LAMB SHIFT IN $(Li^6)^{++}$†

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In a series of high precision experiments, Lamb and his collaborators,[1] using microwave techniques, established the energy difference between the $2S_{1/2}$ and the $2P_{1/2}$ level of a hydrogen atom as 1057.77 Mc/sec.[2] This deviation from the predictions of the Dirac theory was first explained by Bethe[3] as due to the interaction of the atomic electron with the radiation field. By applying relativistic quantum electrodynamics to the calculation of the level shift, the following energy difference between the $ns_{1/2}$ and $np_{1/2}$ levels of a hydrogen-like atom was derived[4]:

$$\Delta W_n = \frac{8\alpha^3}{3\pi}\mathrm{Ry}\frac{Z^4}{n^3}\left[\left(\ln\frac{1}{2Z^2\epsilon}+\frac{23}{24}\right)+\left(-\frac{1}{5}\right)\right.$$

$$\left.+3\pi Z\alpha\left(1+\frac{11}{128}-\frac{1}{2}\ln 2+\frac{5}{192}\right)\right]\left(1-\frac{3m}{M}\right). \quad (1)$$

In this expression, α is the fine structure constant, Ry is the Rydberg constant for infinite nuclear mass, Z is the nuclear charge, m is the electronic mass, M is the nuclear mass, and ϵ is a quantity proportional to an average excitation energy of a hydrogen atom. Using the value 1/137.039 for α,[5] 135.6349 Mc/sec for $\alpha^3\mathrm{Ry}/3\pi$, and 7.6919 for $\ln(1/\epsilon)$, this formula gives 1057.54 Mc/sec for the Lamb shift for the hydrogen atom, which is in good agreement with the experiment.

In Eq. (1) the quantity within the first parentheses comes from the second-order radiative correction, including the effect of the anamalous magnetic moment of the electron, that within the second parentheses from vacuum polarization, and that within the third parentheses from the radiative shift of second order in the external potential. These terms depend on Z differently. Thus, to subject the theory to further test, particles of higher nuclear charge may be used. The measurements of He^+ ions[6] indicated some difference between theory and experiment.

We report the production of a sufficient number of $(Li^6)^{++}$ ions in the $2s$ state to make a measurement of the Lamb shift in $(Li^6)^{++}$ possible. Heretofore, the difficulty of producing $(Li^6)^{++}$ in the $2s$ state is one factor that has made such a measurement impractical. A preliminary result for the shift is given by a new technique. This early result comes within about 1% of that from Eq. (1).

Neglecting hyperfine structure and the radiative width of the $2p_{1/2}$ state, Bethe and Salpeter[7] showed that the lifetime of the $2s_{1/2}$ state of a hydrogen-like atom in an electrostatic field E is given by

$$\tau(2s)=\tau(2p)\left\{1+\frac{\delta^2}{[1-(1+\delta^2)^{1/2}]^2}\right\},$$

$$\delta = 2\sqrt{3}Eea_0/ZL, \quad (2)$$

where $\tau(2p)$ is the lifetime of the $2p_{1/2}$ state, e is the electronic charge, a_0 is the Bohr radius, and L is the Lamb shift. This equation was verified for the case of the hydrogen atom.[8] By assuming the validity of this equation, the Lamb shift can be inferred by measuring $\tau(2s)$. This is the principle of our experimental method.

A schematic diagram of the apparatus is shown in Fig. 1. Lithium ions from a lithium-ion source are accelerated to 2.85 MeV with a Van de Graaff generator, and the $(Li^6)^+$ component is selected with a magnetic analyzer. The energy resolution of the $(Li^6)^+$ beam is about 0.2%, and the beam has no contamination of $(Li^7)^+$. The characteristics of the ion source and the analyzer were published elsewhere.[9] The $(Li^6)^+$ beam then passes through a nitrogen-filled charge-exchange cell in which the beam reaches its charge equilibrium. The emerging beam contains about 62% of Li^{+++}, 36% of Li^{++}, and 2% of Li^+ ions.[10] Some of the Li^{++} ions are in the metastable $2s_{1/2}$ state. The beam then passes through a prequenching region 30 cm long, where a longitudinal electrical field of about 10 kV/cm can be applied, before the beam enters the observation chamber. In the observation chamber a quench voltage mixes the $2s_{1/2}$ and $2p_{1/2}$ states of the metastable ions, and 135Å photons are emitted during the decay to the ground state. These photons are observed with two photon counters located about 3

in. from the nearest edges of the condenser plates, one stationary for monitoring the photon intensity from the beam shortly after the beam enters the quenching field, and the other movable for measuring the photon intensity at variable separation from the first. This method is exactly the same as that used for the lifetime measurement of $2s_{1/2}$ hydrogen atoms.[8] The photon detectors are two Q-gas-filled GM counters which are similar to those described by Ederer and Tomboulian.[11] The long-wavelength limit of the sensitivity of the counter is determined by the transmission of the Zapon window which is 350 Å. No electrons were able to give false counts because of their inability to leave the high-quench field, and the fact that electrons of energy below 10 KeV could not penetrate the windows. In background runs the prequench voltage quenches the $2s$ atoms before they enter the observation chamber so that the background arising from cosmic rays, radiation produced by the beam in the residual gas in the observation chamber, etc., can be measured. A separation of 50 cm between the equilibration cell and the observation region was provided so that short-lived, excited states of the projectiles would decay before the beam enters the observation chamber. The radiative background, determined with prequenching voltage on, is usually about 10% of the signal and is independent of counter positon, indicating that 50 cm is sufficient to render consideration of short-lived excited states decaying in flight unimportant. This independence is observed both with quench voltage on and quench voltage off, and also with both prequench and quench voltages off, indicating that spurious signals are neither created nor destroyed by the prequench system. In any case, the background is separately determined at every counter position and is therefore properly subtracted at each data point. A more precise measurement of beam energy and beam composition is done with the electrostatic analyzer after the beam emerges from the observation chamber, as shown in Fig. 1. The beam composition is in agreement with the values of reference 10.

The experimental result for a typical quench voltage is shown in Fig. 2. A semilogarithmic plot of the ratio of the counting rates (with background subtracted) of the two counters is given as a function of the counter separation. A linear least-squares fit gives a decay length which, when divided by the beam velocity, 0.955×10^{9} cm/sec, gives $\tau(2s)$. The linearity of the plot is consistent with the expectation that the quenching of other possible long-lived states, for example, the metastable states of the helium-like Li^{+} ions, does not make any substantial contribution to the signal.

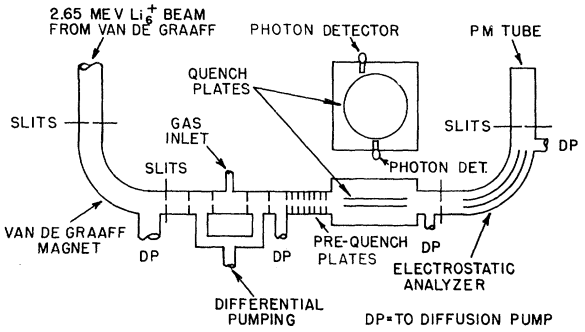

FIG. 1. Schematic diagram of the apparatus.

Taking $\tau(2p)$ as 1.97×10^{-11} sec, $\tau(2s)$ becomes 3.50×10^{-9} sec, at $E=6375$ V/cm. Using Eq. (2), the Lamb shift corresponding to this value is 62 300 Mc/sec. For $Z=3$, Eq. (1) gives 62 800 Mc/sec. Similar results have been obtained at several other field strengths, but with less accurate counting statistics than those of Fig. 2. Also, we have neglected to apply corrections, which amount to about 1%, to the theoretical lifetime given by Eq. (2) due to hyperfine structure (small for Li^{6}) and other small effects. Our present experimental accuracy is still too crude to be sensitive to them. We are presently correcting some small systematic defects.

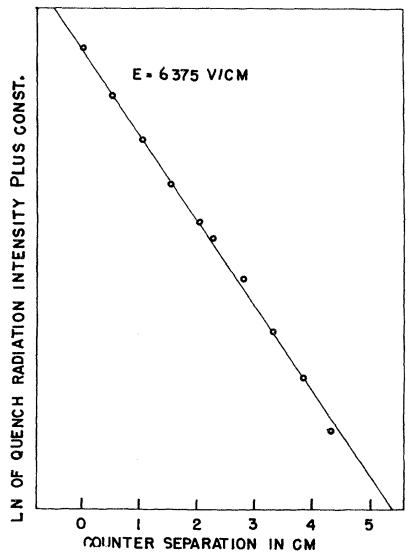

FIG. 2. Semilogarithmic plot of the counting-rate ratio versus counter separation.

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TEMPERATURE DEPENDENCE OF THE $^3A_2 \rightarrow {}^3T_1$ ABSORPTION-BAND PEAK OF THE Ni^{2+} ION IN NICKEL AND MANGANESE SALTS*

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In this paper we report observations regarding the effect of magnetic interactions on the temperature dependence of the $^3A_2 \rightarrow {}^3T_1$ absorption-band peak of the Ni^{2+} ion in $KNiF_3$, $RbNiF_3$, $Mn_{0.99}Ni_{0.01}F_2$, $KMn_{0.99}Ni_{0.01}F_3$, and $RbMn_{0.99}Ni_{0.01}F_3$. The magnetic effects are observed as an additional contribution to the nonmagnetic thermal shifts of the absorption bands.[1,2] The temperature dependence of a nonmagnetic shift, which will be called normal behavior here, has been determined from the absorption-band behavior in $KMg_{0.9}Ni_{0.1}F_3$. A study of the antiferromagnetic nickel compounds, $KNiF_3$ and $RbNiF_3$, demonstrated the effect of magnetic interactions on the absorption-band peak. In $KNiF_3$, the departure from normal behavior occurs just below the ordering temperature. A similar departure from normal behavior allows us to estimate the antiferromagnetic ordering temperature of $RbNiF_3$ as $T_N(RbNiF_3) \approx 220°K$. In those manganese compounds containing nickel ion as an impurity, the departure from normal behavior occurs above the Néel temperature of the host. This result suggests a correlation of the nickel-ion spins with the surrounding magnanese-ion spins at a temperature between the Néel temperature of the pure nickel salt and that of the manganese salt. We believe that the temperature at which the departure from normal absorption behavior occurs is a measure of the Ni^{2+}-Mn^{2+} ion magnetic interaction strength.

Crystals were prepared by the horizontal Bridgman technique in an HF atmosphere. Samples were attached mechanically to a cold finger in a Dewar equipped for optical access. After the coolant of the Dewar reservoir boiled away, warming of the system was sufficiently slow to permit measurements of the optical absorption line as a function of temperature. The temperature was monitored for the larger manganese samples by a thermocouple attached mechanically to the crystal, and the error was estimated to be ±3°K. Temperature measurement of the nickel salts was less accurate because the small-crystal size prohibited direct contact of the thermocouple to the small samples. The error in this case was estimated to be ±6°K. The spectral profiles of the absorption line were recorded by a Perkin-Elmer 112 recording spectrometer, with an S-1 surface photomultiplier for radiation detection. An average of five con-