COOLED $^{7}\text{Li}^{+}$ IONS IN THE TSR STORAGE RING: PRECISION EXPERIMENTS AND LASER BUNCHING

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ABSTRACT

Laser spectroscopy of electron cooled $^{7}\text{Li}^{+}$ ions stored at 6.4% in the TSR storage ring have been used for an accurate test of the special theory of relativity at high velocity. Independent of assumptions on the motion of a hypothetical reference frame the best upper limits for any deviation for the time dilatation factor $\gamma = (1 - v^2)^{-1/2}$ have been obtained and are discussed.

The potential of such experiments depend on the unperturbed interaction between laser and ion beam. The preparation of a laser cooled and bunched ion beam can avoid beam interactions in the focusing fields of the storage ring and give moreover a direct measure of longitudinal temperatures, which up to now are only inferred from model calculations. Calculations for this bunched cooling are presented.

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PRECISION EXPERIMENTS AND LASER BUNCHING

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ABSTRACT

Laser spectroscopy of electron cooled $^7$Li$^+$ ions stored at 6.4% in the TSR storage ring have been used for an accurate test of the special theory of relativity at high velocity. Independent of assumptions on the motion of a hypothetical reference frame the best upper limits for any deviation for the time dilatation factor $\gamma = (1 - \beta^2)^{-1/2}$ have been obtained and are discussed.

The potential of such experiments depends on the unperturbed interaction between laser and ion beam. The preparation of a laser cooled and bunched ion beam can avoid beam interactions in the focussing fields of the storage ring and give moreover a direct measure of longitudinal temperatures, which up to now are only inferred from model calculations. Calculations for this bunched cooling are presented.

Laser spectroscopy in a closed three level system of fast ions can be used for a precise test of the relativistic Doppler shift formula. The moving clocks represented here by an $^7$Li$^+$ ion beam with well controlled parallel motion can interact with two counterpropagating laser beams. Saturation spectroscopy can be observed in the fluorescence signal of a $\Lambda$ type resonance. These experiments have been performed at the TSR storage ring in Heidelberg and their results have been published in [1] [2].

For an exact collinear geometry the Doppler shifted frequencies are given

$$\nu = \nu_1,2(\gamma(1 + \beta \cos(\theta)))^{-1}$$  \hspace{1cm} (1)

with $\cos(\theta) = \pm 1$. The parallel and antiparallel laser frequencies $\nu_p$ and $\nu_a$ and the rest frame clock frequencies of the ions $\nu_1$ and $\nu_2$ obey the relation $\nu_a = \nu_p - \nu_1 \cdot \nu_2$ for special relativism since $\gamma^2(1 - \beta^2) = 1$. At the TSR ring ions at 6.4% speed of light are excited with a parallel Ar$^+$ laser beam with $\lambda_p = 515$ nm and an antiparallel dye laser beam with $\lambda_a = 585$ nm. The $\Lambda$ resonance between hyperfine levels $F = \frac{3}{2}$, $F = \frac{3}{2}$ and $F' = \frac{1}{2}$ in the $1s2p \, ^3S_1(F) \rightarrow 1s2p \, ^3P_2(F')$ line ($\lambda_{1,2} = 549$ nm at rest) is excited. All optical frequencies are measured accurately.

Any deviation given as $\gamma = \gamma_{SR}(1 + \delta \alpha \beta^2 + \delta \beta' \cos(\Omega))$ can be tested to second order by

$$\nu_a = \frac{\nu_1 \nu_2}{\nu_p}(1 + 2\delta \alpha \beta^2 + 2\beta' \cos(\Omega))$$  \hspace{1cm} (2)

where $\beta'$ is the laboratory motion relative to a hypothetical "ether" frame comoving with the cosmic 3 K background radiation. A more complete discussion on the foundations of tests for special relativity and various classes of experimental tests can be found in [1] [3]. The frequency of the antiparallel laser beam $\nu_a$ is compared to the value $\nu_1 \nu_2/\nu_p$ and from $\Delta \nu/\nu < 1.8 \cdot 10^{-8}$
by a time dependent variation of the laser field's intensity. In the left of figure (2) a numerical

\[ \Delta \dot{\phi} = \frac{f \eta}{p} \left( F_{\text{LASER}}(\Delta \phi, \Delta p) + F_{\text{INDAC}} \right) = 0 \]

The phase dependence of the cooling force is shown on the right in figure (2), and is induced
by a time dependent variation of the laser field's intensity. In the left of figure (2) a numerical
Figure 1: Fluorescence signals from the electron cooled $^7\text{Li}^+$ ion beam. In trace 1 only the dye laser's light is sent to the experiment, and the Doppler broadened fluorescence of the $F = \frac{3}{2} \rightarrow F' = \frac{5}{2}$ transition is visible. The FWHM corresponds to $\Delta \nu = 3 \cdot 10^{-6}$. In trace 2 both lasers are sent to the ring, which increases the background, due to the stray light from the Ar$^+$ laser. The Ar$^+$ laser at resonance with the $F = \frac{5}{2} \rightarrow F' = \frac{5}{2}$ transition optically pumps the ions into the $F = \frac{3}{2}$ level and the dye laser's scan shows the almost depleted $F = \frac{1}{2}$ level at the $F = \frac{3}{2} \rightarrow F' = \frac{5}{2}$ transition. The resonance $F = \frac{3}{2} \rightarrow F' = \frac{5}{2}$ yields a strong fluorescence from the simultaneous excitation of the A-system.

Figure 2: On the right the time dependent force acting on a stored ion beam is shown, which leads to a laser bunched ion beam. On the left solutions of equation (6) for several initial conditions are shown. The force acts as a frictional force on the particle momenta and as a spatial filter on the particle phases. Note that the scale for $\Delta \Phi$ running from $-\pi$ to $+\pi$ corresponds to exactly one revolution in the storage ring, which is the fundamental timescale for this particle preparation.
The restrictions imposed by the beam optical fields as seen in the $^7\text{Li}^+$ experiment could be avoided in a new scheme of a two photon experiment on neutral hydrogen prepared from an electron cooled particle beam in a storage ring. Proton beams can be stored and cooled up to $\beta \sim 0.2$ at the TSR ring and to $\beta \sim 0.75$ at the ESR ring at GSI/Darmstadt, and a partly neutralized beam by radiative electron capture in the 1s and 2s state of hydrogen could be extracted from the ring. The highly monochromatic low emittance atomic beam can be excited to a Rydberg state by two-photon resonance with counterpropagating parallel laser beams. By careful matching the atomic beam emittance and the laser beam in a long interaction section ($L<50\text{ m}$) precise angular alignment ($\theta < 20\mu\text{rad}$) and small signal broadening could be realized. For these conditions a state of the art frequency measurement of the $2s \rightarrow nd$ resonance at $\lambda > 515\text{ nm}$ would be limited by the line width ($\sim 700\text{ kHz}$) and shifts in angular misalignment by $\Delta \nu = (\beta \gamma \theta)^2$. A frequency
accuracy of $\frac{\Delta \alpha}{\alpha} < 5 \cdot 10^{-10}$ and a corresponding value $\delta \alpha < 10^{-9}$ should be reachable, testing the special theory of relativity over 1000 times more accurately than in the present experiment.

References