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Lamb Shift in Heliumlike Uranium (U^{90+})

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We report a value of 70.4 (8.1) eV for the one-electron Lamb shift in uranium, in agreement with the theoretical value of 75.3 (0.4) eV. We extract our Lamb shift from a beam-foil time-of-flight measurement of the 54.4 (3.3) ps lifetime of the $1s2p_{1/2}\ {}^3P_0$ state of heliumlike uranium.

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A possible failure of quantum electrodynamics (QED) to predict accurate radiative corrections to bound states at Z= 92 is not ruled out by its success at low Z. The largest contribution to the Lamb shift at Z = 92 comes from terms in the electron self-energy[1] which are high powers of $Z\alpha$ and which are invisible in experiments at low Z. Lamb shift measurements on high-Z electronic and muonic atoms are complementary because muonic atom measurements are sensitive to higher order vacuum polarization effects but not to self-energy effects[2].

We report a value of 70.4 (8.1) eV for the one-electron Lamb shift in uranium. It is in agreement with the theoretical value[3,4] of 75.3 (0.4) eV based upon a calculation of the self-energy by Mohr[3]. We extract our Lamb shift from our beam-foil time-of-flight measurement of 54.4 (3.3) ps for the lifetime of the $1s2p_{1/2}\ {}^3P_0$ state of heliumlike uranium.

The $1s2p_{1/2}\ {}^3P_0$ state (Fig. 1) is the only low-lying excited state found in hydrogenlike uranium or heliumlike uranium whose long lifetime allows its decay to be observed in vacuum downstream from the target in which it is produced. In heliumlike uranium the $1s2p_{1/2}\ {}^3P_0$ state decays 70% of the time to the $1s2s\ {}^3S_1$ state by an electric-dipole (E1) transition. This makes the $1s2p_{1/2}\ {}^3P_0$ lifetime sensitive to the $1s2p_{1/2}\ {}^3P_0$ - $1s2s\ {}^3S_1$ energy difference of 260.0 (7.8) eV (experimental value) and hence to the Lamb shift. At Z=92 the major contributions to the calculated Lamb shift are the self-energy[3] of 56.7 eV, the leading order term in the vacuum polarization[3,4] of -14.3 eV and the finite nuclear size correction[4] of 32.5 eV. In heliumlike uranium there is also a small screening correction to the radiative corrections - expected to be of order 1/Z times the self-energy[2,5]. For zero Lamb shift the $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ states would be split by the difference in the $1s_{1/2}$ - $2s_{1/2}$ and $1s_{1/2}$ - $2p_{1/2}$ Coulomb interactions. This splitting at $Z = 92$ has been calculated by Mohr[6] to be 330.4 eV, which agrees (1 eV) with the calculations of Lin, Johnson and Dalgarno[7] and of Drake[8]. The other significant decay of the $1s2p_{1/2}$ $^3P_0$ state is to the $1s^2$ $^1S_0$ ground state by a two-photon electric-dipole magnetic-dipole (E1M1) transition[8]. To obtain the Lamb shift we combine our measured $1s2p_{1/2}$ $^3P_0$ lifetime and the calculated values for the E1M1 decay rate[8], the $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ E1 matrix element[9], and the $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ Coulomb splitting[6].

In our beam-foil time-of-flight measurement about 0.5% of a beam of 218 MeV/amu hydrogenlike uranium is converted to the $1s2p_{1/2}$ $^3P_0$ state of heliumlike uranium by electron capture in a 0.9 mg/cm^2 Pd foil. Hydrogenlike uranium[10] is obtained from the Lawrence Berkeley Laboratory's Bevalac[11]. Downstream from the Pd foil we observe, not the 260 eV photon from the $1s2p_{1/2}$ $^3P_0 \rightarrow 1s2s$ $^3S_1$ transition, but instead the 96.01 keV x ray from the subsequent fast decay of the $1s2s$ $^3S_1$ state to the $1s^2$ $^1S_0$ ground state. The 96.01 keV x ray is much easier to detect than the 260 eV photon, and the $1s2s$ $^3S_1$ lifetime[7] of 10^{-14} s has no effect on the measured $1s2p_{1/2}$ $^3P_0$ lifetime provided sufficient time is allowed for the initial $1s2s$ $^3S_1$ population to decay.

Fig. 2 shows a spectrum recorded by one of our Ge x-ray detectors collimated to view emission perpendicular to the uranium beam at a point 0.67 cm downstream from the Pd foil. The 96.01 keV x ray from the $1s2p_{1/2}$ $^3P_0$-fed $1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$ decay is Doppler shifted and appears as a peak at 77.76 (0.18) keV. We identified this peak by its correct transverse Doppler shift and exponential decay at two different beam energies, 218 MeV/amu and 175 MeV/amu (here determined from the operating conditions of the Bevalac and corrected for energy loss in foils); by the dependence of the Doppler broadened peak width on the angular acceptance of the detector; by the yield[12] using foils of different Z and thickness; by the peak's absence when the foil is removed; and by the lack of any other long-lived, low-lying states of heliumlike uranium or hydrogenlike uranium besides the $1s2p_{1/2}$ $^3P_0$ state.

The height of the peak above background was found by a maximum-likelihood fit of a quadratic to the background. The decay curve (Fig. 3), which spans 2.7 decay lengths, is a maximum-likelihood fit of a single exponential to the data. The reduced χ^2

for the fit is 0.89. The spectrum shown in Fig. 2 contributes to the first point at 0.67 cm in Fig. 3. The 1/e decay length is 1.182 (0.069) cm, and the 5.8% statistical error dominates our final error in the $1s2p_{1/2}$ $^3P_0$ lifetime. Other contributions to our 6.2% total lifetime error are: 1.2% from the determination of the beam velocity and time dilation using the transverse Doppler shift of the $1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$ transition and 1.8% from the experimental upper limit to contamination of our signal by cascade feeding. Our value for the $1s2p_{1/2}$ $^3P_0$ lifetime is 54.4 (3.3)ps.

A disadvantage in using the $1s2p_{1/2}$ $^3P_0$-fed $1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$ decay as a signal is that it makes the measured $1s2p_{1/2}$ $^3P_0$ lifetime sensitive to cascade feeding of the $1s2s$ $^3S_1$ state. States of heliumlike uranium with principal quantum number $(n) < 22$ will cascade to the $1s^2$ $^1S_0$ ground state before we begin our measurement of the $1s2p_{1/2}$ $^3P_0$ lifetime. Only the very small population of states with $n \geq 22$ and high total angular momentum (J) can perturb our measurement by cascading down the chain of yrast states (states of $J= n$) to reach the $1s2p_{3/2}$ $^3P_2$ state. The $1s2p_{3/2}$ $^3P_2$ state (Fig. 1) decays 2/3 of the time to the $1s^2$ $^1S_0$ ground state but also decays 1/3 of the time to the $1s2s$ $^3S_1$ state, contaminating our $1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$ signal. We set a limit to this contamination by searching for the 100.5 keV x ray from the $1s2p_{3/2}$ $^3P_2 \rightarrow 1s^2$ $^1S_0$ transition, which would appear as an isolated peak Doppler shifted to 81.4 keV. The count rate in this supposed peak, after subtraction of the background, is plotted in Fig. 3. The count rate is consistent with zero with an uncertainty which contributes 1.8% to the uncertainty in the $1s2p_{1/2}$ $^3P_0$ decay length. Cascades from high n,J states in the hydrogenlike fraction of our beam feed the 2 $^2P_{3/2} \rightarrow 1$ $^2S_{1/2}$ transition at 102.2 keV and will not interfere with our signal.

From our $1s2p_{1/2}$ $^3P_0$ lifetime of 54.4 (3.3)ps and Drake's calculated E1M1 decay rate[8] of $0.564(5) \times 10^{10}$ s^{-1} we obtain a $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ E1 decay rate of 1.273 (0.113) $\times 10^{10}$ s^{-1}. Using the dipole length formula for the E1 decay rate[9]: $A = 12\alpha k^3 (Z\alpha)^{-2} [0.792+0.759/Z]^2$ (hbar= m= c= 1) we find for k, the $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ splitting, a value of 260.0 (7.7) eV. Subtracting the calculated Coulomb contribution[6] of 330.4 eV yields a Lamb shift of 70.4 (7.7) eV.

So far we have accounted only for experimental uncertainty; theoretical uncertainty comes from the effect of small terms omitted from the calculations. We estimate that a $Z^{-1} (Z\alpha)^2$ correction to the $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ E1 matrix element, and a 1/Z correction to the E1M1 decay rate, contribute a total of $\approx$ 1 eV to our inferred $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ splitting; that a $Z^{-2} (Z\alpha)^6$ term contributes $\approx$ 2 eV to the 330.4 eV Coulomb splitting of the $1s2p_{1/2}$ $^3P_0$ - $1s2s$ $^3S_1$ states; and that a 1/Z screening correction to the self energy, vacuum polarization and finite nuclear size contributes $\approx$

1 eV to the Lamb shift. These combine to give a separate theoretical error of 2.4 eV in our extracted value of the Lamb shift.

In conclusion, we have measured the Lamb shift in uranium. Our final value of 70.4 (8.1) is in agreement with the theoretical value[3,4] of 75.3(0.4) eV.

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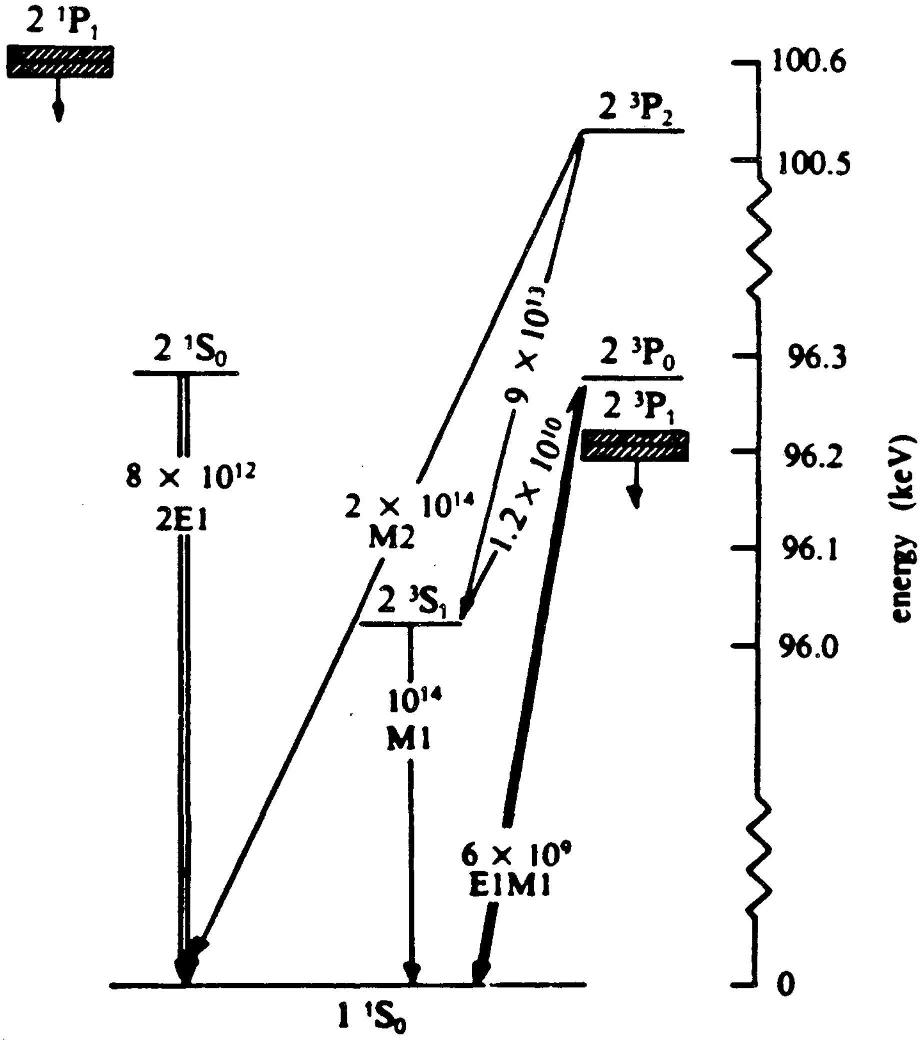
FIG. 1. Energy level diagram of the n=1 and n=2 states of heliumlike uranium. Decay rates, except for the $1s2p_{1/2}$ $^3P_0$ state, are taken from Ref. 7. Energies are taken from Ref. 3,4,7. M1 and M2 decays are magnetic-dipole and magnetic-quadrupole decays, respectively, and decays without labels are electric-dipole decays. An approximate radiative width is indicated for the $^1P_1$ and $^3P_1$ states.

FIG. 2. Spectrum recorded by a Ge x-ray detector collimated to view emission perpendicular to the uranium beam at a point 0.67 cm downstream from the Pd foil. This spectrum represents 135 minutes of counting - about 10^8 uranium ions. The Doppler-shifted peak from the decay of $1s2p_{1/2}$ $^3P_0 \rightarrow 1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$ is at 77.8 keV. Cascades from higher excited states would produce a peak at 81.4 keV. Peaks at 72.8 keV and 75.0 keV are Pb $K_{\alpha 2}$ and Pb $K_{\alpha 1}$ x rays, and those at 84.5 keV - 87.3 keV are Pb $K_{\beta 1-\beta 3}$ x rays. Peaks at 56.3 keV and 57.5 keV are Ta $K_{\alpha 2}$ and Ta $K_{\alpha 1}$ x rays, and those at 65.2 and 67.0 keV are Ta $K_{\beta 1}$ and $K_{\beta 2}$ x rays. Peaks at 45.2 keV - 46.0 keV are Dy $K_{\alpha 2-\alpha 1}$ x rays. Pb and Dy are used for shielding and Ta is used for x-ray detector collimators. The peak at 21.2 keV is scattered Pd $K_{\alpha 1}$ radiation from the Pd foil. Background is caused by bremsstrahlung of the foil electrons in the field of the uranium projectile; by bremsstrahlung of electrons scattered in and ejected from the Pd foil; and by fast nuclear fragments colliding with the Ge in the x-ray detector. Other sources of background may also exist. To reduce background we restricted the scatter of x rays into the detector, held electrons ejected from the foil away from the detector with a magnetic field, and vetoed background from nuclear fragments using scintillators.

Fig. 3 - Linear plots of the intensity of x rays from the transitions (a) $1s2s$ $^3S_1 \rightarrow 1s^2$ $^1S_0$, and (b) $1s2p_{3/2}$ $^3P_2 \rightarrow 1s^2$ $^1S_0$, as a function of distance downstream from the Pd foil. Each point is the sum of the spectra from two x-ray detectors. Error bars are one standard deviation statistical errors. The horizontal line in (b) is the fit of a hypothetical constant count rate to the data. The count rate is consistent with zero and sets a limit to the contamination of our signal by cascade feeding.

Heliumlike Uranium



-- XBL 868-2977 --

Fig. 1

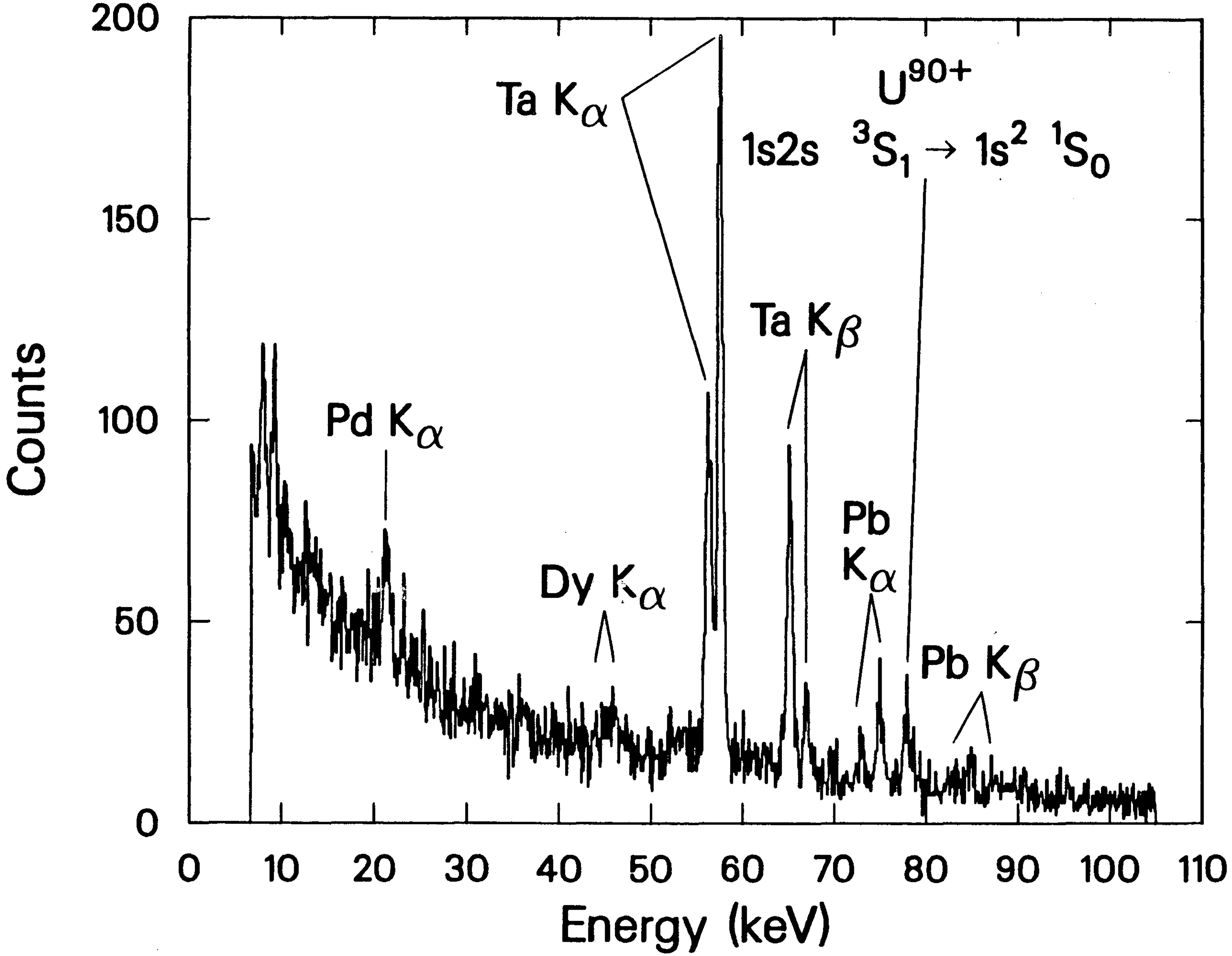


Fig. 2

XCG 867-7332 A

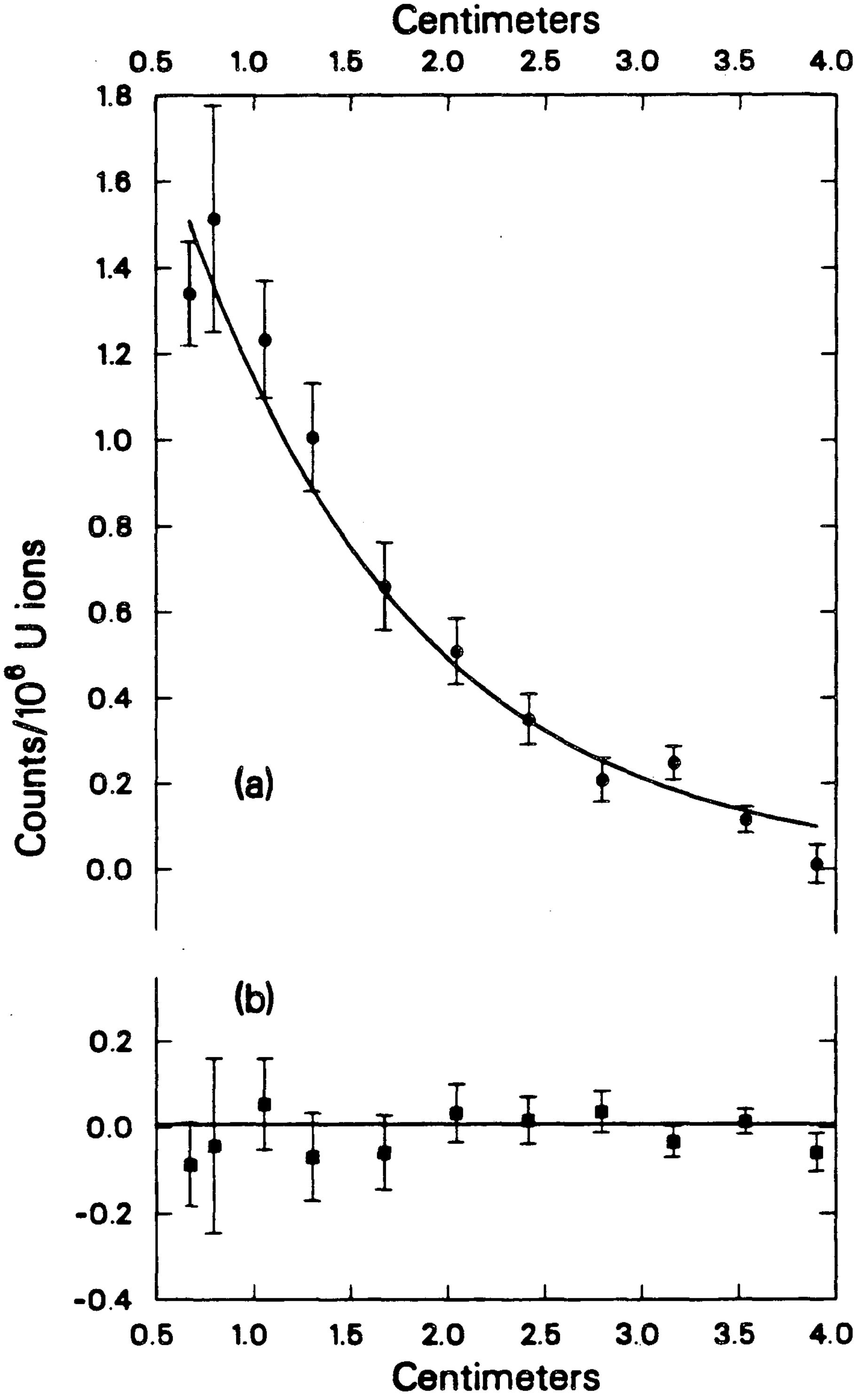


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Fig. 3