ativistic $2P$-state lifetime in O^{7+} to an accuracy of ± 1%, and of the Bethe-Lamb quenching theory[7] which was employed in deriving a Lamb-shift result from the data. While it would appear that the method is applicable to even more highly ionized systems, the practical requirements of greater beam energy and quenching magnetic field and particularly the gross beam deflections in these larger quenching fields will probably limit our present system to the study of F^{8+}. Other high-energy heavy-ion accelerators and new experimental designs should allow extension of this type of experiment to even higher Z.

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Measurement of the Lamb Shift in the $^{16}O^{7+}$ Ion*

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The energy difference between the $2S_{1/2}$ and $2P_{1/2}$ levels in the $^{16}O^{7+}$ ion has been determined by means of a Stark-quenching technique to be 2215.6 ± 7.5 GHz.

Small discrepancies[1] between calculated and measured values of the Lamb shift, $\mathcal{S}$, make it important to measure $\mathcal{S}$ in atomic species of high Z. Experiments on He,[2] Li,[3] and C[4] have given results in agreement with the calculations,[1-5] but the uncertainties have been larger than desired. Herein we report $\mathcal{S}$ for $^{16}O^{7+}$; our value, obtained from a Stark-quenching experiment, is 2215.6 ± 7.5 GHz, where the uncertainty is based on measured quantities only. A similar measurement has been made simultaneously by others.[6]

Some 10–20 nA (charge current) of momentum-analyzed ions of $^{16}O^{8+}$, generated by the Los Alamos tandem Van de Graaff, entered the Lamb-shift apparatus shown in Fig. 1. The uncertainty in beam energy was ± 0.1%. Some of the $^{16}O^{8+}$ ions were converted to $^{16}O^{7+}$ ions in the $2S_{1/2}$ state on passage through 10 cm of oxygen gas at a pressure of 1.5 to 15 mTorr. The target thickness was small enough to preclude appreciable formation of metastable ions of $^{16}O^{6+}$.

Before entering the quenching chamber, the ion beam traveled 2 m to permit decay of short-lived excited states. The top and bottom surfaces of the quenching chamber were the pole pieces of a magnet which generated a field homogeneous to within 1 part in 3000 over the path traversed by the $^{16}O^{7+}$ beam. The effective motional electric field mixed (principally) the $2S_{1/2}$ and $2P_{1/2}$ levels. The 20-Å photons emitted from the decay of the perturbed level to the ground state were recorded by counters whose locations are indicated in Fig. 1. Counters F_1 and F_2 were stationary and monitored the beam intensity and direction. Counters M_1 and M_2 were moved parallel to the zero-field beam direction, and measured the photon flux at variable displacement (x) from the F_1 position. A shielded Faraday cup was used as a monitor of the ion current. The quenching volume was maintained at a pressure of $< 4\times10^{-7}$ Torr.

The photon counts must be corrected for curvature of the particle path and for background. The trajectory was calculated; for $x < 7$ cm, the actual path differed from x by less than 1.5 parts per 1000, and this difference has been neglected. The beam-independent room background was easily measured, but determining the beam-dependent background of γ rays and x rays was complicated.

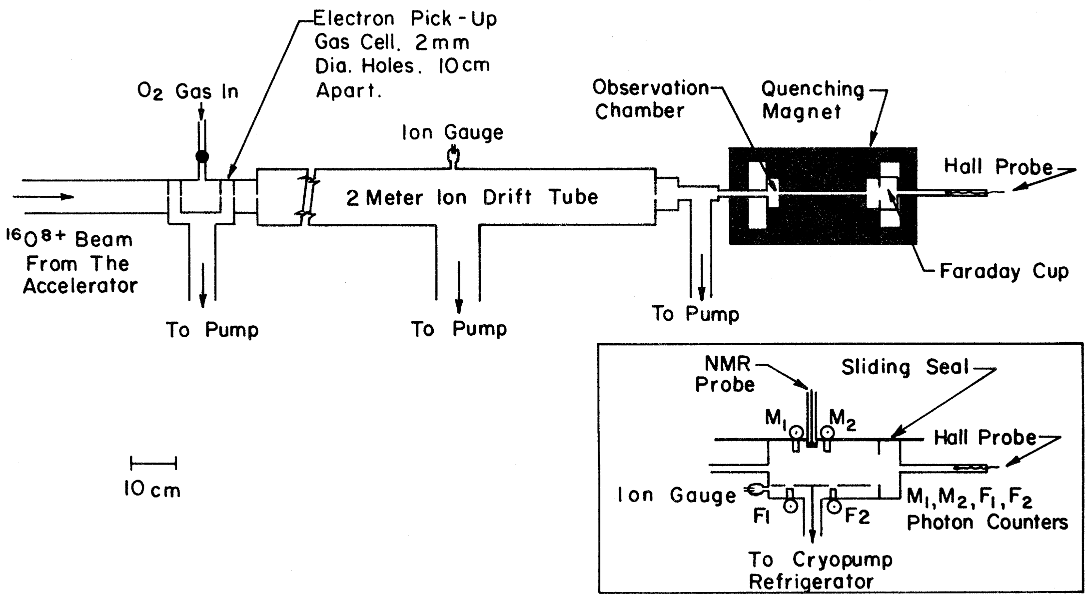

FIG. 1. Arrangement of Lamb-shift apparatus. The NMR and Hall probes were used to map B.

Because the geometrical and background corrections increased rapidly for $x>7$ cm, we restrict our analysis to data taken for $x<7$ cm.

Since the physical significance of our result depends critically on proper treatment of the background, considerable effort was expended to determine its origin and magnitude. A detailed treatment of the background will be given elsewhere; here we simply state that the beam-dependent background is properly determined by evacuating the gas from the charge-transfer cell, but leaving the quenching magnetic field on. The background was not sensitively dependent on the charge composition of the beam. Normalized to the same integrated ion current, the background counts in M_1 amounted to about 1.5% of the total counts at $x=0$ and about 4% at $x=6$ cm.

The correction for curvature of the O^{7+} ion path in the magnetic field was made by adding the counts registered in each detector at a given magnetic field B to the counts registered when the field was precisely reversed. To justify this, let y be the displacement of the beam from its undeflected position, positive or negative according to the polarity of B. The counting rate C of a detector at position x can then be written as

$$C=KN\left[1+\sum_{n=1}^{\infty} a_n\left(\frac{y}{D}\right)^n\right]\exp\left(-\gamma_s\frac{l}{v}\right), \qquad (1)$$

where γ_s is the decay constant to be determined, l the distance traveled along the beam trajectory, N the number of $2S_{1/2}$ ions at $l=0$, v the speed of the ions, and D the distance of the counter window from the undeflected beam position; K and a_n are constants. Therefore, if C_+ and C_- are the counting rates for $+B$ and $-B$, respectively, $\overline{C}=\frac{1}{2}(C_+ + C_-)$ needs a curvature correction of

$$\sum_{n=1}^{\infty} a_{2n}\left(\frac{y}{D}\right)^{2n}.$$

The latter sum can be estimated from the total counts (corrected for background) recorded with F_1 and F_2, for

$$\overline{C}(F_2)=\overline{C}(F_1)\left[1+\sum_{n=1}^{\infty} a_{2n}\left(\frac{y}{D}\right)^{2n}\right] \times\exp(-\gamma_s\,\Delta/v), \qquad (2)$$

where we have used the fact that y/D at F_1 is vanishingly small. For $B=3.56$ kG, $E=36$ MeV, $y/D=0.11$ at F_2, Δ (the separation of F_1 from F_2) $=10.16$ cm, $\overline{C}(F_1)=5.25\times10^5$, and $\overline{C}(F_2)=1.74\times10^5$, we find

$$\sum_{n=1}^{\infty} a_{2n}\left(\frac{y}{D}\right)^{2n}=-4.32\times10^{-3},$$

which we take as negligible. In fact, y/D varied from 5.4×10^{-3} to 5.2×10^{-2} (for $B=3.56$ kG) as x varied from 0 to 6 cm, so the actual error was even smaller than indicated above.

The $2S_{1/2}$-state ions can decay to the $1S_{1/2}$ ground state either by emitting two photons simultaneously or one Stark-quenched photon. Since the Zeeman splitting of the energy levels in the magnetic field results in a different decay probability for ions in the magnetic substates $m_J = \frac{1}{2}$ and $m_J = -\frac{1}{2}$, the decay constant γ_s determined by a least-squares fitting of $\ln\overline{C}$ versus l with a straight line is related to the probabilities of the two decay processes in a complicated way. However, if the Zeeman splitting is much less than the Lamb shift, it can be shown, to an accuracy sufficient for the present experiment, that $\gamma_s = \gamma_{2\nu} + \overline{\gamma}$, where $\gamma_{2\nu}$ is the decay constant for the two-photon process, and $\overline{\gamma}$ is the mean of the decay constants for the two magnetic substates. In our work, the Zeeman splitting was less than $5\times10^{-3}\mathcal{S}$ (for $B = 3.56$ kG), so the approximation is satisfactory.

It can also be shown[7] that $\overline{\gamma}$ is related to $\mathcal{S}$ and the $P_{1/2}$-$P_{3/2}$ splitting ω by

$$\overline{\gamma} = \gamma\left(\frac{|V|^2}{\hbar^2(\mathcal{S}^2+\gamma^2/4)} + \frac{2M^2}{\hbar^2[(\omega-\mathcal{S})^2+\gamma^2/4]} - \frac{3|V|^4\mathcal{S}^2}{\hbar^4(\mathcal{S}^2+\gamma^2/4)^2}\right), \tag{3}$$

where $\gamma = 2.568\times10^{12}$ sec is the decay constant of the $2P$-to-$2S$ transition in the dipole approximation; from Shapiro and Breit[8]

$$\gamma_{2\nu} = Z^6\gamma_{2\nu}(2S_{1/2}\text{-state hydrogen atom}) = 8.226Z^6/\text{sec}; \quad V = \langle 2P_{1/2}|e\vec{\mathrm{E}}\cdot\vec{\mathrm{r}}|2S_{1/2}\rangle = \sqrt{3}\,a_0E/Z;$$

$$M = \langle 2P_{3/2}|e\vec{\mathrm{E}}\cdot\vec{\mathrm{r}}|2S_{1/2}\rangle = \sqrt{6}\,a_0E/Z;$$

$a_0 = 5.291\,77\times10^{-9}$ cm is the Bohr radius; $e = 4.803\,25\times10^{-10}$ esu is the electronic charge; $Z = 8$ is the atomic number of oxygen; and $E = \beta B(1-\beta^2)^{-1/2}$ is the Lorentz motional field. Therefore, $\mathcal{S}$ can be calculated from the measured γ_s.

The Lamb shift was determined at two different ^{16}O ion energies [36.000(1 ± 0.001) and 42.000(1 ± 0.001) MeV] in slightly different magnetic fields (3.5625 ± 0.0006 and 3.5238 ± 0.006 kG). Figure 2 shows the decay curve of 36.000-MeV O^{7+} ions in a 3.5625-kG field as an example. At these two energies, the values of γ_s were found to be $2.2488\times(1\pm0.7\%)\times10^8$/sec and $2.4885(1\pm0.7\%)\times10^8$/sec, respectively. When time dilation is included, they become 2.2543 and 2.5395, respectively, and yield an average value $\mathcal{S} = 2215.6 \pm 7.5$ GHz. The uncertainty in the experimental value includes the statistical uncertainty of the data and the background, and the uncertainty in the ion velocity.

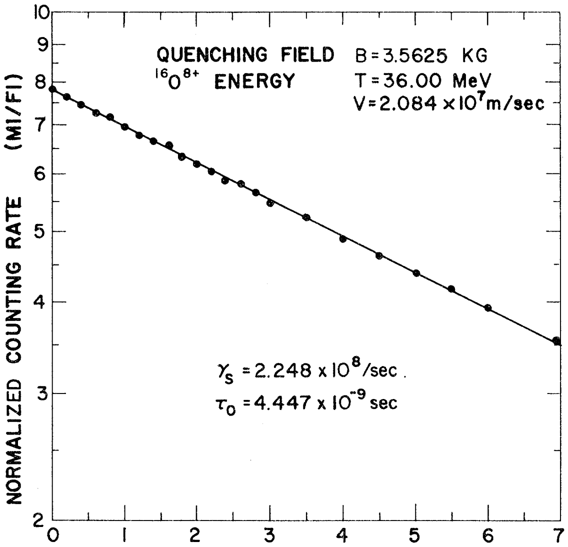

FIG. 2. Counting rate of M_1 normalized to that of F_1 as a function of M_1 position for the experimental parameters listed. The point size exceeds the calculated uncertainty. The constants γ_s and τ have not been corrected for time dilation.

A comprehensive discussion of the Lamb shift by Erickson and Yennie[9] gives $\mathcal{S} = 2210.8 \pm 9.5$ GHz. The uncertainty comes mostly from higher-order contributions of the one-photon diagram. Recently, Erickson[10] has derived a formula for $\mathcal{S}$ in which the Z dependence is factored out in a closed form. This expression gives $\mathcal{S} = 2205.17 \pm 1.51$ GHz. Both of the values are in agreement with the present experiment.

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Metastable Autoionizing States in Sodiumlike Chlorine*

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We have observed metastable autoionizing states associated with partially stripped, highly excited chlorine ions. Charge-state-fraction, electron-energetic, and series-limit arguments indicate that these states are primarily associated with *sodiumlike chlorine* (Cl^{6+}), but few energy-level calculations exist for firm identification. Prominent peaks occur in the electron spectrum at 90 ± 3, 101 ± 3, 138 ± 3, and 182 ± 3 eV. A long-lived component of the 182-eV peak has a lifetime ≥ 43 nsec.

We report here experimental evidence for the existence of significant numbers of highly metastable autoionizing states associated with partially stripped, highly excited chlorine ions. Figure 1 shows the spectra of energy-analyzed electrons that were emitted in autoionizing decays of these states in the energy range ~70–220 eV (in the rest frame of the emitting ion). We have recently reported[1] on the study of a metastable autoionizing state ($1s2s2p\,^4P_{5/2}$) associated with lithiumlike chlorine (Cl^{14+}) and argon (Ar^{15+}) ions. The autoionizing electrons emitted by those highly stripped ions were of considerably higher energy (~2000 eV) than in the present experiment in which ions in much lower charge states are of importance. We believe that the observed spectral features are primarily due to the decay of metastable autoionizing states associated with sodiumlike chlorine (Cl^{6+}). While some evidence for the existence of such states in the neutral alkali atoms has been shown by Feldman and Novick,[2] to our knowledge the present work is the first study of a sodiumlike system in which energy analysis of the emitted electrons has been exploited. Firm identification of the electron spectral lines is at present precluded by an almost complete lack of theoretical calculations of the energies and lifetimes of such states. There

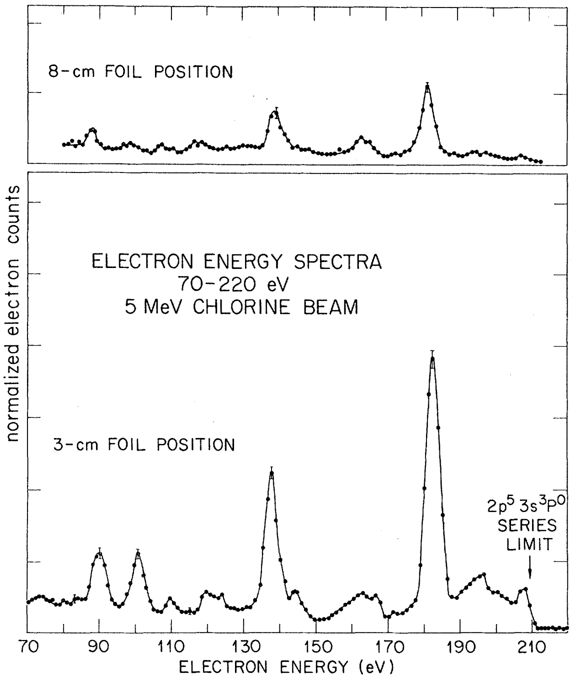

FIG. 1. Segment of electron spectra from 5-MeV chlorine ions undergoing decay in flight, plotted in the ionic rest frame. Data are shown for two different target positions, 3 and 8 cm from the spectrometer viewing region.