Nuclear magnetization distributions in heavy atoms and ions with applications to Tl and Fr

Martin G.H. Gustavsson and Ann-Marie Mårtensson-Pendrill

Atomic Physics, Physics and Engineering Physics
Göteborg University and Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Tel +46-31-772 3215, Fax +46-31-772 3496
E-mail: f3amghg@fy.chalmers.se, f3aamp@fy.chalmers.se
Website: http://fy.chalmers.se/~f3amghg/, http://fy.chalmers.se/~f3aamp/

Nuclear distributions affect many aspects of atomic spectra. Information about the charge distribution can be deduced from experimental isotope shifts. The charge distribution, in turn, affects other atomic properties, that are sensitive to the electronic wavefunction close to the nucleus, such as hyperfine structure and parity non-conserving effects. Also other nuclear distributions are important for these effects: the hyperfine structure is sensitive to the distribution of the magnetization, the electroweak electron-nucleus interaction involves the neutron distribution, and the search for possible P and T violating effects in the nucleus involve so-called "Schiff moments". The observed effects are connected to more fundamental properties through calculations of electronic factors. Studies of isotope shifts and hyperfine structures for neutral atoms have a long history, but are still extended to more shortlived isotopes. The information about nuclear properties extracted from experiments for neutral or weakly charged systems provide calibration for experiments for hydrogen-like systems. Here we consider the chain of Fr isotopes and also the stable isotopes of Tl.

The isotope shifts in the chain of Fr isotopes in the range ^{207}Fr to ^{228}Fr were measured in the mid-eighties at ISOLDE [1]. The mass shift amount to only about 1% for Fr, and the field isotope shift can be expressed as $F\kappa\delta\langle r^2\rangle^{AA'}$. The combination with calculated electronic factors obtained by MBPT leads to the slightly revised value, $F(7\mathrm{s}-7\mathrm{p}_{3/2})\kappa = -21.0$ GHz/fm^2 with an uncertainty of about 2% [2]. This value is smaller than that used by Coc et al. in their analysis of the experimental results [1], giving values for $\delta\langle r^2\rangle$ in Fr, slightly larger than earlier tabulations.

The extracted charge radii can be combined with recent accurate hyperfine anomaly measurements, and may give a handle on neutron distributions in Fr [3, 4]. The hyperfine anomaly arises from differences in charge and magnetization distribution within the nucleus, through the "Breit-Rosenthal" [5] and "Bohr-Weisskopf" [6, 7] effects, respectively. For Fr, the magnetic moment measurement are quite uncertain, whereas the ratio $A(7\mathrm{s})/\mathrm{A}(7\mathrm{p}_{1/2})$ can be accurately determined [3, 4], and the isotopic variation results from the *difference* in hyperfine anomaly [8] between the 7s and $7\mathrm{p}_{1/2}$ states. The coupled-cluster calculations show that the many-body corrections for these transitions can be neglected. A combination of experimental data for the anomalies with extracted changes in charge radii can provide information about the magnetization distribution.

During the last decade, much effort has been put into the studies of highly charged hydrogen-like systems, where higher-order quantum electrodynamic contributions are large enough to be discernible compared to the experimental uncertainty. However, the uncertainty in the nuclear magnetization distribution complicates the analysis. In certain cases, additional information may be obtained from neutral systems. One example is the hydrogen-like systems $^{203}\mathrm{Tl}^{80+}$ and $^{205}\mathrm{Tl}^{80+}$, where measurements are now underway at the Super-EBIT at LLNL, California [9, 10]. Calculations of the ground-state hyperfine structure give energy splittings of 3.229(17) eV and 3.261(17) eV for $^{203}\mathrm{Tl}^{80+}$ and $^{205}\mathrm{Tl}^{80+}$, respectively, where the accuracy is limited by the uncertainties in the Bohr-Weisskopf effects [11]. The difference in energy splitting for these systems is thus about 0.03 eV, corresponding to a transition-wavelength difference of about 3 nm. The value of the energy difference can, however, be determined with an substantially improved accuracy by using an accurate magnetic moment ratio [12] and hyperfine anomaly data from measurements on neutral thallium [13, 14]. The interpretation makes also use of data from measurements of muonic isotope shifts. The difference in energy-splitting due to hyperfine structure for $^{203}\mathrm{Tl}$ and $^{205}\mathrm{Tl}$, respectively, is then found to be 0.031 04(1) eV, which corresponds to a transition-wavelength difference of 3.640(1) nm [11, 15].

The combination of atomic calculations and experimental data is a powerful tool to study various nuclear distributions. In addition, the study of neutral systems can provide important calibration for experiments on highly charged systems.

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