HYPERFINE TRANSITIONS IN GROUND STATE HYDROGEN-LIKE $^{165}Ho^{66+}$ AND $^{185,187}Re^{74+}$

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Spontaneous line emission due to the hyperfine splitting of the ground state of highly charged hydrogen-like ions excited by electron collisions was measured using an Electron Beam Ion Trap. The F=4 to F=3 transition of the 1s $^2S_{1/2}$ configuration of $^{165}Ho^{66+}$ was identified at (5726.4 ± 1.5) Å. The F=3 to F=2 transition for the two isotopes $^{185,187}Re^{74+}$ were found at (4512 ± 2) Å and (4557 ± 2) Å. We infer the nuclear dipole magnetic moment of ^{165}Ho to be 4.1267(11) n.m., with five times higher accuracy than previous measurements. For $^{185,187}Re$ we determine 3.153(2) n.m. and 3.184(2) n.m., respectively, in disagreement with a tabulated NMR measurement.

INTRODUCTION

The large hyperfine splitting (HFS) (several eV's) of the ground state of a highly charged hydrogen-like ion is sensitive to the nuclear magnetic moment, to nuclear size effects and to QED radiative corrections. Only sparse data are available; the spontaneous 1s hyperfine transition in H, D and He^+ has been observed in astrophysical sources, but only few laboratory measurements have been carried out (H, D, T, He^+) due to the extremely long lifetime of the upper hyperfine levels (1,2) in neutrals and low-charged ions. Laser pumping has been recently applied to H-like Bi^{82+} in a heavy-ion storage ring (3) resulting in the first measurement of the hyperfine splitting in a multiply charged ion.

We have measured the F=4 to F=3 hyperfine transition of the 1s ground level of H-like $^{165}Ho^{66+}$ using passive emission spectroscopy (4), and also the F=3 to F=2 transition in the two rhenium isotopes ^{185}Re and ^{187}Re. We use the results to determine their respective nuclear magnetic moments.

EXPERIMENT

Hydrogen-like holmium and rhenium ions are produced and stored in a high-energy electron beam ion trap (SuperEBIT) by an electron beam of variable energy axially compressed by a high magnetic field. The ion trap is monitored by two germanium detectors to determine the ionic species present and the charge balance. At a beam energy of 132 keV and 285 mA beam current, the He-like Ho^{65+} ion was the most abundant species in the trap (40 %), followed by Li-like Ho^{64+} (25%). The concentration of H-like Ho^{66+} was 6 %, that of bare Ho^{67+} around 0.5%. Lower charge states made up the rest. For the rhenium experiment, the beam energy was 163 keV.

Two main processes are expected to populate the upper hyperfine level of the H-like ion in our trap. The most important is collisional ionization of He-like ions, were one of the two 1s electrons is removed leaving a H-like ion behind with similar probability for population in any of the two HFS states. The second process is radiative recombination of beam electrons with bare ions, also populating both HFS levels nearly evenly. Collisional excitation requiring a spin flip is far less probable than these two mechanisms and can be neglected. With these processes, the observed count rate can be explained.

We use an optical prism spectrograph equipped with a cryogenic CCD camera to detect the spontaneous emission from the hyperfine transitions in those H-like ions. Due to the extreme low number of emitting ions (thousands), and the low excitation rate (<10 s^{-1}), great care was necessary taken to separate the signals on the order of few hundred photons per hour from much higher levels of background. The thermal and atomic line background are eliminated by subtracting from every spectrum taken with hydrogen-like ions in the trap another one taken without any hydrogen-like. Cosmic rays are detected by the CCD during the long exposure times. Their contribution is largely reduced by appropriate software discriminator level during the data reduction. To obtain spectra from the two-dimensional images, the pixel counts on the CCD detector are integrated along one dimension. Many days of observation were necessary to obtain appropriate signal-to-noise ratios for the wavelength determination.

The holmium result, after addition of 18 background corrected spectra (36 hours of data) is displayed in Fig 1. A single feature at (5726.4 ± 1.5) Å with a peak height 10 times larger than the standard deviation of the background the line and a FWHM of 15 Å appeared. The total number of counts above the background over the line profile was around 4000. We attribute this feature to the hyperfine transition in Ho^{66+}. To exclude the possibility that the line

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was emitted by a lower charge state, the experiment was repeated, but making sure that no H-like Ho^{66+} could be produced, while

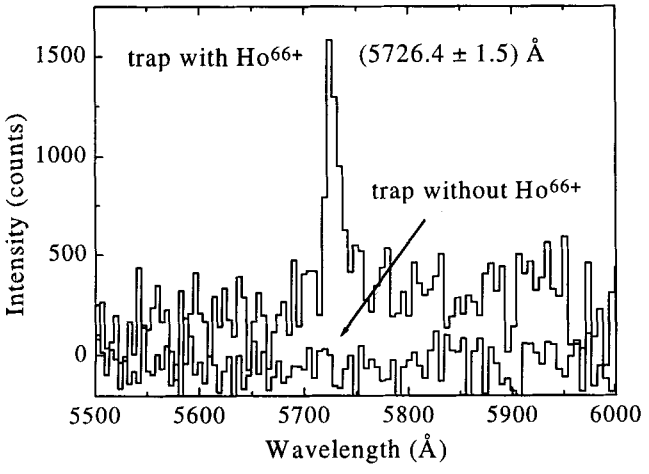

FIGURE 1. The F=4 to F=3 hyperfine transition in hydrogen-like Ho^{66+} and its baseline.

keeping the other charge states in the trap more or less unchanged. Again, spectra with and without holmium were subtracted from each other. The resulting spectra displayed no indication of any line at any position throughout the range of observation. The rhenium measurement was performed in the same way, and delivered two features at (4512 ± 2) Å and (4557 ± 2) Å, which are identified as the HFS ground state transitions of the two natural isotopes of that element. Their relative intensities are consistent with the isotopic abundances for natural rhenium.

DISCUSSION

The energy difference Δ between two neighboring levels in a H-like ion is given by Shabaev (5) as

$$\Delta = \frac{\alpha^4 Z^3}{n^3} \cdot \frac{\mu_I}{I} \cdot \frac{m_e}{m_p} \frac{(I+j)\cdot m_e c^2}{j\cdot(j+1)\cdot(2l+1)} \left[A\cdot(1-\delta)\cdot(1-\varepsilon)+\kappa_{rad}\right]$$

with following terms: α, fine-structure constant; Z, nuclear charge; n, j, l: principal, total moment and orbital moment electron quantum numbers; μ_I, nuclear magnetic moment; m_e, m_p: electron, proton mass; I, nuclear spin; A, relativistic factor; δ, nuclear charge distribution correction; ε, nuclear magnetization distribution (Bohr-Weisskopf) correction; κ_{rad}, QED radiative corrections. The two dominant QED corrections have recently been calculated (6, 7). Based on the calculations of the self energy correction by Persson et al. (6), we estimate for holmium (Z=67) a -19.3 meV shift. The vacuum polarization was given by Schneider et al. in (7). From their work we estimate this contribution to be 9.4 meV. The total net QED correction therefore is -9.9 meV. Using the above formula with the mentioned QED corrections, we obtain a nuclear magnetic moment of 4.1267(11) n.m., in good agreement with the latest published value from the Shirley table of isotopes (8) of 4.132(5). For $^{185, 187}Re$, a QED net shift of -14.0 meV as given in (6,7) leads to nuclear magnetic moments of 3.153 n.m. and 3.184 n.m. respectively. This results disagrees with values (3.1871 n.m. and 3.1921 n.m.) tabulated in (8) where a standard diamagnetic correction was applied to the original NMR data of Alder (9) (3.1437 n.m. and 3.1759 n.m.) measured in a liquid solution of $NaReO_4$. Chemical shifts of the NMR frequency, which were not accounted for, and the fact that the electronic structure of the rhenium in that experiment was not that of a free atom, but a chemically bound Re^{7+} i.e., Re(VII), making the diamagnetic correction inaccurate, can however explain the difference.

The HFS of the ground state in H-like ions is sensitive to contributions from the nuclear magnetic moment, nuclear size effects and QED. The small QED contributions can be predicted with high accuracy; the nuclear size corrections as well, to a lesser extent. The absolute size of the nuclear magnetic moment can therefore be determined from the 1s hyperfine splitting. This method avoids both the uncertainty in the theoretical atomic diamagnetic correction, which affects atomic beam resonance measurements, and chemical frequency shifts, for the values obtained through NMR measurements. Nuclear size effects are at present the largest source of systematic error.

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