Optica High-brightness Sources and Light-driven Interactions Congress 2024 (EUVXRAY, HILAS, MICS)© Optica 2024

Gamma/X-Ray Refractive Index of Materials Near Nuclear Resonances and Simulated Experiments Using Laser-Compton Sources

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Abstract: Nuclear resonance fluorescence is the process by which atomic nuclei absorb and emit radiation. Around these resonances, the refractive index changes according to the Kramers-Kronig relations. We discuss how to measure such physics using laser-Compton sources.

1. Nuclear Resonance Fluorescence

Nuclear resonance absorption/fluorescence (NRA/F) is the process by which an atomic nucleus absorbs/emits electromagnetic radiation [1]. The energy of NRF happens in the hard x-ray to gamma ray regime (478 keV for the first excited state of ^{7}Li). Since the resonant motion of the nucleus is dependent on the nucleon constituents, the energy levels are specific to the isotope. For that reason, NRF has been proposed to be used for a number of applications that require isotope identification/assays [2,3]. Some examples of which include nuclear security, organic pharmaceutical purity measurements, and isotopic quantification assays.

The absorption cross section for nuclear transitions is exceedingly narrow. As such, their linewidth is significantly determined by broadening due to thermal motion. Even after Doppler broadening, their linewidths are as narrow as 10^{-6} ΔE/E full width at half maximum (FWHM). For an unpolarized source incident on a Doppler-broadened ($\Delta \gg \Gamma$) unpolarized target without branching ratio, the absorption cross section, σ, approaches a Gaussian form [1],

$$\sigma(E) = \frac{\pi^{3/2} g \bar{\lambda}^2 \Gamma}{\Delta} e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$

Here, E_r is the resonance energy, $g = (2J_1 + 1)/(2J_0 + 1)$ is the degeneracy of the states where J_0 and J_1 are respectively the angular momentum of the ground and excited states, Γ is the resonance linewidth, $\bar{\lambda}$ is the reduced wavelength, and $\Delta = E_r\sqrt{2k_BT/Mc^2}$ is the Doppler width where T is the temperature, k_B is Boltzmann's constant, c is the speed of light, and finally M is the mass of the isotope. Figure 1 shows the absorption cross section profile for ^{7}Li.

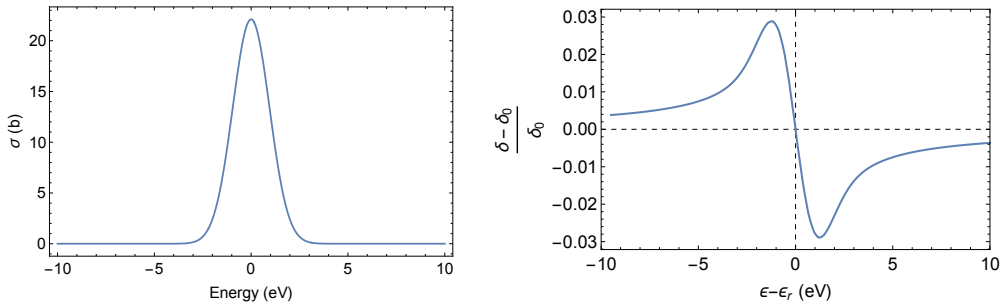

Fig. 1. (left) Doppler-broadened NRF cross section for ^{7}Li. (right) Net change in refractive index around the nuclear resonant line.

2. Refractive Index Around Nuclear Resonant Transitions

Absorption can be described as the imaginary component of the index of refraction ($n = 1 - \delta - i\beta$). According to the Kramers-Kronig relations that describe how the real and imaginary parts are related to each other, as long as the scattering cross section is smooth, so will be the refractive index. Near an NRF energy, however, there is a large resonant change in the imaginary component. This will change the real part of the index of refraction according to

$$\delta(E) = \frac{2}{\pi}\mathcal{P}\int_0^\infty \frac{E'\beta(E')}{E'^2 - E^2}d\omega' = \delta_0 + \frac{N\hbar c}{\pi}\mathcal{P}\int_0^\infty \frac{\sigma(E')}{E'^2 - E^2}dE'$$

Here, δ_0 is the refractive index without a resonance and N is the number density of the isotope. Solving this formula results in the expected oscillation around the resonance energy. An example of this calculation for ^{7}Li is shown in Figure 1. The total peak-to-peak magnitude of this change for ^{7}Li is approximately 6% of the baseline refractive index. For other materials, like enriched ^{154}Gd, this change can be as large as 60%. In general, the magnitude of change of real part of the refractive index will be directly related to the oscillation strength of the resonance absorption. However, there is a competing inverse relationship with energy, which is why oscillations at gamma ray energies are not as high as in the optical regime. Such phenomena have been described in the past as "anomalous dispersion", though in the x- and gamma ray regime, the index of refraction is well known to decrease with light frequency.

3. Laser-Compton Computational Experiments and Results

Since nuclear resonant transitions are extremely narrow, if one would like to measure the change in index of refraction around an NRF line, then a narrow bandwidth and high brilliance source is required. Moreover, since the refractive index is very close to one ($\delta \sim 10^{-8}$), the deviation of high energy photons is also small. This further requires a well collimated source with a small spot. All these requirements are satisfied with state-of-the-art laser-Compton sources (LCSs) [4,5].

Simulated experiments using a bandwidth filtered LCS are shown in Figure 2. A plastic 75-micron sphere was used as the test object. The LCS photons will refract away from the normal vector to the sphere surface resulting in edge enhancement. The amount of edge enhancement will be determined by the refractive index. To maximize this difference in refractive index to achieve a measurement with the best possible signal-to-noise, the LCS was tuned to the peak of the refractive index. This was then compared to another simulation that was placed on the minimum of the refractive index. Figure 2 shows the results of these simulations and the measurable difference between the two energies. Utilizing a Fourier phase reconstruction algorithm on the subtracted image demonstrates the possibility of contrast enhanced phase imaging.

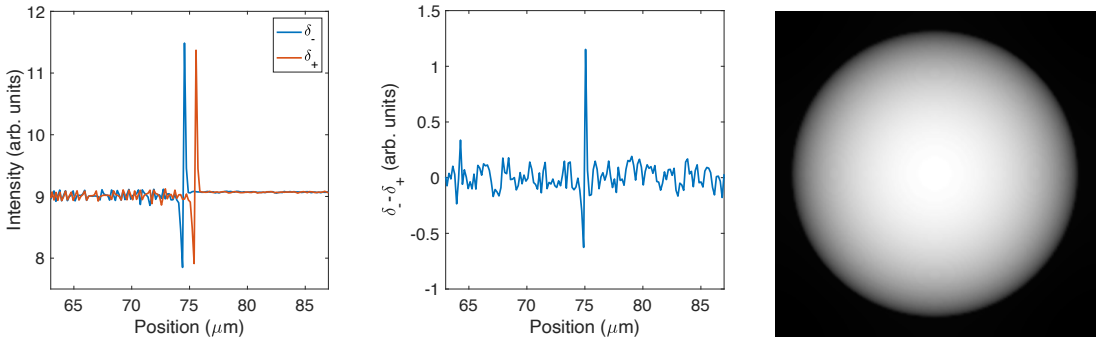

Fig. 2. (left) Central lineout of sphere demonstrating difference in edge enhancement between the two energy tunings. Curves are shifted in x relative to each other for clarity. (middle) The difference of the two curves on the left yield a measurable difference in the signal at the edge of the sphere. (right) Fourier reconstruction on difference image.

4. References

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