Atomic Parity Violation in Heavy Ion Colliders

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It has long been a dream of atomic physicists to measure PNC in hydrogen (for a review of hydrogen experiments, see [i]), or a hydrogenic system. It appears that recent developments in relativistic ion colliders, high-brightness ion sources, and laser cooling methods of ions in storage rings, may open such a possibility for relatively light (Z~10) hydrogenic ions [ii]. Due to their simple atomic structure, high precision theoretical calculations can be carried out in these ions. In addition, neutron distribution uncertainties will not present a serious problem in relatively light ions considered here, both because the structure of light nuclei is much better understood than that of the heavy nuclei, and because the electron wavefunction gradient at the nucleus is relatively small for light nuclei.

Consider the conceptually simplest variant of a PNC experiment in a hydrogenic system: circular dichroism (i.e. the difference in transition rates for right- and left-circularly polarized light) on the 1S→2S transition in the absence of external electric and magnetic fields. Dichroism arises due to interference between the $M1$ and the PNC-induced $E1$amplitudes of the transition.

Due to the PNC interaction, the 2S state acquires an admixture of the $2P_{1/2}$ state; the magnitude of the PNC admixture is probed by tuning the laser in resonance with the highly forbidden 1S→2S $M1$-transition and observing circular dichroism. Tracing Z-dependences of various atomic parameters, one finds that while the weak interaction matrix element increases $\propto Z^5$, the PNC asymmetry, i.e. the relative difference in absorption for the two circular polarizations, decreases $\propto Z^{-2}$, while the statistical sensitivity increases $\propto Z^4$ [ii].

The frequencies of the 1S→2S transitions for the hydrogenic ions lie outside the range directly accessibly to laser sources. This problem can be solved by using relativistic Doppler tuning. For an ion with relativistic factor $\gamma = \frac{1}{\sqrt{1-\beta^2}} >> 1$ colliding head-on with a photon of frequency ω_{lab}, the frequency in the ion's rest frame is given by:

$$\omega_{ion\ frame} = \gamma(1+\beta)\omega_{lab} \approx 2\gamma\omega_{lab}. \qquad (7)$$

In order to tune to the 1S→2S resonance for a hydrogenic ion, it is necessary to satisfy the condition:

$$\Delta E_{2S-2P} \approx Z^2 \cdot 10.2 \text{ eV} = 2\gamma \ \omega_{lab} . \qquad (8)$$

Using the Relativistic Heavy Ion Collider (RHIC, $\gamma \approx 100$), with visible and near-UV lasers, it is possible to access 1S→2S transitions for ions with Z up to ≈11 (Na).

Evaluating the statistical sensitivity of the experiment, one arrives at the following expression:

$$\delta H_w = \frac{1}{4}\sqrt{\frac{\Gamma_D \Gamma_{2P}}{\dot{N}_{ions} T \chi_{E1}}} \ . \qquad (9)$$

Here $\Gamma_D \approx \omega_{ion\,frame} \cdot \frac{\Delta\gamma}{\gamma}$ is the Doppler width, $\dot{N}_{ions}$ is the average number of ions entering the interaction region per unit time, T is the overall measurement time, and χ_{E1} is a dimensionless saturation parameter. This shows that for an optimally designed PNC experiment, the statistical sensitivity is completely determined by the total number of available ions and by the transition widths. In order to obtain a certain sensitivity to weak interaction parameters, e.g. to $sin^2\theta_w$, where θ_w is the Weinberg angle, it is necessary to have exposure $\dot{N}T$ which can be represented in units of particle-Amperes×year:

$$Exposure[part.\, Amp \times year] \geq \frac{\Delta\gamma}{\gamma} \cdot \frac{0.1}{Z^4 \cdot (\delta \sin^2\theta_w)^2 \cdot \chi_{E1}} . \qquad (10)$$

As an example, for $\delta\sin^2\theta_w = 10^{-3}$, using Ne ions (Z=10) in RHIC, and substituting $\chi_{E1} = 6\cdot 10^{-2}$ (which is found to be an optimal value limited by laser photoionization), one obtains the necessary running time ~ 1 week. In this estimate we assumed $\Delta\gamma/\gamma = 10^{-6}$, which is possible to achieve using laser cooling [iii,ii].

Many technical problems would have to be addressed before a PNC experiment could be carried out. This includes development of a hydrogenic ion source for the accelerator, implementation of laser cooling, design of an efficient detection scheme for ions excited to the 2S state, etc. However, all of these problems appear, at least in principle, tractable, and the proposed technique may offer sensitivity sufficient for testing physics beyond the standard model.

Another promising technique involving heavy (Z up to 92) helium-like ions has been discussed in [iv].

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[ii] M. Zolotorev and D. Budker, Phys. Rev. Lett. **78**(25), 4717 (1997); Prospects for Measuring Parity Nonconservation in Hydrogenic Ions Using High-Energy Accelerators, in: "Parity Violation in Atoms and Electron Scattering" B. Frois and M. A. Bouchiat, eds., World Scientific, 1999, p. 364.

[iii] D. Habs, V. Balykin, M. Grieser, R. Grimm, E. Jaeschke, M. Music, W. Petrich, D. Schwalm, A. Wolf, G. Huber, and R. Neumann, in *Electron Cooling and New Cooling Techniques*, R. Calabrese and L. Tecchio, eds, World Scientific, Singapore, 1991.

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