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MEASUREMENT OF THE MAGNETIC MOMENT OF THE NEGATIVE MUON IN THE 1S-STATE OF DIFFERENT ATOMS

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It was shown by Breit in 1928 [1] that the electron in the 1s-state should possess a magnetic moment different from the free-electron value due to its relativistic motion. This effect was considered in more detail later in [2]. Unfortunately, measurement of the magnetic moment of a deeply bound electron is practically impossible. In 1958 Hughes and Telegdi [3] paid attention to the fact that the muon in the 1s-state should also possess a magnetic moment different from the free-muon one and the relativistic effect on the magnetic moment of a Dirac particle in a bound state can be examined in an experiment with negative muons.

The corrections to the magnetic moment of the negative muon bound to a zero spin nucleus and surrounded by a zero spin electronic shell were considered in [4, 5], where corrections to the muon g-factor were given for different atoms:

$$\mu_\mu = (g/2)\mu_{\mathrm{B}}, \qquad (g - g_0) = \sum_{i=1}^{7} g_i \tag{1}$$

where μ_μ and μ_{B} are the magnetic moment of the bound negative muon and the Bohr magneton for the muon, respectively; $g_0 = 2$; $g_1 ... g_7$ are the corrections to the g-factor value: g_1 is the radiative correction, g_2 is the relativistic correction to the radiative one, g_3 is the relativistic correction, g_4 is the nuclear polarization correction, g_5 is the correction for polarization of the electron shell of the atom, g_6 is the correction for diamagnetic screening of the external magnetic field by the electron shell of the atom, g_7 is the center-of-mass correction. For a free muon $g = g_0 + g_1 = g_+$ (g_+ is the g-factor of the positive muon).

The radiative correction to the magnetic moment of the free muon is known with a high accuracy: $g_1/g_0 = 0.0011659230(84)$ [6]. The radiative correction to the magnetic moment of a bound muon differs from g_1 by g_2. The value of g_2 does not exceed 2% of the relativistic correction g_3 [5] even in the case of large Z. The center-of-mass correction is also much smaller than the relativistic one and is about $g_7/g_3 \sim m_\mu/M$ [5], where m_μ and M are the muon and nucleus masses, respectively.

The largest correction to the magnetic moment of a bound negative muon is due to its relativistic motion in the Coulomb field of the nucleus [2]:

$$g_3/g_0 = -\frac{4}{3}\int F^2 dr \tag{2}$$

where F is the small component of the radial wave function of the muon.

Since the magnitude of F is proportional to v/c, the relativistic correction is proportional to the kinetic energy of the muon in the 1s-state ($v^2/c^2 = T/mc^2$) and increases with the nuclear charge increasing. The results of the numerical calculations show [4, 5] that the relativistic correction to the magnetic moment of a bound muon is about 0.1%, 1.1%, and 3.2% in the case of oxygen, zinc, and lead, respectively. Thus, the relativistic correction is comparable with the radiative one in the case of oxygen and exceeds the latter by one order of magnitude for zinc.

Up to now there have only been three experimental investigations performed [7–9] where the magnetic moment of the negative muon in the 1s-state of light (C, O, Mg, Si, S) [7, 9] and heavy (Zn, Cd, Pb) [8] atoms was measured. The accuracy of the measurement of the corrections to the negative muon g-factor in Mg, Si, and S atoms is $\sim 3\%$, close to the accuracy of theoretical calculations. In [7] satisfactory agreement between the experimental and calculated data was obtained for C, O, Mg, Si, and S. But the values of $(g_+ - g_-)/g_+$ (g_- is the negative muon g-factor in the 1s-state of the atom) measured in [9] for negative muons in Mg, Si, and S appeared to be smaller than in [7] by $17 \cdot 10^{-4}$ of absolute value. According to [7], $(g_+ - g_-)/g_+$ is $(29.6 \pm 0.7) \cdot 10^{-4}$, $(36.3 \pm 1.1) \cdot 10^{-4}$, and $(48.2 \pm 1.6) \cdot 10^{-4}$ for Mg, Si, and S, respectively. In the case of heavy atoms the accuracy of measurements is about 50% [8]: the ratio $(g_+ - g_-)/g_+$ is equal to $(120 \pm 62) \cdot 10^{-4}$, $(201 \pm 140) \cdot 10^{-4}$, and $(468 \pm 220) \cdot 10^{-4}$ for Zn, Cd, and Pb, respectively. Despite the fact that the experimental data for heavy atoms do not contradict the calculated ones, they cannot be considered as a proof for the effect of a decrease in the magnetic moment of a Dirac particle at its relativistic motion in the Coulomb field of the nucleus.

In the present work preliminary results of the measurements of the magnetic moment of the negative muon in the 1s-state of carbon, oxygen, magnesium, and silicon atoms are presented. Analogous measurements are now being carried out by J.H.Brewer at TRIUMF (Canada).

When the negative muon is implanted in a medium, it slows down and is captured by a medium atom. In condensed matter the muon reaches the 1s-state within the time less than 10^{-10} s. Because of its large mass, the Bohr radius of the muon is 200 times smaller than that of the K-electron. The negative muon is an unstable particle and decays mainly through the mode $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$. As a consequence of the parity nonconservation in this process, the spatial distribution of the decay electrons is asymmetric. This phenomenon serves as the basis for measuring the magnetic moment of the muon. In the transverse magnetic field its magnetic moment (and spin) precesses with the frequency $\nu = 2\mu_\mu H/h = g\mu_B H/h$, where μ_B is the Bohr magneton for the muon. For polarized muons the exponential curve of the time distribution (with respect to muon stops in the sample) of decay electrons is modulated by a cosine with the frequency ν. The cosine amplitude is proportional to the muon polarization in the 1s-state. Therefore, by measuring the muon spin precession frequency one can determine the magnetic moment of the bound muon. Experimentally the correction to the magnetic moment (g-factor) of a bound negative muon is determined by comparing the spin precession frequencies of the positive and negative muons in the external magnetic field:

$$\frac{g_+ - g_-}{g_+} = \frac{\omega_+ - \omega_-}{\omega_+} \tag{3}$$

where g_+, g_-, ω_+, and ω_- are the g-factors and the precession frequencies for the positive and negative muons.

The present measurements were carried out with the "Stuttgart LFQ-spectrometer" [11] at the μE4 beamline of the Paul Sherrer Institute accelerator (Switzerland). The momentum of the muon beam was $\sim$ 68 MeV/c. The external magnetic field of 0.1 T transverse to the direction of the muon spin was produced on the sample by the Helmholtz coils. The middle diameter of the coils was 510 mm, the distance between the coil centers was 240 mm. These dimensions are close to the optimal ones for obtaining the magnetic field with homogeneity not worse than 10^{-5} in the volume of 3x3x3 cm^3 in the center of the coils. The components of the terrestrial magnetic field and stray fields from the magnetic elements nearest to the spectrometer were compensated by three pairs of additional coils with an accuracy of 10^{-2} oersted. The residual magnetic field was measured by three reciprocally perpendicular permalloy sensors. The positioning of the Helmholtz coils relative to the beam axis (collimator) was done with a laser.

The samples investigated were shaped as cylinders of 30 mm in diameter and 12, 18, 11, and 10 mm thick in case of carbon (reactor grade graphite), oxygen (water), magnesium, and silicon, respectively. Water was packed in a cylindrical container made of phenoplast with 2 mm thick walls. The weight of the water container was 1.7 gram. The silicon sample was an intrinsic silicon crystal ($\rho \sim 10^4$ Ohm·cm). The samples were positioned so that the cylinder axis coincided with the axis of the beam. The beam spot size on the sample was about 16 mm. The position of the sample relative to the beam axis was fixed with an accuracy better than 1 mm.

To find out the muon distribution in the sample volume, the dependence of the muon stopping rate on the thickness of a copper degrader (muon range curve) was measured for a 1 g/cm^2 thick graphite sample. The muon range curve has a maximum at ~ 4 g/cm^2 and the full witdth at the half-maximum (at the 5% level of the maximum) 0.8 g/cm^2 (1.4 g/cm^2). Thus, the volume of the muon stop region in the samples investigated was not larger than 6 cm^3.

The free muon spin precession frequency was determined by the precession frequency of the μ^+ spin in graphite. Thus the measurements in graphite were carried out alternatively with the positive and negative muon beams obtained with the same momentum in the μE4 channel. The measurements with the negative muon beam and the O($H_2$0), Mg, and Si samples alternated with the graphite measurements. The following values were obtained for the asymmetry coefficient in the space distribution of electrons (positrons) from the $\mu^-(\mu^+)$ decay in C, O(H_2O), Mg, and Si: 0.0486±0.0003 (0.167±0.0007), 0.0177±0.0004, 0.0324±0.0004 и 0.0304±0.0004.

Table: The measured muon spin precession frequency $\omega_-(\omega_+)$ and the deduced correction to the g-factor of the bound negative muon $(g_+ - g_-)/g_+ = (\omega_+ - \omega_-)/\omega_+$ for carbon, oxygen (water), magnesium and silicon samples. The positive muon precession frequency ω_+ is corrected for the paramagnetic shift in carbon $(3.8 \cdot 10^{-4}$ [7])

target	$\omega_-(\omega_+)$, rad/μs present exp.	$\frac{g_+-g_-}{g_+}$, 10^{-4} present exp.	$\frac{g_+-g_-}{g_+}$, 10^{-4} exp. [7]	$\frac{g_+-g_-}{g_+}$, 10^{-4} theor. [5]	
				total	relativistic
C(graphite, μ^+)	(85.109±0.003)				
C(graphite)	85.044±0.006 85.060±0.008 85.031±0.009 85.047±0.009				
(mean value)	85.045±0.004	7.5±0.7	7.6±0.3	8.2±0.1	6.29
O, in H_2O	85.053±0.014	6.5±1.6	9.4±1.0	14.3±0.2	11.04±0.01
Mg, in metal	84.931±0.014	21.0±1.6	26.4±0.7	29.8±0.6	23.79±0.06
Mg, in MgH_2			29.6±0.7		
Si, crystal	84.811±0.024	35.1±2.8	36.3±1.1	39.1±1.0	31.70±0.10

Table shows measured spin precession frequencies of positive and negative muons for the samples investigated. The precession frequency for the positive muon is corrected for the paramagnetic shift in carbon ($3.8 \cdot 10^{-4}\omega_+$ [7]). The corrections to the g-factor of the negative muon in the 1s-state of carbon, oxygen, magnesium, and silicon atoms are compared in the table with the analogous data of [7] and theoretical calculations [5]. In the last column of the table the calculated value [5] of the relativistic correction to the muon magnetic moment is shown. As is seen from the table, the precession frequencies of the negative muon spin in graphite measured at different time (the time interval between the measurements was about 5 hours) coincide within statistical errors thus characterizing the long-term stability of the external magnetic field on the sample is not worse than 10^{-4}.

The corrections to the g-factor (magnetic moment) of the negative muon in the 1s-state of carbon, oxygen, and silicon agree with the data [7] and do not confirm the results [9], where measured $(g_+ - g_-)/g_+$ for negative muons in Mg, Si, and S were smaller by $17 \cdot 10^{-4}$. Thus, the results of the present investigation are close to the experimental data [7] and indicate that the magnetic moment of the negative muon bound in the Coulomb field of the nucleus differs from the one of the free muon. But the experimental corrections to the negative muon g-factor (present work and [7]) are systematically smaller than the calculated ones by (10 – 30) %. To find out the causes of the systematic discrepancy between the theoretical and experimental data additional theoretical calculations are to be carried out.

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