errors on ρ are estimated by the authors[12] to be ± 0.02, due mainly to the subtraction of radiative tails. Finally the fact that for $x > 0.1$ the nucleus does indeed behave like a noninteracting collection of protons and neutrons suggests that *if scaling is valid,* high-Z targets can be used for the study of muon-nucleon scattering at very high energies.

We are indebted to the staff of the Brookhaven National Laboratory alternating-gradient synchrotron for their support and to Mr. J. Yee, Mr. J. Kim, and Mr. J. Sanders for assistance at various stages of this experiment.

*Work supported in part by the U.S. Energy Research and Development Administration and the National Science Foundation.

†During the performance of this experiment the authors held guest appointments at Brookhaven National Laboratory, Upton, N.Y. 11973.

[1]A. Entenberg *et al.*, Phys. Rev. Lett. 32, 486 (1974).

[2]I. J. Kim *et al.*, Phys. Rev. Lett. 33, 551 (1974).

[3]R. M. Sternheimer, in *Methods of Experimental Physics,* edited by L. C. L. Yuan and C. S. Wu (Academic, New York, 1961), Vol. 5; B. Rossi, *High Energy Particles* (Prentice Hall, New York, 1952). See, also M. May, Ph.D. thesis, Columbia University, Nevis Laboratory Report No. 209, 1975 (unpublished).

[4]W. Atwood, private communication. This fit to the structure function $\nu W_2^{\,p}$ is almost equivalent to that of V. Rittenberg and H. R. Rubinstein, Phys. Lett. 35B, 50 (1971), and that of M. Breidenbach and J. Kuti, Phys. Lett. 41B, 345 (1972).

[5]R. M. Sternheimer, Phys. Rev. 103, 511 (1956); P. M. Joseph, Nucl. Instrum. Methods 75, 13 (1969). If E_0 and E_0' are the true incident and scattered muon energies and E and E' the observed energies, then $\nu = E_0 - E_0' = E - E' - \delta$, where δ is the energy loss for a muon traversing the entire length of the target.

[6]L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41, 205 (1969).

[7]E. J. Moniz *et al.*, Phys. Rev. Lett. 26, 445 (1971).

[8]D. O. Caldwell *et al.*, Phys. Rev. Lett. 23, 1256 (1969); G. R. Brookes *et al.*, Phys. Rev. D 8, 2826 (1973).

[9]D. Schildknecht, Nucl. Phys. B66, 398 (1973).

[10]E. D. Bloom, in *Experiments on High-Energy Particle Collisions —1973,* edited by R. S. Panvini, AIP Conference Proceeding No. 12 (American Institute of Physics, New York, 1973), p. 277; H. Kendall, in *Proceedings of the International Conference on Electron and Photon Interactions at High Energies, Ithaca, New York, 1971,* edited by N. B. Mistry (Cornell Univ. Press, Ithaca, N.Y., 1972).

[11]J. Bailey *et al.*, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975). See also F. J. Gilman, *ibid.*

[12]S. Stein *et al.*, SLAC Report No. SLAC-PUB-1528, 1975 (unpublished).

Test of Quantum Electrodynamics by Muonic Atoms: An Experimental Contribution

L. Tauscher, G. Backenstoss, K. Fransson, H. Koch, A. Nilsson, and J. De Raedt
CERN, Geneva, Switzerland, and Institut für Physik, University of Basle, Basle, Switzerland, and Institut für Experimentelle Kernphysik, Karlsruhe, Germany, and Research Institute for Physics, Stockholm, Sweden, and Instituut voor Kern- en Stralingsfysika, Leuven, Belgium
(Received 10 June 1975)

The large unexplained deviations of the experimental muonic 4-3 transitions in Ba and 5-4 transitions in Pb from calculations were found not to be existent. The absolute energies of these transitions agree, on the average, with theory to within 10 eV: The differences between experimental and calculated energies $E^{\rm calc} - E^{\rm exp}$ are $+2 \pm 13$ and -2 ± 12 eV for the μ^--Ba $4f_{5/2}$-$3d_{3/2}$ and $4f_{7/2}$-$3d_{5/2}$ transitions, respectively, and 10 ± 16 and -13 ± 14 eV for the μ^--Pb $5g_{7/2}$-$4f_{5/2}$ and $5g_{9/2}$-$4f_{7/2}$ transitions, respectively.

Several experiments have been performed in recent years to check the validity of quantum electrodynamics (QED) by x-ray transitions in muonic atoms, where the vacuum polarization is the largest QED correction.[1-4] One of these experiments[2] showed significant deviations from calculations for energies above 400 keV, the experimental values being smaller than the calculated ones. The measurement of Ref. 3 seemed to confirm the deviations of Ref. 2, though it is not really incompatible with calculations. The recent measurement of the μ-He Lamb shift[4] is in perfect agreement with calculation. Slight, but not significant, deviations were observed in Ref. 1.

The result of Refs. 2 and 3 stimulated many authors to consider possible theoretical explanations for the deviations.[5] It also became clear, however, that the present methods of absolute energy calibration with Ge(Li) spectrometers have been pushed to their limits: Systematic uncertainties of unknown magnitude may dominate the errors when calibrating with radioactive sources, even under "beam conditions."

In this Letter we want to communicate the results of measurements which will be described in detail in a forthcoming paper.[6] The measurements were done on muonic Ba and muonic Pb. The spin doublets of the 4-3 transitions in Ba and the 5-4 transitions in Pb interleave with each other, thus providing an excellent opportunity for a high-precision relative-energy measurement. Furthermore, the availability of a nearby muon-induced γ line of ^{137}Cs, whose energy was separately determined with high precision,[6] facilitated the measurement of absolute energies. Hence we believed that we had a good chance to settle the important question of possible deviations from QED as far as experiments are concerned.

The measurement was performed at the CERN synchrocyclotron muon channel. The target was X shaped, one V being made from Ba, and the other from Pb. The target was inverted during the measurement to avoid directionally correlated deviations. As external calibration we used sources of ^{75}Se and ^{198}Au, which were placed close to the target, and whose γ rays were recorded in accidental prompt coincidence of the Ge(Li)-detector signal with the counter-telescope stop signal. Two Ge(Li) detectors were used with volumes of 200 mm$^2 \times$ 5 mm and 400 mm$^2 \times$ 7mm, respectively. The resolution in beam was 1.50 keV at 450 keV for both detectors. The advantage of the method is that Ba and Pb x rays are recorded simultaneously. Thus their relative position could be measured very accurately, without systematic uncertainties from the apparatus.

The spectra were analyzed very carefully. Almost every line in the spectrum above 80 keV and above 0.5% yield was identified. Transitions between noncircular orbits (satellite lines) were considered as well as transitions with $\Delta n > 1$. Most nuclear γ lines could be identified. The muonic lines of ^{12}C and ^{16}O coming from telescope counters were analyzed as well. The relative intensities of the x-ray transitions were evaluated in order to fix the cascade parameters (initial distribution, initial main quantum numbers) which are mainly determined by transitions with $\Delta n \geq 2$. Cascade calculations with adapted parameters were performed to obtain the intensities of unresolved x-ray transitions. The line shape was obtained from well-resolved single lines. The calibration was performed in the following way: In addition to the external calibration with radioactive sources of ^{75}Se and ^{198}Au,[7] we used the muonic lines of Pb and Ba, having energies of less than 300 keV, as well as the muonic lines of ^{16}O and ^{12}C. These lines are supposed to be good calibration lines, as their energies can be calculated very accurately[8] or have already been accurately measured.[9] No significant deviation of these energies from calculation has been reported yet. The most important calibration point, however, is the ^{137}Cs line at 455.490 keV,[10] which was measured separately to an accuracy of 10 eV.[6] This nuclear transition originates from the μ absorption in Ba and has a lifetime less than 1 nsec. As the muon itself has a lifetime in the 1s orbit of Ba of about 100 nsec, this line is prompt in the time scale of our experimental electronics, and thus very well suited for calibration. No systematic shift between this calibration line and the x rays is expected. As a further calibration point we used the e^+e^--annihilation line. No reason could be found for this line to be shifted significantly.[11] Even a shift of 30 eV[11] would not affect our result by more than 3 eV.

The results are shown in Table I. The errors quoted include the statistical errors, and a calibration error of 9 eV. A systematic error of about 5 eV must be added to account for possible shifts of the annihilation line. A comparison of these values with the calculated values[8,12] (a summary of calculations may be found in Ref. 5) shows that the deviations are generally smaller than the experimental errors. Especially the very large deviations for Ba have disappeared, not only with respect to Pb but also absolutely:

TABLE I. Experimental results.

Transition	$E^{\exp\,a}$ (keV)	E^{calc} (keV)	$E^{\text{calc}}-E^{\exp}$ (eV)
μ-Ba $4f_{5/2}$-$3d_{3/2}$	441.366 ± 13	441.368	+2 ± 13
μ-Ba $4f_{7/2}$-$3d_{5/2}$	433.916 ± 12	433.914	−2 ± 12
μ-Pb $5g_{7/2}$-$4f_{5/2}$	437.744 ± 16	437.754	+10 ± 16
μ-Pb $5g_{9/2}$-$4f_{7/2}$	431.353 ± 14	431.340	−13 ± 14

[a]The new, unpublished Au standard of 411.806 keV [Deslattes *et al.*, in Proceedings of the Fifth International Conference on Atomic Masses and Fundamental Constants, Paris, 2–6 June 1975 (to be published)] would increase these values by about 10 eV.

The average deviations for Pb and Ba differ by only 2 ± 14 eV. The recent evaluations of a graph of order $\alpha^2(\alpha Z)^2$ gave controversial results, two papers[13] claiming this contribution to be of the order of 1 eV or less, and one paper[14] quoting contributions to the transition energies in question of -35 eV for Pb and -22 eV for Ba. The present experiment does not confirm such large corrections. It should be mentioned that the calculated energies in Table I also suffer from uncertainties of 7–10 eV.[5]

From our measurement we conclude that the validity of QED in the domain of muonic atoms, even for high-Z atoms, is confirmed to an accuracy of about 0.5%, regarding the average deviation from calculation. The measurement is in contradiction to the measurements of Ref. 2, and also, although less significantly, to the conclusions of Ref. 3. It is, however, in agreement with our early measurement on muonic Pb.[1]

This work was partly supported by the Bundesministerium für Forschung und Technologie, Germany.

[1] G. Backenstoss, S. Charalambus, H. Daniel, Ch. v.d. Malsburg, G. Polez, H. P. Povel, H. Schmitt, and L. Tauscher, Phys. Lett. 31B, 233 (1970); G. Backenstoss, H. Daniel, H. Koch, Ch. v.d. Malsburg, G. Poelz, H. P. Povel, H. Schmitt, and L. Tauscher, Phys. Lett. 43B, 539 (1973).

[2] M. S. Dixit, H. L. Anderson, C. K. Hargrove, R. J. McKee, D. Kessler, H. Mes, and A. C. Thompson, Phys. Rev. Lett. 27, 878 (1971).

[3] H. K. Walter, J. L. Vuilleumier, H. Backe, F. Boehm, R. Engfer, A. H. v. Gunten, R. Link, R. Michaelsen, C. Petitjean, L. Schellenberg, H. Schneuwly, W. U. Schröder, and A. Zehnder, Phys. Lett. 40B, 197 (1972); R. Engfer, J. L. Vuilleumier, and E. Borie, in *Proceedings of the Fourth International Conference on Atomic Physics, Heidelberg, Germany, 1974*, edited by G. zu Putlitz, E. W. Weber, and A. Winnacker (Plenum, New York, 1975).

[4] A. Bertin, G. Carboni, A. Placci, E. Zavattini, U. Gastaldi, G. Gorini, G. Neri, O. Pitzurra, E. Polacco, G. Torelli, A. Vitale, J. Duclos, and J. Picard, Phys. Lett. 55B, 411 (1975).

[5] P. J. S. Watson and M. K. Sundaresan, Can. J. Phys. 52, 2037 (1974); R. Rafelski, B. Muller, G. Soff, and W. Greiner, Ann. Phys. (Leipzig) 88, 419 (1974).

[6] L. Tauscher, G. Backenstoss, K. Fransson, N. Hassler, H. Koch, A. Nilsson, and J. De Raedt, to be published.

[7] The Au standard of 411.794 ± 0.007 keV was used.

[8] L. Tauscher, "Improved Vacuum Polarization Calculations for Mesic Atoms and Their Effect on the π^- Mass" (to be published).

[9] T. Dubler, L. Schellenberg, H. Schneuwly, R. Engfer, J. L. Vuilleumier, H. K. Walter, A. Zehnder, and B. Fricke, Nucl. Phys. A219, 29 (1974).

[10] Based on Ir, the Au standard of 411.794 keV, and the 511 keV annihilation line.

[11] B. N. Taylor, W. H. Parker, and D. N. Langenberg, Rev. Mod. Phys. 41, 375 (1969).

[12] M. Gyulassy, Phys. Rev. Lett. 32, 1393 (1974); G. A. Rinker and L. Wilets, Phys. Rev. A (to be published).

[13] L. Wilets and R. A. Rinker, Phys. Rev. Lett. 34, 339 (1975); E. Borie, "Corrections of Order $\alpha^2(\alpha Z)^2$ to Energy Levels of Muonic Atoms" (to be published).

[14] M. Y. Chen, Phys. Rev. Lett. 34, 341 (1975).

Coherent K_S^0 Regeneration in Hydrogen and Deuterium from 3.5 to 10.5 GeV/c*

D. Freytag,† C. Schultz, P. Patel, C. Rippich, D. G. Ryan, S. L. Meyer, W. E. Cleland, and E. Engels

University of Massachusetts, Amherst, Massachusetts 01002, and McGill University, Montreal, Quebec, Canada, and Northwestern University, Evanston, Illinois 60201, and University of Pittsburgh, Pittsburgh, Pennsylvania 15260

(Received 12 March 1975)

The amplitude and phase for coherent regeneration in hydrogen and deuterium have been measured for six momentum bins in the range 3.5–10.5 GeV/c. Over this region the phase, φ_f, is consistent with being constant and has the value $-60° \pm 8°$ for hydrogen and $-46° \pm 8°$ for deuterium. Power-law fits of the form p_{1ab}^n for the amplitudes when combined with other data give $n = -0.60 \pm 0.02$ for hydrogen and $n = -0.52 \pm 0.02$ for deuterium.

In its interactions with matter the K_L^0 state must be considered as a superposition of the strangeness eigenstates K^0 and $\bar{K}^0$. Since their respective forward elastic scattering amplitudes $f(0)$ and $\bar{f}(0)$ are not equal, a nonzero amplitude for the K_S^0 state is coherently regenerated. This regenerated amplitude can be observed via the $\pi^+\pi^-$ decay mode as it interferes with the known