of a superheavy element is in the region of 6 keV. The distance between corresponding lines of adjacent elements is about 100 eV. The M shell will be excited in a specific way giving rise to simple spectra with only a few, probably two main lines. Using Si(Li) detectors the position of a line may be determined to better than 50 eV. From this point of view there should be no difficulty in determining an exact Z value. However, for colliding heavy ions and atoms an energy shift is observed for the collision-induced L radiation compared with the photon-induced characteristic L radiation.[3,12,13] Such a shift is expected for the M radiation as well. Considering that the M-shell excitation of a superheavy element seems to be quite equivalent to the L-shell excitation in systems investigated,[3,12,13] the shift will be not too large, but has to be taken into account in any Z determination. The shifts of the M lines may be studied using systems like I-U. Preliminary investigations of this system[14] substantiate the presumptions that the collision-induced M spectrum of the superheavy element may be very simple and that the shift may be not too large. Therefore, an unambiguous nuclear-charge determination seems to be possible.

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[10] The beam of recoils has to be free from strong contaminants of the primary accelerator beam in order to limit the counting rate of the x-ray detector. In any case a reduction of the high number of primary-beam particles is necessary before applying the proposed technique. This method seems suitable to determine the nuclear charge of superheavy elements with lifetimes larger than 10^{-6} sec, as discussed in an equivalent case by P. Armbruster, D. Hovestadt, H. Meister, and H. J. Specht, Nucl. Phys. 54, 586 (1964).

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Determination of the Hydrogenic-Carbon Lamb Shift via $2S_{1/2}$ Metastable Quenching

D. E. Murnick and M. Leventhal
Bell Telephone Laboratories, Murray Hill, New Jersey 07974

and

H. W. Kugel
Rutgers, The State University, New Brunswick, New Jersey 08903, and*
Bell Telephone Laboratories, Murray Hill, New Jersey 07974

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We have measured the Lamb shift in the $n=2$ state of hydrogenic carbon-12. The result is 780.1 ± 8.0 GHz as compared with the quantum-electrodynamic calculation of 783.7 ± 0.24 GHz. The ratio of the electron-pickup cross section to the $2S_{1/2}$ metastable state to the total electron-pickup cross section has also been determined as 0.022 ± 0.010 in argon at 25 MeV.

Measurements and calculations of the hydrogenic-atom Lamb shift $\mathcal{S}$ (the $2P_{1/2}$-$2S_{1/2}$ splitting) are of fundamental importance to our understanding of quantum electrodynamics (QED) and the values of the fundamental constants. Because of the strong Z dependence of the QED series expansion[1] for $\mathcal{S}$ [terms of order $(\alpha Z)^6$ have been calculated to date] it is important to extend Lamb-shift measurements to high-Z hydrogenic atoms in order to probe the limits of validity of the calculations.

In a previous publication[2] we demonstrated the feasibility of Lamb-shift measurements for the $n=2$ state of $^{12}\mathrm{C}^{5+}$ via metastable quenching of the $2S_{1/2}$ state, and reported preliminary results which were about 5% lower than theoretical predictions. Metastable beam intensities have been increased by an order of magnitude, new detectors have been employed for the carbon Lyman-α line (33.8 Å), and possible systematic errors and uncertainties have now been thoroughly investigated and understood. A result of $\mathcal{S} = 780.1 \pm 8.0$ GHz has been obtained, in agreement with calculations.

The experiment was carried out using a beam of monoenergic C^{5+} ions in the $2S_{1/2}$ metastable state. The beam passes through a homogeneous magnetic field, and the intensity of C^{5+} Lyman-α radiation is monitored as a function of distance traveled in the field region. The measured decay lengths Λ are used to obtain $\mathcal{S}$ from the relation

$$\frac{1}{\tau_{2S}} = \frac{v}{\Lambda} = \frac{1}{\tau_{2P}} \frac{|V|^2}{\hbar^2(\mathcal{S}^2 + 1/4\tau_{2P}^2)}, \qquad (1)$$

where v is the particle velocity, τ_{2P} is the lifetime of the $2P$ states, and V is the matrix element coupling the $2S$ and $2P$ states:

$$V = \sqrt{3} E a_0 / Z, \qquad (2)$$

$\vec{E}$ being the effective dc electric field, $(1 - v^2/c^2)^{-1/2} \vec{v} \times \vec{B}/c$, on the charged particle moving with velocity $\vec{v}$ in the applied magnetic field $\vec{B}$; Z is the atomic number, and a_0 is the Bohr radius for hydrogen. Data have been obtained at beam energies of 25 and 35 MeV and at applied magnetic fields from 2000 to 3300 G.

As in Ref. 2, the metastable beam was obtained by post stripping the C^{4+} beam from the Rutgers University–Bell Laboratories tandem van de Graaff accelerator and choosing the C^{6+} component with the 90° analyzing magnet. Typically, at 25 MeV, 100 nA (charge current) of C^{4+} yields 60 nA of C^{6+}. The carbon nuclei pass through a gas cell at about 0.1 Torr where about 50% are converted to C^{5+}. The new C^{4+} component is less than 5% of the total intensity, with the rest remaining as C^{6+}. About 2.2% of the C^{5+} component is in the $2S_{1/2}$ metastable state corresponding to a cross section for the reaction

$$C^{6+} + Ar^0 \rightarrow C^{5+}(2S_{1/2}) + Ar^-$$

of about 1.4×10^{-18} cm^2 at 25 MeV.

The value for the absolute cross section has been obtained by accurate measurement of the 5^+-state charge fraction and the number of metastable decays in a given field. The total number of metastables formed per coulomb of beam is calculated from known detector efficiency and calculated prequenching in the measured fringing magnetic field. The total electron-pickup cross section estimated by Martin is then used for normalization.[3] The large value for the metastable-formation cross section is believed to be due to the pickup nature of the process. The velocity of an electron in the $2S_{1/2}$ state is comparable to the atomic velocity of the beam. Pickup to higher states is less likely because of poorer velocity matching, and is expected to be proportional to n^{-3}. Atoms excited to such higher states will decay (some no doubt to the metastable state) before traversing the 2 m to the homogeneous quenching-field region.

The fractional pickup to the $2S_{1/2}$ state, 0.022 ± 0.010, can be compared with Born-approximation calculations of Schiff.[4] These calculations are for pickup by nuclei to hydrogenic states *from* a hydrogenlike atomic gas, and predict 0.09 fractional pickup to all of the $n = 2$ states.

For each metastable decay curve measured, Lamb-shift values are extracted by a nonlinear least-squares fit to the exponential decay with the decay constant given by Eq. (1) corrected for background, Zeeman effect, unequal prequenching of Zeeman levels, coupling to the $2P_{3/2}$ state, magnetic field deflections, and time dilation. Figure 1 shows the distribution of extracted Lamb-shift values for the wide range of decay lengths measured. The error bars on each point represent 1 standard deviation as given by the nonlinear least-squares fitting program.[5] The distribution about the mean is not quite normal, indicative of residual nonconstant systematic errors. There are no obvious dependencies on magnetic field or velocity. (The total error quoted is the sum of statistical and estimated systematic errors added in quadrature.)

Sources of experimental systematic error which have been carefully studied include magnetic field effects, geometric effects, residual gas and charge-state effects, and background count rates. Details of all measurements and corrections will be included in a forthcoming report.[6]

The only significant correction to our earlier data was a geometric magnetic field correction. The signal measured at a point X_0 is

$$N(X_0) = \int_{X_0 - l}^{X_0 + l} \exp[-(X_0 - x)/\Lambda] \epsilon(x)\, dx\, d\Omega(x) \approx 2\Lambda \exp(-X_0/\Lambda) \sinh(l/\Lambda) \epsilon\, d\Omega, \qquad (3)$$

where l is one half the length of beam visible to the detector, $d\Omega$ is the solid angle subtended, and ϵ is the detector efficiency. The approximation is good if l, $d\Omega$, and ϵ are independent of position x. In fact, l, $d\Omega$, and ϵ are functions of X_0 because of possible beam misalignment and deflections of the beam in the applied magnetic field.

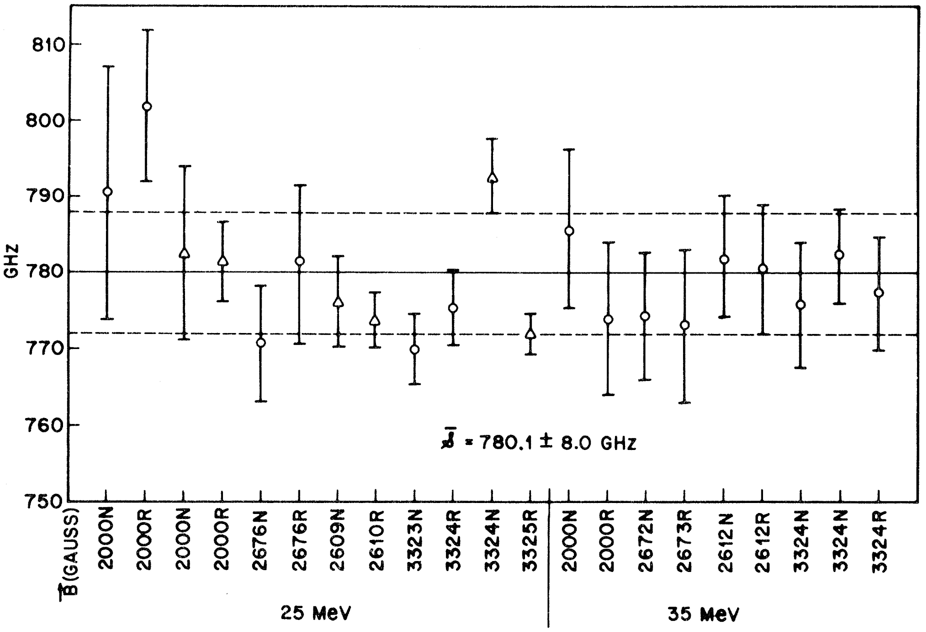

FIG. 1. Best-fit values for C^{5+} Lamb shift obtained from decay curves at 25- and 35-MeV particle energies as a function of quenching magnetic field. *N* and *R* refer to normal and reverse field directions. Points indicated by triangles were obtained using a proportional counter for the 363-eV C^{5+} Ly-α radiation.

In our early experiments we used circular collimators for maximum count rate. A small transverse velocity component coupled with a small displacement from the collimator center led to a large relative change in l as a function of position and field, and because of the coupling of the measured Λ with field, allowed internal consistency for the range of fields and velocities first studied. We now use rectangular collimators and more stringent alignment procedures which are far less sensitive to this effect.

There is a 1.5-mm uncertainty in centering the 3-mm-diam beam on the 11-mm-wide detector collimator and a 0.5° uncertainty in aligning the detector motion with the beam direction and perpendicular to the magnetic field. These uncertainties have a negligible effect on the final result. A possible beam "halo" which was not observed might still contribute to systematic error, however. We estimate ± 2-GHz uncertainty for this effect.

The low-intensity, position-independent background measured with the Spiraltron multiplier detector has been studied with the use of a thin-window gas-flow proportional counter. Several decay curves have also been obtained with this device. Proportional-counter Lamb-shift points are indicated by triangles in Fig. 1. Figure 2 shows a typical photon spectrum with quenching

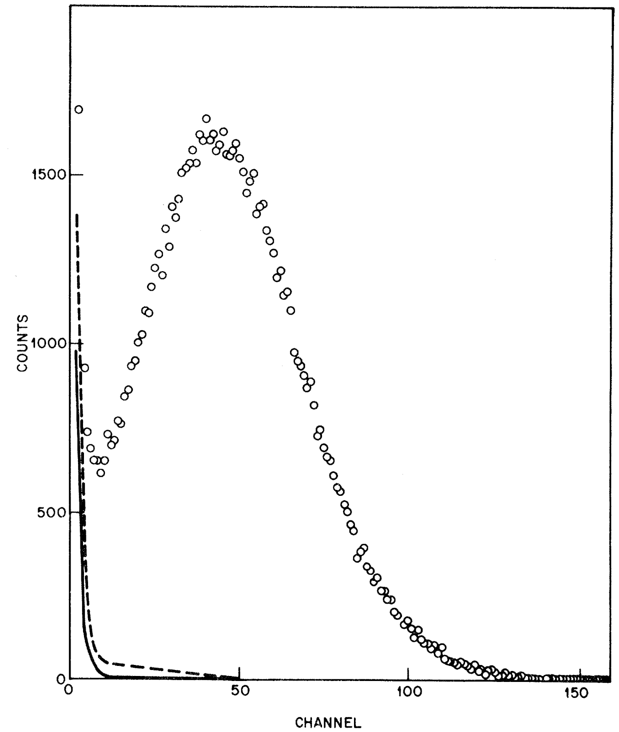

FIG. 2. Typical proportional-counter photon spectrum of C^{5+} Ly-α quenching radiation. The dashed curve is the background radiation with quenching field off, and the solid curve is the dark current and electronic noise with beam off.

field on, quenching field off, and beam off. The background which is independent of position is seen to be centered at lower energies than the carbon Lyman-α line. It may be due to scattering of x-rays produced when the high-energy carbon beam stops in the Faraday cup.

The proportional-counter Parylene window is 3000 Å thick compared with the 1000-Å-thick Parylene filter used with the Spiraltron multiplier. The background with the proportional counter is about one half that measured with the Spiraltron, possibly because of the greater longer-wavelength absorption of the thicker Parylene. Uncertainties in background are still estimated to contribute ± 5 GHz to the total error.

We have also made detailed measurements of the effects of charge-exchange gas and pressure, and residual gas pressure. Thus far, N_2 and Ar have been used in the adder canal with no effect observed on the quenching decay rate. At higher gas pressures, such that the 4^+ component was 20% of the beam, the background change was minimal. For quenching-region pressures greater than 5×10^{-6} Torr, collisional quenching was observed. All decay curves were obtained at pressures less than 6×10^{-7} Torr. The estimated uncertainty caused by these effects is less than 1 GHz. The total quoted error, 8 GHz, consists of 3 GHz statistical, 5 GHz for background, 2 GHz geometrical, and 5 GHz for all other systematic effects, added in quadrature.

In summary, the new results presented here confirm QED Lamb-shift calculations for $Z = 6$ to 1% and indicate that all possible corrections to the assumed nonrelativistic $2P$-state lifetime are less than about 2%. The relatively large cross section for electron pickup to the $2S_{1/2}$ metastable state was crucial to the success of these experiments. Further investigations of this process, both experimental and theoretical, are called for. We are extending the measurements to other adder gases and to hydrogenic oxygen.

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Production of Pulsed Particle Beams by Photodetachment of H^-†

H. C. Bryant and P. A. Lovoi
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87106

and

Gerald G. Ohlsen
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

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Photodetachment of electrons from an H^- beam by means of a Q-switched Nd laser can produce a pulsed H^0 beam. We have been able to produce 20–40-nsec H^0 pulses with near 100% efficiency. The technique is proposed for selection of single micropulses ($\frac{1}{4}$ nsec) at the Los Alamos Meson Physics Facility for use in a high-resolution time-of-flight system, and is of potential usefulness for other negative-ion accelerators.

Photodetachment of an H^- beam by a laser-produced photon beam, followed by a magnetic deflection of the charged beam, can be used as a means of producing short pulses of protons. Such a technique is of interest in connection with the selection of single micropulses ($\frac{1}{4}$ nsec) at the Los Alamos Meson Physics Facility (LAMPF) in a proposed high-resolution time-of-flight system, as well as for extraction of short and precisely timed pulses from other negative-ion accelera-