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Nuclear Radii and Magnetic Moments of ^{128,131}Ba from High-Resolution Laser Spectroscopy

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Mass-separated samples of the unstable nuclides ^{128}Ba ($T_{1/2}$ = 2.4 d) and ^{131}Ba ($T_{1/2}$ = 11.5 d) have been investigated by means of Doppler-free laser spectroscopy, using cw dye lasers and a well-collimated atomic beam. From isotope shifts and hyperfine structure of the $^1S_0$-$^1P_1$ transition (λ = 553.6 nm) we obtained the differences of mean-square charge radii $\delta\langle r^2\rangle(^{131}\text{Ba}-^{130}\text{Ba}) = -0.006(3)$ fm^2 and $\delta\langle r^2\rangle(^{130}\text{Ba}-^{128}\text{Ba}) = 0.022(3)$ fm^2 and the magnetic moment of ^{131}Ba, $\mu = -0.714(6)\mu_N$.

The development of narrow-band tunable dye lasers has provided a tool for high-resolution optical spectroscopy measurements on very small amounts of atoms. Thereby it has become possible to investigate isotopic shifts and hyperfine splittings of rather short-lived radioactive atoms of which only very small samples can be produced. This allows, in principle at least, the determination of nuclear charge radii for rather long rows of isotopes, i.e., as a function of neutron number, as demonstrated, e.g., for the even Hg [1] and Ca [2] isotopes.

This Letter presents the results of measurements on the neutron-deficient isotopes ^{128}Ba ($T_{1/2}$ = 2.43 d) and ^{131}Ba ($T_{1/2}$ = 11.5 d) using a different experimental method. The hyperfine structure of the λ = 553.6 nm resonance transition $6s^2\,{}^1S_0$-$6s6p\,{}^1P_1$ of Ba I was investigated by resonance fluorescence on a well-collimated beam of the respective radioactive atoms, using a single-mode dye laser as a light source. The principle of the experimental setup is shown in Fig. 1. The arrangement consists of a well-collimated atomic-beam apparatus for the radioactive atoms and a second reference beam operated with the natural isotopic mixture. Two cw dye lasers of a design similar to that of Hartig and Walther[3] are pumped by the λ = 514.4 nm line of an argon-ion laser (not shown in Fig. 1). A dye solution of rhodamine 504 in a water-methanol mixture was used. Single-mode operation of the dye lasers is achieved with one prism and two etalons. The linewidth of the free-running lasers is about 10 MHz. Fine tuning of the laser frequency is accomplished by piezoelectric translation of the end mirrors. One dye laser is locked to the transition frequency of a stable Ba isotope in the reference beam and provides an optical reference frequency. The frequency of the other laser, which is used to excite fluorescence of the unstable atoms, is controlled by stabilizing the difference of the two laser frequencies. This is

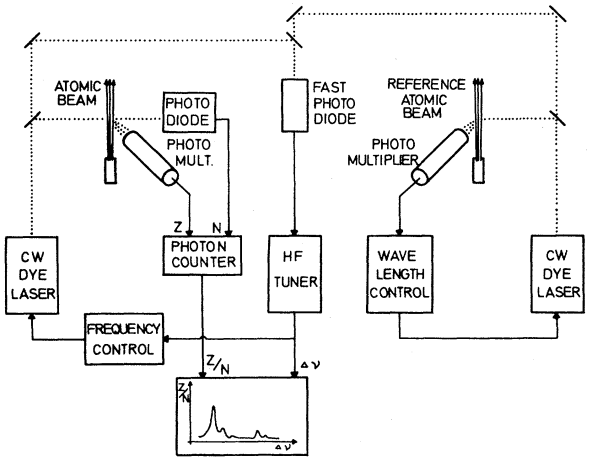

FIG. 1. Schematic of the experimental setup. The dye lasers are pumped by an Ar^+ laser not shown in the figure. The left atomic beam contains the radioactive material.

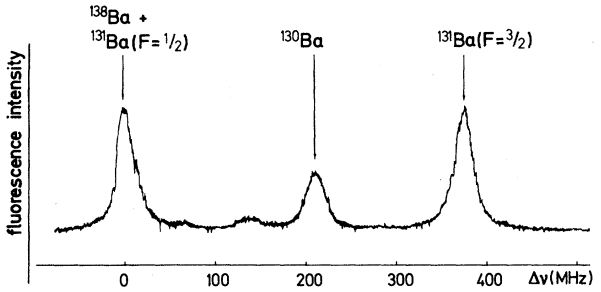

FIG. 2. Fluorescence spectrum of the ^{131}Ba sample observed perpendicular to the polarization direction of the laser light. The middle line is due to the ^{130}Ba source material. Both ^{131}Ba and ^{138}Ba from a contamination of natural Ba contribute to the left line.

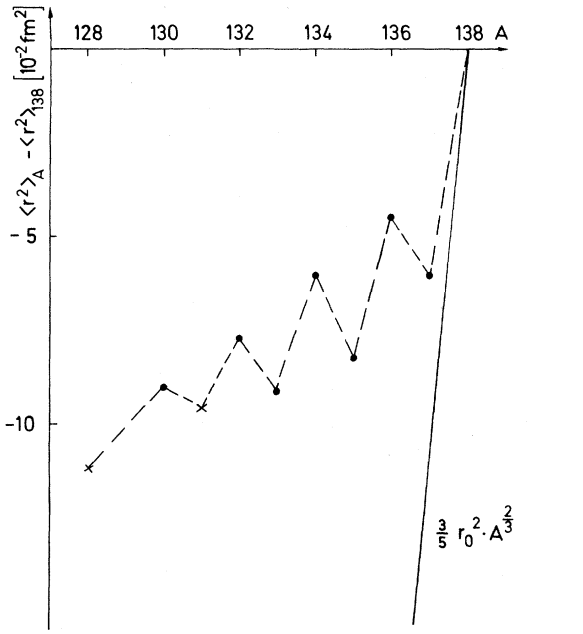

FIG. 3. Differences of rms radii of light barium isotopes from optical isotopic shifts (Refs. 8 and 9). The straight line represents the dependence expected for the standard homogeneous sphere.

achieved by mixing the two laser beams on a fast photodiode and by comparing the difference frequency with the output of a stable tunable rf generator. By changing this frequency, the frequency of the second laser is shifted by the same amount within a range of 5 GHz. At the same time, the fluorescence intensity is measured by photon counting. An example of such a measurement on ^{131}Ba is shown in Fig. 2. The main contribution to the observed linewidth of 24 MHz are the natural linewidth (19 MHz), laser width (6 to 8 MHz), and residual Doppler broadening (8 MHz).

We produced ^{128}Ba and ^{131}Ba via (d, xn) reactions and subsequent β^+ decay from enriched ^{130}Ba and ^{134}Ba, respectively, at the Karlsruhe Isochronous Cyclotron. ^{131}Ba was also produced by neutron irradiation of enriched ^{130}Ba in the Karlsruhe Research Reactor FR 2. The isotope in question was enriched in an electromagnetic mass separator.[4] Separation yield was about 10%, and the ratio of stable to unstable Ba isotopes in the sample was reduced by a factor of about 10^4. At the beginning of the measurements the atomic-beam oven contained about 1 to 10 ng of the isotope to be investigated.

For the even isotope ^{128}Ba, the $^1S_0$-$^1P_1$ transition has only one component. We identified this line by observing its decrease due to radioactive decay because it almost coincides with one hyperfine component of ^{137}Ba. The resulting isotope shift is $\Delta\nu(^{128}\text{Ba}\text{-}^{130}\text{Ba}) = 2.08 \pm 0.04$ mK. The ground-state spin of ^{131}Ba was shown to be $I = \frac{1}{2}$ via the ^{130}Ba(d, p) reaction.[5] Consequently, the optical transition should be split into two components. This was confirmed by our experiment, verifying the spin assignment. The weaker of the two components was difficult to identify because it coincides within 2 MHz with the line of the most-abundant stable isotope ^{138}Ba. Measurements of the fluorescence intensity parallel and perpendicular to the linear laser polarization led to a unique assignment of the total spins F to the two ^{131}Ba lines. The separation of the two components which represents the hyperfine splitting of the $^1P_1$ state is 12.49(7) mK. From these data, the isotopic shift $\Delta\nu(^{131}\text{Ba}\text{-}^{130}\text{Ba}) = 1.33(7)$ mK and the magnetic moment $\mu = -0.714(6)\mu_N$ are obtained using the well-known hyperfine splittings[6] and nuclear moments[7] of the stable odd isotopes ^{135,137}Ba and neglecting a possible hyperfine anomaly. With these results isotopic shifts of eleven Ba isotopes with mass numbers between 128 and 140 are now known.[8,9]

The problem of determining differences of nuclear charge radii of Ba isotopes from optical isotopic shifts is discussed in detail by Fischer *et al.*[8] Following their procedure, we obtain the radius differences $\delta\langle r^2\rangle(^{131}\text{Ba}\text{-}^{130}\text{Ba}) = -0.006(3)$ fm^2 and $\delta\langle r^2\rangle(^{130}\text{Ba}\text{-}^{128}\text{Ba}) = 0.022(3)$ fm^2. These results are shown in Fig. 3 together with those of other isotopes.[8,9] It can be seen that the general trend of charge radii continues smoothly for the even isotopes and that the large odd-even stag-

gering is markedly reduced at neutron number 75.

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Measurement of Spin-Exchange Effects in Electron-Hydrogen Collisions: Impact Ionization

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We have measured the interference between the direct and exchange scattering amplitudes in electron impact ionization of atomic hydrogen over the energy range 15 to 197 eV in a crossed-beams experiment utilizing spin-polarized electrons and spin-polarized hydrogen atoms. The experimental values for the asymmetry $A=(\sigma^{\uparrow\downarrow}-\sigma^{\uparrow\uparrow})/(\sigma^{\uparrow\downarrow}+\sigma^{\uparrow\uparrow})$ in the total ionization cross section for antiparallel and parallel incident- and atomic-electron spins are inconsistent with all theoretical calculations below 50 eV.

Although the electron-hydrogen collision problem is the most fundamental of all electron-atom collision problems, the mathematical description of the process cannot be carried out in closed form because a solution to a three-body problem is required. The situation is further complicated by the requirement that the two-electron wave function be totally antisymmetric, with the symmetric triplet spinor paired with the antisymmetric-configuration space wave function, and the antisymmetric singlet spinor paired with the symmetric-configuration space wave function.

The spin-averaged triple-differential electron scattering cross section for electron impact ionization of atomic hydrogen can then be written as the statistically weighted sum of singlet and triplet cross sections. In terms of the direct and exchange scattering amplitudes, $f(\vec{k}_1',\vec{k}_2')$ and $g(k_1',k_2')$, respectively, the electron scattering cross section can be expressed as[1]

$$\frac{d^3\bar{\sigma}}{d\Omega_1 d\Omega_2 dE_1'}=\frac{k_1'k_2'}{k_1}\left(\tfrac{1}{4}|f+g|^2+\tfrac{3}{4}|f-g|^2\right), \qquad (1)$$

with $|f+g|^2$ corresponding to the singlet and $|f-g|^2$ to the triplet cross section. Here $\vec{k}_1$, $\vec{k}_1'$, and $\vec{k}_2'$ are, respectively, the momenta (in atomic units) of the incident, scattered, and ejected electrons, and E_1' is the energy of the scattering electron. Since f and g are complex quantities, three independent parameters are needed to describe the problem; for example, $|f|^2$, $|g|^2$, and $\mathrm{Re}(f^*g)$. These separately calculable quantities can only be determined by polarization experiments. As an ancillary benefit, experiments with polarized particles remove the requirement of the absolute determination of beam fluxes, target densitites, and detector efficiencies—quantities which are often difficult to measure with precision. In the case of electron impact ionization of atomic hydrogen, the imprecise knowledge of the ion-detection efficiency might account for the disagreement among the various experimental measurements.[2]

In this Letter we report on the first polarized-beams experiment involving the collision of polarized electrons with polarized hydrogen atoms.[3]