Properties of Halo Nuclei from Precision Atomic Physics

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A halo nucleus is an atomic nucleus containing one or more planetary neutrons outside a more tightly bound core. The simplest example is ^{6}He, consisting of a strongly bound ^{4}He (alpha particle) core plus two additional neutrons that form a weakly bound halo [1]. Other recently studied examples are ^{8}He [2], containing four halo neutrons, and ^{11}Li [3]. They all have lifetimes of only a second or less, and the low abundance makes conventional measurements of the RMS nuclear charge radius $\bar{r}_c$ from electron scattering a practical impossibility. The use of the isotope shift to provide an indirect measurement of $\bar{r}_c$ therefore offers a unique measurement tool. Accuracies at the level of ± 100 kHz are required for both theory and experiment. The results provide a sensitive probe of various theoretical models for the effective low-energy nucleon-nucleon interaction potential.

The principle of the method begins by writing the isotope shift between isotopes A and B for a particular atomic state a in the form

$$\Delta E_a(B-A) = F_a(B-A) + \left[\bar{r}^2_{\mathrm{c},B} - \bar{r}^2_{\mathrm{c},A}\right] G_a \qquad (1)$$

where $F_a(B-A)$ contains all the contributions to the isotope shift coming from the atomic physics part of the problem, such as the normal and specific isotope shifts, including the mass-dependent parts of the nonrelativistic, relativistic, and quantum electrodynamic contributions to the energy. The coefficient G_a is proportional to the electron density at the nucleus, and is simply calculated from its definition $G_a = (2e^2/3)\langle\sum_{i=1}^{N}\delta(r_i)\rangle_a$, summed over the N atomic electrons, and the expectation value calculated with respect to state a. A comparison between theory and experiment for a particular atomic transition $a \to b$ then yields the quantity $\bar{r}^2_{\mathrm{c},B} - \bar{r}^2_{\mathrm{c},A}$, and so the rms charge radius of an unknown halo nucleus B is determined relative to a known isotope A.

The experimental work requires sophisticated methods of atom trapping and single-atom spectroscopy in order to obtain sufficient signal. The most recent measurement determines the charge radius of ^{8}He to be 1.93 ± 0.03 fm relative to ^{4}He. This value is perhaps somewhat surprisingly smaller than the value 2.068 ± 0.011 fm for ^{6}He, indicating that the alpha-particle core does not recoil as much in the center-or-mass frame. The next case to be studied by Nörtershäuser and coworkers at GSI Darmstadt will be ^{11}Be$^+$ [4], using the $2\,^2$S $-$ $2\,^2$P transition. Further results will be presented at the conference.

[1] L.B. Wang, Phys. Rev. Lett. **93** (2004) 142501 .

[2] R. Sanchez *et al.* Phys. Rev. Lett. **96** (2006) 033002.

[3] P. Mueller *et al.*, Phys. Rev. Lett. **99** (2007) 252501.

[4] Z.-C. Yan, W. Nörtershäuser, and G.W.F. Drake, Phys. Rev. Lett. (2008) in press.