Reply to comment on: Lorentz violation in high-energy ions

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Abstract. This response clarifies that, without accounting for the transverse Doppler effect [1], the experimental analysis cannot rule-out (and develop bounds on) the Lorentz violation, especially since the energy of the transition being excited (in the moving high-energy ion, under the experimental conditions) is not measured directly. Therefore, the transverse Doppler effect, in the emissions, should be accounted for when analyzing the results of saturation spectroscopy experiments referred to in the Comment [2].

From special relativity (SR), the transverse Doppler provides a unique relation between the ratio of the emitted photon frequencies ν_e^* (in the ion frame F_I), ν_e (in the laboratory frame F_L), and the measurement angle ϕ (as in Fig. 1)

$$R_\nu = \frac{\nu_e^*}{\nu_e} = \frac{\lambda_e}{\lambda_e^*} = \frac{[1-\beta\sin\phi]}{\sqrt{1-\beta^2}} = \gamma\,[1-\beta\sin\phi] \qquad (1)$$

where the measurement angle ϕ is the deviation of the photomultiplier tube (PMT) axis from the perpendicular to the laser axis (and the ion velocity) in the laboratory frame F_L, λ_e^*, λ_e are the corresponding wavelengths, $v = \beta c$ is the speed of the ion, and c is the speed of light.

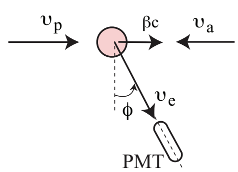

Fig. 1. Experimental setup in the laboratory frame F_L

If the photon emissions are at $\lambda_e^* = \lambda_o = 548.5nm$ in the ion frame (where λ_o is measured for stationary ions), then the expected wavelength λ_e (in the laboratory frame) at a measurement angle ϕ is shown in Fig. 2 for two experimental cases: (i) $\beta = 0.064$ [3]; and (ii) a higher speed $\beta = 0.338$ [4].

The measurement angle of $\phi = 0$ of the PMT axis in previous experiments, e.g., [3,4], does not match the center of the filters used before the PMT. The center $\lambda_{PMT} = 548nm$ of the interference filter used before the PMT (Ref. [3], page 42) for $\beta = 0.064$ matches the expected ion emissions ($\lambda_o = 548.5nm$ in the ion frame) when the PMT axis is $\phi = 3$ degrees away from the perpendicular to the ion velocity (see Fig. 2). This deviation from the perpendicular becomes even more significant at higher ion speeds. For example, with $\beta = 0.338$ [4], the center of the BG39 filter is at $\lambda_{PMT} = 500nm$, which would match emissions from the expected transition at λ_o when the angle of the PMT axis is $\phi = 25$ degrees.

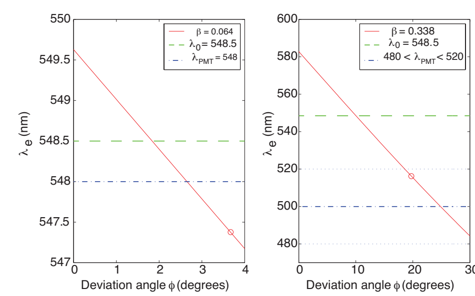

Fig. 2. Variation of expected emission wavelength λ_e in the laboratory frame F_L for different measurement angles ϕ.

Even if the majority of the photons are assumed to be perpendicular to the laser axis in the ion's frame of reference (rather than perpendicular in the laboratory frame), the SR expression for the measured emissions in the laboratory frame,

$$\lambda_e = \lambda_e^*/\gamma = \lambda_o/\gamma; \qquad \cos(\pi/2 - \phi) = \beta \qquad (2)$$

yields $\lambda_e = 547.3nm, \phi = 3.7$ degrees (for $\beta = 0.064$) and $\lambda_e = 516nm, \phi = 19.8$ degrees (for $\beta = 0.338$) represented by circles in Fig. 2. Thus, a noticeable deviation ϕ from the perpendicular to the laser axis (in the laboratory frame) is expected when compared to the perpendicular placement of the PMT axis ($\phi = 0$) in the experiments [3,4].

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The deviation angle ϕ of photons in the laboratory frame can be accommodated by using lenses that enable such photons to enter the PMT even though the PMT axis is perpendicular to the laser axis (and ion velocity). This loss of control over the angle ϕ of the photons entering the PMT, coupled with the relatively broad half-width of the filter, implies that the experiment cannot ensure that the photon being measured has the expected wavelength-angle (λ_e, ϕ) relation. Then, the experimental analysis (e.g., for the two-level system in [3]) needs to rely on the assumption that the measured photon is from a transition that was excited at $\nu_o = c/\lambda_o$ in the ion's frame of reference under the specific experimental conditions. However, the results cannot rule out Lorentz violation without this assumption that the transition being excited still corresponds to ν_o in the ion's frame (under the experimental conditions). As shown in [1], photons at frequency ν_o (the center of the filter with $\beta = 0.064$ in the laboratory frame) that are aligned with the PMT axis ($\phi = 0$) would be observed by the PMT, which can imply Lorentz violation.

It is noted that systematic Lorentz violation is directly related to the amount of uncertainty in the transition. Uncertainty can occur because in addition to potential changes in the transition under the experimental conditions, the transition itself is a distribution, with a range of values. Self-selection (of the transition) is possible depending on the conditions under which the photons are observed in the Laser Spectroscopy experiment. For example, let the Lorentz violation modify the time dilation from γ to $\gamma\Delta_\gamma$, and let the self-selected transition be $\nu_o\Delta_{\nu_o}$ instead of ν_o, under the specific experimental conditions. Then, SR analysis, which assumes no change in the transition (for a two-level transition [3]), yields

$$\nu_p = \frac{\nu_o}{\gamma(1-\beta)}; \qquad \nu_a = \frac{\nu_o}{\gamma(1+\beta)}, \tag{3}$$

where ν_p and ν_a are the measured frequencies (in the laboratory frame) of the lasers parallel and anti-parallel to the ion velocity. However, potential Lorentz violation, which matches the experimentally observed laser frequencies (ν_p, ν_a), can be found as

$$\nu_p = \frac{\nu_o}{\gamma(1-\beta)} = \frac{\nu_o\Delta_{\nu_o}}{\gamma\Delta_\gamma(1-\beta)} \tag{4}$$

$$\nu_a = \frac{\nu_o}{\gamma(1+\beta)} = \frac{\nu_o\Delta_{\nu_o}}{\gamma\Delta_\gamma(1+\beta)}. \tag{5}$$

Note that the Lorentz violation factor has the potential to be of the same order as the change in the transition frequency with

$$\Delta_\gamma = \Delta_{\nu_o}. \tag{6}$$

Although, bounds on the potential deviation in the transition $(\Delta_{\nu_o} - 1)$ can be estimated theoretically, an experimental design that accounts for the transverse Doppler effect, enables validation of the assumption that the transition being evaluated in the moving ion (under the experimental conditions) is the same as the expected transition ν_o (measured for stationary ions).

Early experiments, with much smaller ion speeds, had relatively-small angle deviations due to transverse Doppler. For example, with $\beta = 0.004$ [5], the angle deviation was only $\phi = 0.2$ degrees. Therefore, it was difficult to experimentally verify the transition frequency being excited in the moving ion. However, with larger speeds ($\beta = 0.064$ and $\beta = 0.338$), the need to assume that the transition being excited is still ν_o in the moving ion frame, can be removed by including the transverse Doppler effect in the experimental measurements, i.e., matching the PMT axis angle ϕ to the center ν_e of the PMT filter according to the (ν_e, ϕ) relation in Eq. 1 (with $\nu_e^* = \nu_o$). Additionally, deviations of measured photons from this (ν_e, ϕ) relation should be minimized, in high energy experiments, by: (i) using collimation to limit the variation from the chosen angle ϕ; and (ii) selecting narrow filters (e.g., when compared to BG39 at $\beta = 0.338$ [4]) centered around the chosen frequency ν_e.

In summary, the transverse Doppler effect, in the emissions, is substantial in high-energy ion experiments [2]. It should be accounted for in order to rule out Lorentz violations in high-energy ions.

References

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