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Vacuum polarization test and search for direct muon-hadron interaction from muonic X-rays*

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Abstract. Results are reported on wavelength measurements of $3d$-$2p$ X-ray transitions in muonic ^{24}Mg, ^{28}Si and ^{31}P. The experiments were performed with the bent-crystal spectrometer at SIN. The results are analysed as a QED test and, alternatively, as a search for muon-hadron interactions. The relative difference between theory and experiment for the vacuum polarization effect is $(0.6 \pm 2.4) \times 10^{-3}$.

The particular feature of muonic-atom experiments [1–4] as a test of QED is the dominance among the radiative corrections, of the vauum polarization effect. This is because the average muonic orbit size is of similar magnitude as the spatial extension of the polarization charge around the nucleus (which is of the order of the Compton wavelength of the electron). Muonic atom experiments are therefore complementary to other high-precision QED tests [5].

Three types of QED experiments with muonic atoms have been reported:

(i) In heavy muonic atoms X-ray energies of transitions connecting circular orbits have been measured with Ge(Li) detectors [1].
(ii) The $2s$-$2p$ energy differences in muonic ^{4}He have been measured in a tunable-laser experiment [2].
(iii) Crystal-spectrometer measurements of $3d$-$2p$ X-rays in muonic ^{28}Si [3] and ^{31}P [4].

In the present work we report on new crystal-spectrometer measurements of $3d$-$2p$ transitions in the same Z region with considerably improved precision [6].

An ideal system for testing the vacuum polarization effect would be an isolated muonic atom in which the muon moves in the Coulomb field of a

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point-like nucleus. In such a system the radiative corrections would be simply the difference between the measured transition energy and the well-known energy difference as calculated from the Dirac theory (with the Coulomb potential of a nuclear point charge). In reality, nuclear structure effects and electron screening shifts generally have to be included. The $3d$-$2p$ transitions in muonic atoms with Z around 12 are of particular interest because they are very similar to an ideal, "hydrogen-like" system. In all other experiments the corrections due to one or more of the following effects are sizeable: the nuclear finite-size shift, the electron screening correction and the nuclear polarization effect. The wavelength of each of the six $3d$-$2p$ transitions reported here can be calculated at present with a total uncertainty of 6 ppm (including nuclear structure and electron screening effects). Still further improvements in the precision of the theoretical values can be anticipated [8].

The experimental results of the present work are interesting also from a different point-of-view. Instead of interpreting the results as a QED test, one could *assume* that this theory is correct and consider the muon as a probe for an additional muon-nucleus interaction [4]. If a direct muon-nucleon interaction were mediated by a scalar, isoscalar boson of mass m, the muon would feel an additional (Yukawa) potential of the form

$$V(r) = -A \frac{g_\mu \cdot g_N}{4\pi} \frac{e^{-rm}}{r}, \tag{1}$$

where g_μ and g_N are the boson-muon and the boson-nucleon coupling constants, respectively, and A is the atomic mass number. Potential (1) gives rise to an additional shift of the muonic energy levels. A particular example of such an interaction is the one mediated by the Higgs boson of the Weinberg–Salam theory [9, 10].

The experiments were performed with the curved-crystal spectrometer facility at the superconducting Muon Channel I of SIN [4]. All X-rays were measured relative to either the 84 keV γ-ray of ^{170}Tm or the 63 keV γ-line of ^{169}Yb, both of which have recently been calibrated to about 1 ppm [11]. Both the $3d_{5/2}$-$2p_{3/2}$ and the $3d_{3/2}$-$2p_{1/2}$ X-ray transition for all three atoms were measured. The weak and unresolved transitions $3d_{3/2}$-$2p_{3/2}$ (near the $3d_{5/2}$-$2p_{3/2}$ line) and $3s_{1/2}$-$2p_{3/2}$ (near the $3d_{3/2}$-$2p_{1/2}$ line) have been considered in the analysis, as well as the $3d$-$2p$ transitions of the rare isotopes ^{29}Si and ^{30}Si in the case of μ-^{28}Si. (The magnesium target was enriched to more than 99% ^{24}Mg.)

The measured ratios of the muonic X-ray wavelength and the γ-ray wavelength are shown in Table I. The values in column four of Table I are corrected for effects due to the vertical extension of the source and the crystals. The quoted errors include uncertainties from geometrical effects and the data analysis procedure. The dominant contribution to the error in each measured wavelength ratio comes from counting statistics.

The experimental values for the muonic X-ray wavelengths, together with the results from Refs. 3, 4, are given in the third column of Table II. They are obtained from the ratios λ_x/λ_γ by using the γ-ray wavelengths from Ref. 11:

84 keV (^{170}Tm): $\lambda_\gamma = 14.715430(13)$ pm;

63 keV (^{169}Yb): $\lambda_\gamma = 19.642536(26)$ pm

Table I
Measured ratios of wavelengths between muonic X-ray and calibration γ-rays, λ_x/λ_γ. Run 15 was calibrated with the 63.12 keV line of ^{169}Yb; in all other runs the 84.26 keV γ-line of ^{170}Tm was used.

		λ_x/λ_γ		
Isotope	transition	uncorrected[a]	corrected[b]	reference
^{24}Mg	$3d_{5/2}$-$2p_{3/2}$	1.122824(13)	1.122813(15)	run 15
	$3d_{5/2}$-$2p_{3/2}$	1.498795(14)	1.498780(15)	run 18
	$3d_{3/2}$-$2p_{1/2}$	1.494104(22)	1.494089(24)	run 18
^{28}Si	$3d_{5/2}$-$2p_{3/2}$	1.099710(35)	1.099710(38)	run 11
	$3d_{5/2}$-$2p_{3/2}$	1.099699(16)	1.099689(18)	run 17
	$3d_{3/2}$-$2p_{1/2}$	1.095047(26)	1.095037(27)	run 17
^{31}P	$3d_{5/2}$-$2p_{3/2}$	0.957332(47)	0.957323(48)	run 19
	$3d_{3/2}$-$2p_{1/2}$	0.952848(80)	0.952839(85)	run 19

[a] Statistical errors are given.
[b] Corrected for source-height effect; total errors are given.

The theoretical (QED) values of the X-ray wavelengths (Ref. 8) are also given in Table II (column six). They include the nuclear structure effects (finite size and nuclear polarization) and the electron screening shift, as well as higher-order radiative corrections (see also Refs. 7, 12). The over-all uncertainty in each value of λ_{th} is 6 ppm (Ref. 8). The experimental wavelength values are compared to the QED values in the last column of Table II. Averaging the six values we obtain the final result:

$$\overline{\frac{\lambda_{\text{exp}}-\lambda_{th}}{\lambda_{th}}}=(2\pm 8)\times 10^{-6}. \tag{2}$$

Thus, we find agreement between the measured transition wavelengths and QED calculations.

The vacuum polarization contribution, averaged over the transitions measured

Table II
Experimental X-ray wavelength values and comparison with theory (QED). Earlier published results are included.

Isotope	transition	λ_{exp}(pm)[a]	reference	λ_{exp}(pm)[b]	λ_{th}(pm)[c]	$\frac{\lambda_{\text{exp}}-\lambda_{th}}{\lambda_{th}}$ (ppm)
^{24}Mg	$3d_{5/2}$-$2p_{3/2}$	22.05490(29)	run 15	22.05507	22.05501	3 ± 10
	$3d_{5/2}$-$2p_{3/2}$	22.05519(24)	run 18			
	$3d_{3/2}$-$2p_{1/2}$	21.98616(34)	run 18	21.98616	21.98641	−11 ± 17
^{28}Si	$3d_{5/2}$-$2p_{3/2}$	16.18219(57)	ref. 3	16.18242	16.18234	5 ± 15
	$3d_{5/2}$-$2p_{3/2}$	16.18271(56)	run 11			
	$3d_{5/2}$-$2p_{3/2}$	16.18240(25)	run 17			
	$3d_{3/2}$-$2p_{1/2}$	16.11393(40)	run 17	16.11393	16.11408	9 ± 25
^{31}P	$3d_{5/2}$-$2p_{3/2}$	14.08630(45)	ref. 4	14.08662	14.08668	−5 ± 28
	$3d_{5/2}$-$2p_{3/2}$	14.08742(71)	run 19			
	$3d_{3/2}$-$2p_{1/2}$	14.02144(120)	run 19	14.02144	14.01861	202 ± 89

[a] All experimental errors included.
[b] Average over all experiments.
[c] Ref. 8, see also ref. 7.

(with appropriate weighting factors) is 3.4×10^{-3} of the average wavelength (see e.g. Ref. 7). Result (2) thus implies that the vacuum polarization effect has been measured to be correct to $(0.6 \pm 2.4) \times 10^{-3}$.

Alternatively, if we assume that QED describes the electromagnetic interaction in muonic atoms correctly, our result can be used to put a limit on an additional muon-nucleus interaction. Such an interaction can be described by potential (1). From the corresponding energy-level shift and result (2) we deduce limits for $(g_\mu \cdot g_N)/4\pi$ as a function of m. The two solid curves in Fig. 1 correspond to the mean value of $(g_\mu \cdot g_N)/4\pi$ plus and minus one standard deviation. The calculation was done separately for each element measured; the curves show an average over all elements. Also shown in Fig. 1 (broken curves) are the limits deduced from the μ-^{4}He experiment (Ref. 2); the r.m.s. radius of ^{4}He from Ref. 13 was used in this analysis.

This experiment provides the most stringent limit to a long range interaction (zero-mass limit) between the muon and the nucleons beyond QED. For example, if the mass m of the exchanged boson were smaller than 1 MeV, the product of coupling constants is:

$$\frac{g_\mu \cdot g_N}{4\pi} = (-4 \pm 17) \times 10^{-9}. \tag{3}$$

In case of the Weinberg–Salam theory, the muon-nuclean interaction is mediated by the Higgs boson [14]. If one assumes that the coupling of the Higgs boson to

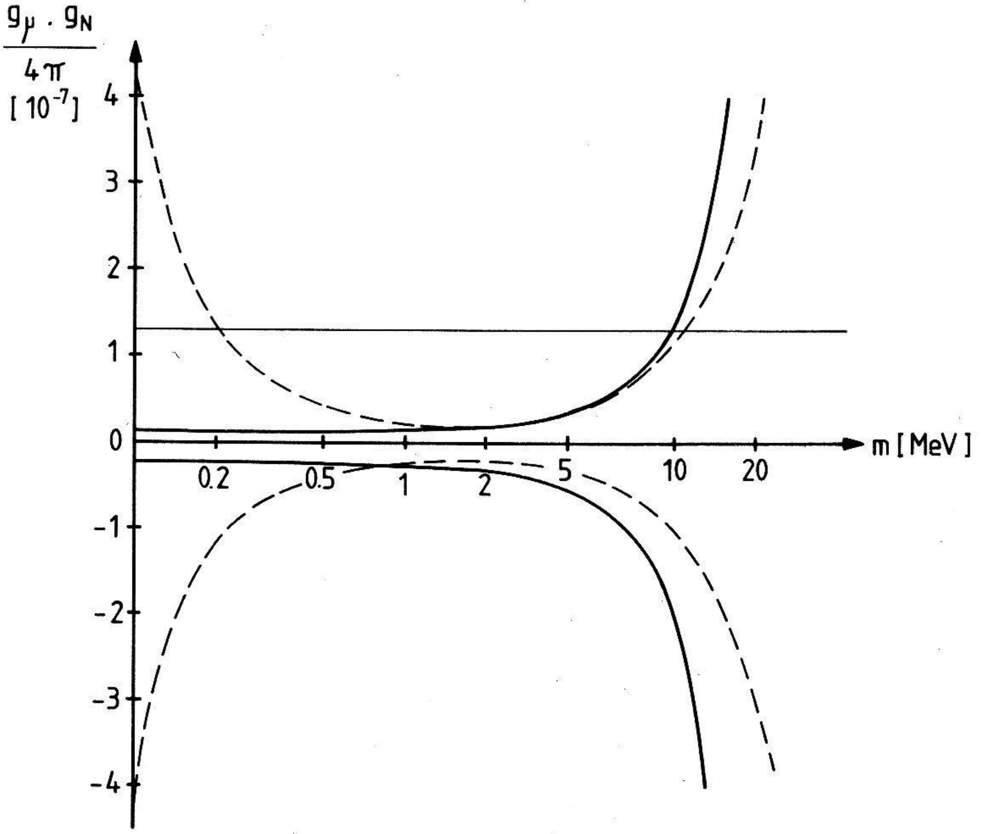

Figure 1
Limits on the product of coupling constants for a muon-nucleon interaction mediated by a boson of mass m. The solid lines are derived from equation (2). The broken curves stem from the μ-^{4}He experiment [2]. The straight line is the Higgs boson interaction as predicted from the Weinberg–Salam model.

the nucleons is of the same form as the coupling to the leptons (proportional to the fermion mass), one finds [4]

$$\frac{g_\mu \cdot g_N}{4\pi} = 1.29 \times 10^{-7}, \tag{4}$$

independent of the boson mass. The value (4) corresponds to the straight line in Fig. 1. We obtain from (4) and the upper solid curve in Fig. 1 a lower limit for the mass of the Higgs boson:

$$m \geqslant 8.5 \text{ MeV (90\% confidence level)} \tag{5}$$

This value is compatible with and similar to the results from experiments which are based on the *electron*-nucleon interaction mediated by the Higgs boson [15]. Within the framework of the Weinberg-Salam theory the above mass limit excludes a narrow mass range of heavy fermions [16, 17].

There is still another (third) interpretation of our result (2). In the calculation of the transition wavelengths (λ_{th}) the negative muon mass was assumed equal to the precisely measured positive muon mass [8]. If we now assume that QED is correct and there are no additional muon-nucleus interactions, then the null result of equation (2) establishes that the masses are in fact equal. Hence the CPT theorem for the muon is confirmed to within the quoted error of ±8 ppm.

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