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Nuclear Resonant Scattering of Synchrotron Radiation as a Method for Distinction between Covariant Ether Theories and Special Relativity

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Abstract. The paper stresses the importance for basic physics of the new proposed Champeney-like rotor experiment with nuclear resonant scattering of synchrotron radiation. Such an experiment, being sensitive to energy shifts proportional to c^{-3} (c is the light velocity in vacuum), should be able to distinguish between predictions of special relativity theory and covariant ether theories, and thus allow to differentiate between them. The results of computer simulations of experiments with the 14.4 keV resonance in ^{57}Fe show that an energy resolution $\Delta E/E$ at the level of 10^{-16} can be expected which is enough to reveal the third order term.

Key words: Mössbauer effect, special theory of relativity, synchrotron radiation.

Experimental data obtained in high-energy physics and cosmic-ray physics during the past decade again induced an exciting discussion about a possible violation of the Lorentz-invariance in Nature. In this connection some space–time theories with a covariant description of a hypothetical “absolute space” in the Universe (covariant ether theories, CETs) again attract great attention. The ideas of CETs go back to works by Lorentz and Poincaré. However, for a long time, various CETs were considered as physically senseless formal mathematical constructions. The principal possibility of the existence of phenomena, where a hypothetical violation of Einstein’s relativity principle might occur within the general relativity principle, was pointed out by Dirac [1]. The possible existence of such phenomena on a laboratory scale was substantiated and predicted in [2].

Let us briefly discuss some important characteristics of the Special Relativity Theory (SRT) and CETs. The SRT is based on two postulates: (a) All inertial reference frames (IRF) have equal rights, they are equivalent. The fundamental physical equations are the same (they are form-invariant) in inertial reference frames. (b) The velocity of light in vacuum c is a constant in all IRF. From these two postulates the Lorentz transformations follow in Minkowski space–time with its Galilean metrics. In particular, an “absolute” inertial frame, distinguished amongst all other inertial frames, does not exist. Lorentz transformations between two IRF are fully determined by their relative velocity. The principal characteristics of CETs are the following: (a) Space–time homogeneity, space–time isotropy, the causality principle as well as the general relativity principles (covariance of fundamental physical equations for admissible space–time transformations) are all valid [2, 3]. (b) An "absolute" inertial frame K_0 is allowed to exist. Therefore the postulates of SRT mentioned above are violated. (c) An "absolute" inertial frame K_0, if it exists, is unique. In K_0 the geometry of space–time is pseudo-Euclidean with Galilean metrics. In any other IRF moving at a constant "absolute" velocity, the metrics of physical space–time is oblique-angled [3]. True (physical) values differ, in general, from their magnitudes measured in experiment.

As a general consequence of these principles, two theorems of CETs follow [3]: (1) A transformation of measured space and time intervals from K_0 to any arbitrary IRF K has a Lorentzian form. (2) Lorentz transformations between two inertial frames $K_1(x_i)$ and $K_2(x_i'')$ always have to proceed via the absolute frame $K_0(x_i')$, where x_i, x_i', and x_i'' are experimentally measured space–time four-vectors. Therefore in CETs, Nature does not "know" a direct relative velocity between two inertial frames K_1 and K_2. Nature only "operates" with absolute velocities, being applied in the Lorentz transformations. A very important consequence of this transformation rule via the absolute frame is the appearance of a frequency (energy) shift between emitter and receiver of electromagnetic radiation, which is proportional to the "absolute" velocity of the Earth [3, 4]. Such a shift appears, e.g., when source and receiver rotate at different distances from a common rotational axis. The shift is proportional to c^{-3}:

$$\Delta E/E = u^2 v/4c^3 \tag{1}$$

(u is the linear velocity at the perimeter of the rotor and v is the absolute velocity of the Earth). Although such a possible violation of Einstein's relativity principle represents a tiny effect, it nevertheless can be detected by the modern technique of nuclear resonant scattering of synchrotron radiation. In Ref. [4] we considered a possible experiment with resonant radiation of ^{67}Zn, which, however, faces large experimental difficulties. In this paper we propose an experimental scheme involving the ^{57}Fe resonance, where a high sensitivity is reached due to the application of the recently discovered Nuclear Lighthouse effect [5]. The principal setup, to be realized at an undulator beamline of a third-generation synchrotron radiation source like the ESRF, is shown in Figure 1.

The high-speed rotor carries two targets: the inner target close to the central axis of the rotor and the outer target covering the circumference of the rotor. Both targets are made from metal foils containing the Mössbauer isotope ^{57}Fe with the transition energy of 14.4 keV. After monochromatization to a few meV around the nuclear transition energy achieved by Bragg reflections in Si channel-cut stages, the synchrotron radiation pulse of typically several 100 ps in length excites the nuclei in both targets. This excitation of the nuclei is phased in time by the SR pulse and extends over both spatially separated targets. Such a collective nuclear excitation

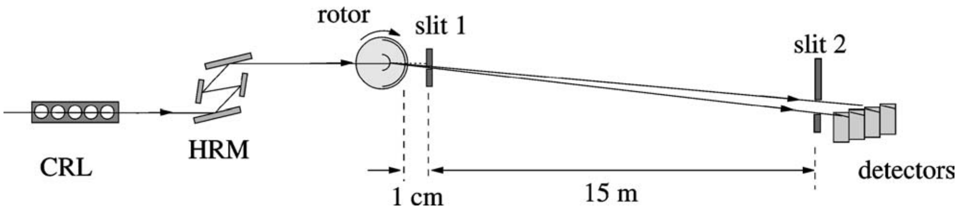

Figure 1. Schematic layout of an experiment at an undulator beamline, e.g., at the ESRF. CRL denotes a compound refractive lens, and HRM a high-resolution monochromator.

(nuclear exciton) follows the rotation of the rotor. This gives rise to the Nuclear Lighthouse Effect because the direction of spatially coherent forward reemission is rotated together with the target. As a result, the time evolution of the nuclear decay is mapped to an angular scale and can be recorded with a position sensitive detector [6]. One can show that background radiation arising from small-angle X-ray scattering (SAXS) from the rotor and the sample itself can be significantly reduced by the use of single-crystalline materials like Al_2O_3 (sapphire) [6]. An additional effect for background reduction relies on the spatial displacement of the nuclear exciton during its lifetime. Due to the motion of the exciton, the radiation sources of the small-angle scattering and the delayed resonant radiation are spatially separated. This allows one to apply a system of slits to almost fully suppress SAXS from the rotor and the sample. In order to avoid SAXS in air, the rotor has to be operated in vacuum.

Due to the energy difference (1), to which the conventional second order Doppler shift (SOD), $\Delta E_{\mathrm{SOD}}/E = u^2/2c^2$, has to be added, the radiation from both targets recorded in the detector shows a characteristic Quantum Beat (QB) interference pattern. The QB has the period $T = h/\Delta E$, where h is Planck's constant. In the absence of the effect predicted by CETs, the SOD gives a QB with the period

$$T_{\mathrm{SOD}} = \frac{h}{\Delta E_{\mathrm{SOD}}}. \tag{2}$$

If the CETs effect is present, as it follows from Equation (1), the T should vary between the extremal values [4]:

$$T_1 = h/(1 + v/2c)\Delta E_{\mathrm{SOD}}, \quad \text{and} \quad T_2 = h/(1 - v/2c)\Delta E_{\mathrm{SOD}}. \tag{3}$$

Therefore,

$$T_2 - T_1 \approx \frac{v}{c} \cdot \frac{h}{\Delta E_{\mathrm{SOD}}} = \frac{v}{c} T_{\mathrm{av}}, \tag{4}$$

where the average period T_{av} is given by Equation (2). If the observation window τ_{ob} of the experiment is much larger than T_{av}, the number n of QB maxima within τ_{ob} will be

$$n \approx \frac{\tau_{\mathrm{ob}}}{T_{\mathrm{av}}}. \tag{5}$$

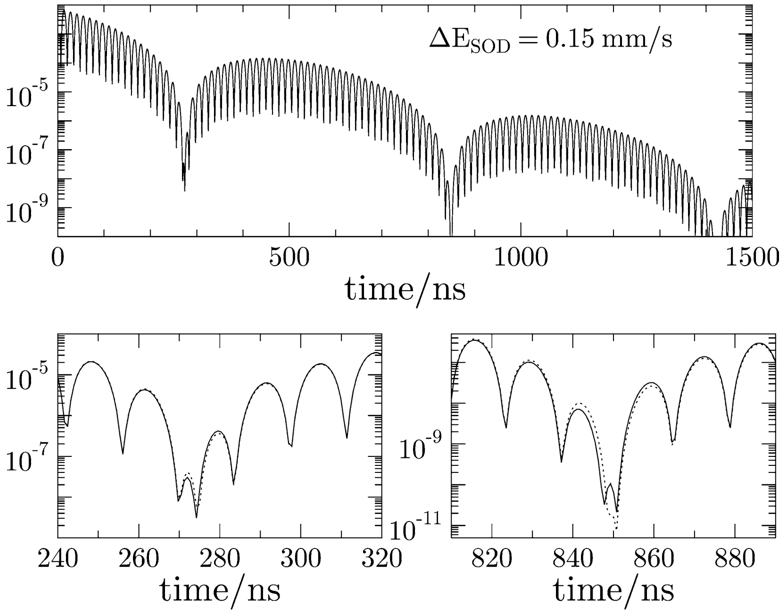

Figure 2. The top graph displays the time spectrum of nuclear resonant forward scattering from two 100 nm thick α-Fe foils with a difference in SOD of 0.15 mm/s. The lower figures display the time ranges around the first two minima of the SOD. It was assumed that CET is valid and introduces the extremal modulation periods of =0.1499 mm/s (solid line) and =0.1501 mm/s (dashed line).

Then the time difference for n QB maxima between the two extremal periods is given by

$$\Delta T = n(T_2 - T_1) = \frac{\tau_{\text{ob}}}{T_{\text{av}}} \cdot \frac{v}{c} T_{\text{av}} = \frac{v}{c} \tau_{\text{ob}} \approx 10^{-3} \tau_{\text{ob}}. \tag{6}$$

Here and in the further analysis we assume the velocities $u = 300$ m/s and $v = 300$ km/s (a typical value for Galaxy objects relative to the cosmic microwave background radiation). An observation window of $\tau_{\text{ob}} = 1500$ ns has been chosen corresponding to about 10 times the nuclear lifetime τ_s of the Mössbauer level ($\tau_s \approx 141$ ns). Then we obtain $T_{\text{av}} = 575$ ns, i.e. there are about three maxima within τ_{ob}, and $\Delta T \approx 1.5$ ns. Using fast modern electronics such a value for ΔT can be expected to be observable.

A high sensitivity for the measurement of small energy shifts can be achieved when the time response from the foils is additionally modulated by a fast quantum beat pattern. The basic idea is to analyze the structure of the beat pattern in the minima of the SOD oscillations, as well as the shift of the minima. We will explain these features for the case of ferromagnetic Fe metal with an internal hyperfine field of 33.3 T at room temperature. If magnetized perpendicular to the storage ring plane, only the $\Delta m = 0$ transitions are excited, leading to a quantum beat period of 9.5 ns. Figure 2 displays the results of a calculation for an average SOD of 0.15 mm/s ($u = 300$ m/s), that would be modulated between values of 0.1499 mm/s and 0.1501 mm/s if CET were valid. The samples are two iron foils with a thickness of 100 nm each, highly enriched in ^{57}Fe. The calculations show that significant effects can be observed already at early times. Simultaneously it proves the high sensitivity of this method. In particular, the expected relative energy resolution obtained from the calculations of Figure 2 will be better than 10^{-16}. This will be sufficient for a reliable measurement of the effects predicted by CETs.

Concerning the experiment itself, the incident synchrotron radiation beam is focused to the rotor position by a CRL (compound refractive lens) to a vertical beam height of less than 50 μm. The radiation is monochromatized by a HRM (high-resolution monochromator) to a bandwidth of 6.5 meV to reduce the non-resonant background. As indicated in Figure 1, the rotor spins around a horizontal axis with a frequency of 1600 Hz. The detector is located at a distance of approximately 15 m from the rotor, where the resonant radiation is deflected by about 150 mm off the primary beam. The time window of 50 ns around the first QB minimum due to the SOD is selected by a 7.5 mm wide slit. An array of avalanche photodiodes (APDs) covers this time range to monitor the intensity around this minimum. APDs are proposed here because of their very low background noise. However, an ideal detector would be a position sensitive detector with a spatial resolution of about 50 μm and a very low background noise.

Finally, we want to give a rough estimate of the count-rate in such an experiment. The integrated intensity over the time range from 832 ns to 860 ns in Figure 2 amounts to that within an energy range of about $2 \times 10^{-6}\ \Gamma_0$. This sets a limit for the observable effect. For this reason, the experiment has to be performed at one of the strongest X-ray sources available, like the European Synchrotron Radiation Facility ESRF (Grenoble, France). The best high-resolution monochromator available at beamline ID18 delivers a flux of almost 8×10^9 s^{-1} within a band of 6.4 meV, which corresponds to 6000/(s$\cdot\Gamma_0$) with $\Gamma_0 = 4.7$ neV. With this intensity, one arrives at approximately 130 counts during a 3-hour period falling into the time range mentioned above. Considering the flux available at present third-generation synchrotron radiation facilities, to be sensitive to an effect of $\Delta E/E \approx 3 \times 10^{-16}$ as predicted by CETs, measuring times of several weeks will be required.

Due to the fundamental role of the SRT in modern physics, this new experimental test described here is highly important.

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