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New Muonic-Atom Test of Vacuum Polarization*

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In order to check the discrepancy between calculation and experiment in muonic atoms, we have remeasured the $5g$-$4f$ transitions in Pb and the $5g$-$4f$ and the $4f$-$3d$ transitions in Ba. Our new results show no discrepancy and confirm recent theoretical calculations of vacuum polarization to within 0.5%.

The energy levels of muonic atoms can be calculated to high precision by solving the Dirac equation, taking into account corrections for nuclear size and polarization, electron screening, vacuum polarization, Lamb shift, and other smaller effects. Accordingly, precise measurements of transition energies can be used to test the accuracy of these corrections. In particular, certain transitions in medium- and high-Z atoms whose energies are in the 100–500-keV region tend to be relatively insensitive to either nuclear or electron screening effects and so provide a sensitive test of the higher-order quantum-electrodynamics corrections.

The results of an experiment designed to make this test were published by Dixit *et al.*[1] in 1971. Our measurements disagreed with those of Backenstoss *et al.*[2] and with the theory for a number of lines in the 100–500-keV region for several elements. In particular, near 450 keV, the $5g$-$4f$ lines of muonic Pb and the $4f$-$3d$ lines of muonic Ba showed discrepancies amounting to more than 5 times the stated error. Since then, much of the discrepancy has been removed by careful theoretical work (see the review by Watson and Sundaresan[3]). Although the measurements of Walter *et al.*[4] on Hg and Tl confirmed our results, the theoretical calculations had now positioned themselves between the earlier measurements of Backenstoss *et al.*[2] and those of our group[1] and Walter *et al.*[4] In view of this a new series of measurements seemed warranted.

We have in progress such measurements using the muon beam of the Space Radiation Effects Laboratory synchrocyclotron. Although this work is not yet complete, we believe there has been sufficient interest in the subject during the past four years for the results obtained thus far to be reported without delay. A full report will be published in due course.

The techniques used in this experiment were similar to those used before.[1,5] A standard telescope was used to define μ^- stops in each of two targets. The targets were positioned perpendicular to the beam direction and a Ge(Li) detector was placed in the beam directly behind the muon veto counter. The detector had high resolution (525 eV full width at half-maximum at 122 keV and 1050 eV at 468 keV), an area of 1 cm^2, and a small thickness, 0.5 cm, chosen to reduce the sensitivity to high-energy photons and beam muons. The response of this detector turned out to be considerably more asymmetric than that used previously, complicating the line-fitting procedure. The digital-to-analog calibration method was not used this time. On the other hand, we used an improved analog-to-digital converter (ADC) which showed exceptionally good linearity and long-term stability. It was stabilized with the ^{7}Be γ ray at 477 keV. To simulate the way the muonic x rays were brought into the apparatus, the calibration nuclear γ-ray sources were brought in by accidental coincidence with a 900-nsec pulse triggered by a telescope placed upstream in the beam. The Ge pulses associated with μ stops were stored in prompt and delayed spectra using a time window of ~15 nsec for prompt events. The source data were kept separately.

X-ray and γ-ray peak positions were determined using an empirical line shape[6] derived from the shape of the ^{228}Th 238-keV γ ray. The energy calibration of the ADC was obtained by fitting seven source energies to their ADC channel positions using a quadratic function. The standard deviation of the fit was 4.9 eV. The x-ray line shapes included a Lorentzian function to take into account their natural widths. A number of tests were made to determine the sensitivity of the peak positions to various parameters, as a result of which we assigned an uncertainty of ± 4 eV due to fitting procedures.

Corrections (typically 6± 3 eV for $5g$-$4f$ in Pb) were applied to the x-ray energies for the angular effect and the extended target geometry. Account was also taken of the unresolved inner transitions. For example, the uncertainty of the intensity determination of the $5f_{7/2}$-$4d_{5/2}$ line in Pb causes an uncertainty of ± 6 eV for the $5g_{7/2}$-$4f_{5/2}$ transition.

The energy of the primary calibration standard ^{198}Au (412 keV) has recently been redetermined with improved accuracy by Deslattes *et al.*[7] resulting in a 12-eV upward shift. The other source energies and their errors are also affected[8] by this measurement. We use these new energies for our calibration.

Different timing conditions may give rise to systematic shifts between prompt x-ray and calibration source spectra. We looked for this effect by comparing the positions of the μ-capture γ rays in prompt and delayed spectra at 279 keV from ^{204}Pb and 455 keV[9] from ^{138}Ba with the energies of their corresponding sources ^{203}Hg and ^{137}Cs, respectively. We also compared the 477-keV ^{7}Be and the 122-keV ^{57}Co γ-ray positions in prompt, delayed, and source spectra. We have taken the weighted mean of these measurements and applied a correction of +1± 6 eV to the data.

In Table I we give the different transitions, the theoretical vacuum polarization values, theoretical and experimental transition energies, and the differences $\Delta E = E_{\text{theor}} - E_{\text{exp}}$.

The theoretical values are those given by Watson and Sundaresan[3] in their recent review, except that we have replaced the contribution of the $\alpha(Z\alpha)^{n\geq 3}$ terms given there by those calculated by Rinker and Wilets[10] to include the finite-size effect on these terms. For Pb ($5g$-$4f$) this raises the energy by 8 eV. We have also included the contribution of $\alpha^2(Z\alpha)^2$ diagrams as calculated by Sundaresan and Watson.[11] This amounts to adding 1 eV to the Pb ($5g$-$4f$) transition energies. This calculation is in agreement with the independent calculation of Wilets and Rinker[12] and Fujimoto[13] but disagrees with that of Chen.[14]

The results of the present experiment are in disagreement with our earlier work[1] but agree with the measurements recently reported by Tauscher *et al.*[15] The theoretical calculations of vacuum polarization effects appear, from this evidence, to be confirmed to within 0.5%.

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TABLE I. Vacuum polarization; theory and experiment (eV).

Element	Transition	Vac. pol. (theor)	E_{theor}(total)	E_{exp}	$E_{\text{theor}}-E_{\text{exp}}$
Ba	$4f_{5/2}$-$3d_{3/2}$	2432	441 355± 10	441 371± 12	−16± 16
	$4f_{7/2}$-$3d_{5/2}$	2326	433 907± 7	433 910± 12	−3± 14
	$5g_{7/2}$-$4f_{5/2}$	759	201 273± 4	201 282± 9	−9± 10
	$5g_{9/2}$-$4f_{7/2}$	744	199 906± 4	199 915± 9	−9± 10
Pb	$5g_{7/2}$-$4f_{5/2}$	2163	437 747± 7	437 762± 13	−15± 15
	$5g_{9/2}$-$4f_{7/2}$	2079	431 338± 7	431 341± 11	−3± 13

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Effect of Langmuir Turbulence on Stimulated Brillouin Backscattering

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The threshold for stimulated Brillouin backscattering in a weakly inhomogeneous plasma in the presence of a low level of Langmuir turbulence has been estimated. Such background turbulence is found to induce a small space-dependent wave-number mismatch through the modified ion-acoustic-wave dispersion relation, leading to convective saturation of the scattered wave. The threshold values are found to be quite significantly altered compared to those calculated for quiescent plasmas.

The interaction of an intense laser beam with a plasma has gained a great deal of importance because of its relevance to laser fusion.[1] Of special interest are the various nonlinear processes which can lead to efficient coupling of the radiation to the plasma and thereby cause heating.[2] However, some of these nonlinear processes, e.g., stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), can also work against efficient heating by preventing the radiation from reaching the critical region. In fact, theoretical[3] estimates as well as computer simulation results foresee them as major hurdles to parametric heating. Experimental[4] evidence available so far, on the other hand, seems to belie such predictions and scattering is observed