

$$\omega^{free} = \omega(\mu^+, Cu)/(1+K)$$

$$K = (60.0 \pm 2.5) \cdot 10^{-6}$$

$$\frac{\sigma(\omega)}{\omega} = \frac{\sqrt{2}}{\omega \cdot \tau \cdot a \cdot \sqrt{N}} \infty \frac{1}{H}$$

- Sample:

1. Zn (0.99)
2. Zn (0.9999)
3. Ge impurities $<10^{-6}$
4. Cd (0.99).

τ_μ(Zn)=159.4 ± 1.0 ns, τ_μ(Ge)=166.5 ±1.0 ns, τ_μ(Cd)=90.7±1.5 ns

TDC calibration, test of the fit procedure

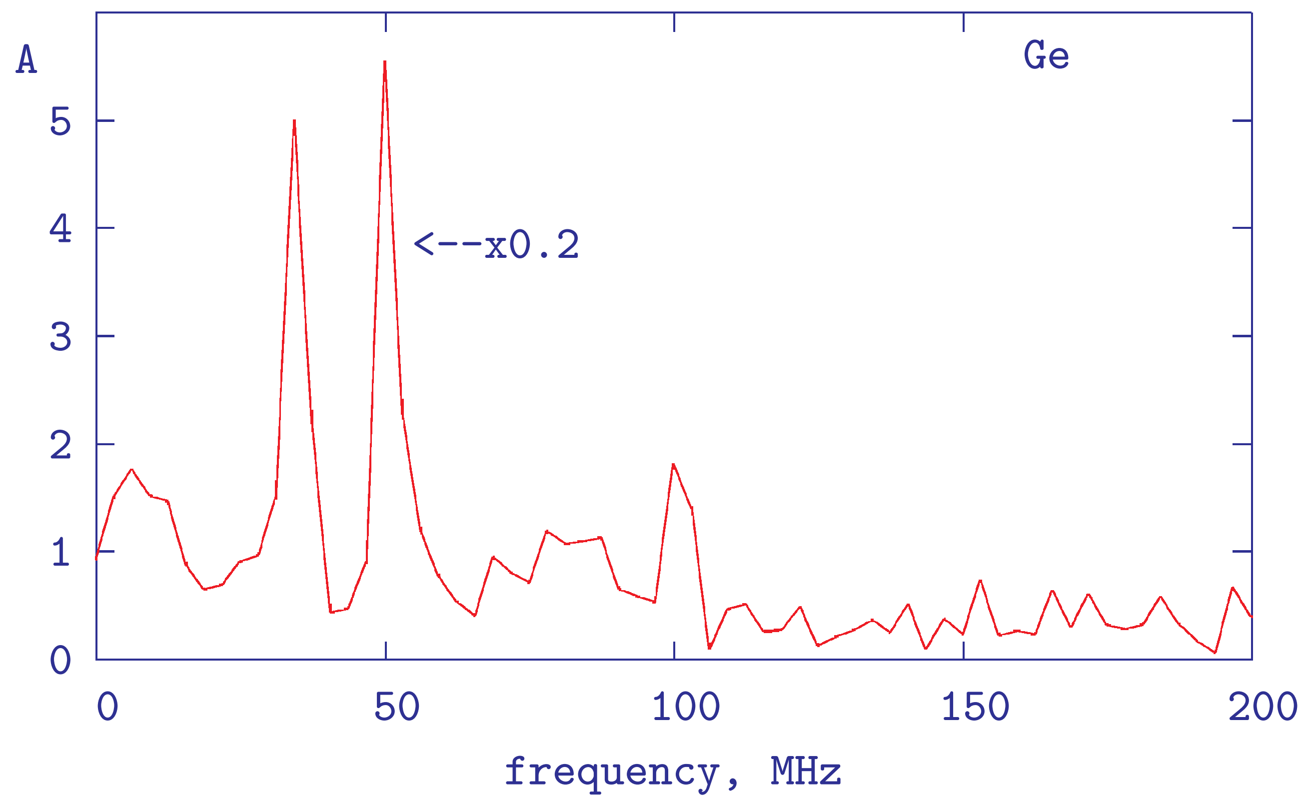
- Of line calibration

Rohde&Schwarz SML01 precision quartz clock with a frequency of 100 MHz was used for of line calibration of the TDC (PTA ORTEC-9308). The bin width was the same with accuracy better than 2·10-4 in range of 0 –10 μs.

- The correctness of the fit procedure tested by the simulated data. It was simulated a spectr with a statistic and background analogous to that we had in case of Cd sample. The value of parameters (including precession frequency) find by the fit of the simulated data were in good agreement whit those used in simulation.

Calibration using banched electron contamination in muon beam:

Data in range of 50 < t <320 ns (bins 450 – 900) analyzed. This time correspond to 1.75 τ_{μ}(Ge) . From fit of the experimental data was found ν_{ac} =50.62±0.01 MHz (3 10^{-4})



Sample	$10^4 \cdot (g_\mu^{free} - g_\mu^{1s})/g_\mu^{free}$					
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Ca, metal			51.55±2.5			
Ti, metal			67.9±2.4			
Zn, metal	67±6	75.3±8.3	115.0±2.6		120±62	129.0 (≥ 122)
Zn (0.9999)	62±9					
Ge, crystal	77±7	75±10				
Cd, metal	42±10	67±22	214.8^{+17}_{-21}		201±140	218 (≥ 175)
Pb, metal		98±38	260.1^{+22}_{-23}		468±220	383

References

[1] J.H.Brewer,.A.M.Froese, B.A.Fryer, K.Ghandi, Phys.Rev. A 72, 022504 (2005).

[2] D.P.Hutchinson, J.Menes, G.Shapiro, A.M.Patlach, Phys. Rev. 131, 1362 (1963).

[3] T.Yamazaki, S.Nagamiya, O.Hashimoto et.al., Phys.Lett. 53B, 117 (1974).

[4] K.W.Ford, V.W.Hughes, J.G.Wills, Phys.Rev. 129, 194 (1963).

12.10.2005

Conclusion

- The present results confirm our previous one and differ from that of Brewer et al. for Zn and Cd atoms by about 8 standart deviations. The possible systematic error in our measurements is shown to be negligible.

THE END !

The possible reasons of disagreement the results of the theoretical calculation and the measured value of g_μ^{1S} :

- There may be some systematic shift in measurements due to shorter μ life time in case of heavy nuclear (mismeasurement);
- The measurements were performed in medium and the solid state effects were not correctly taken into account (misinterpretation);
- Probably, it is difficult to take into account in theoretical calculation the fact that in case of heavy nuclear muon about half time founds inside of nuclear (miscalculation).

$a_\mu^{(7)}$ - electronic polarization correction (Knight shift from experimental data in alloys $A_{1-x}B_x$) ;

- C: B in C
- O: N in H2O
- Mg: Na in Mg
- Si: Al in Si
- S: P in S

Zn: Cu in Zn

Ge: Ga in Ge

Cd: Ag in Cd

Pb: Tl in Pb

$H^{int} = K\,H^{ext}$

$Zn_{1-x}\,Cu_x$ Li Bai_Qin et al., //Phys.Rev., B47, 16582 (1993)

S.Rubini et al., //Phys.Rev., B49, 12590 (1994)

for Cu in $Zn_{1-x}\,Cu_x$ $(x < 0.4)$ $K < (7 \pm 1)\cdot 10^{-4}$

$Cd_{1-x}\,Ag_x$ L.E.Drain //Philosophical.Mag., 4, 484 (1959)

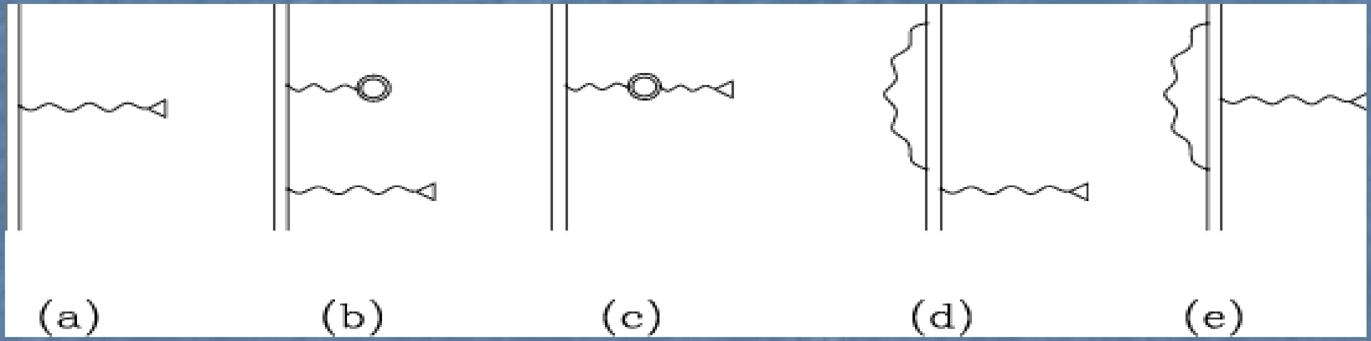
R.L.Odle //Philosophical.Mag., 13, 484 (1966)

S.Rubini et al., //Phys.Rev., B49, 12590 (1994)

for Ag in $Cd_{1-x}\,Ag_x$ $(x < \quad)$ $K < (42.9 \pm 0.4)\cdot 10^{-4}$

- H.Grotch et.al., //Phys.Rev. A, 4, 59 (1971)
- H.Persson et.al., //Phys.Rev. A, 56, R2499 (1997)
- S.G.Karshenboim et.al., //JETP 93, 477 (2001)
- A.P.Martunenko, R.N.Faustov //JETP 93, 471 (2001)

- $\Delta E = -\langle a|\boldsymbol{\mu}\mathbf{B}|a\rangle = g_j \mu_B \langle a|\mathbf{j}_z|a\rangle B_z = (1/2)\, g_j \mu_B B_z$
- $g_j = 2 \dfrac{\Delta E}{\mu_B B_z}$
- $\mathbf{A} = -(\mathbf{r} \times \mathbf{B})/2$
- $g_e^{\mathrm{Breit}} = 2[1 - (4/3)\int F^2\, dr] = (2/3)\, [1 + 2\sqrt{(1 - (Z\alpha)^2)}\,]$



Feynman diagrams: a) the first –order interaction ; b)– c) the one-photon radiative correction to the bound-electron g-factor. The triangle represents the external magnetic field