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Optical method for observing the hidden population inversion of nuclear states (possible experimental scheme)

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***Abstract*. The possibility of observation of the hidden nuclear inversion below the lasing threshold from a change in the optical spectra of atoms containing the nuclei is considered.**

Keywords: *hidden population inversion, nuclear states.*

The hidden population inversion in free nuclei, which consists in the relative shift of the energies of nuclear transitions with emission or absorption of gamma quanta and in their additional Doppler shift, underlines the concept of a gamma laser, whose action does not require an excess of the number of excited nuclei over the number of unexcited nuclei and is based on the nuclear recoil upon radiative transitions (see, for example, [1]). Therefore, although this effect is theoretically obvious, the observation of both its components even below the lasing threshold in the absence of amplification of the gamma-photon flux would play a crucial role in the progress towards a full-scale gamma-laser experiment. Note that the first component, the shift of the transition energy, was reliably detected many times by the methods of gamma spectroscopy, whereas it seems that the second component – the Doppler shift has not been experimentally observed.

The possibility of indirect detection of the hidden nuclear inversion is based on the fact that the Doppler shift of nuclear transitions, which indicates to the appearance of hidden nuclear inversion, is accompanied by the corresponding shift of the transition frequencies of atoms containing the nuclei. Following in detail the basic results obtained in paper [2], we can claim that the observation and reliable measurement of this frequency shift by purely optical methods would be a conclusive confirmation of the appearance of hidden population inversion in free nuclei. An advantage of such an experiment with the reduced incoherent X-ray pump energy below the lasing threshold is that its accomplishment does not require a 'hot' laboratory.

Consider a nuclear medium consisting of free atoms containing nuclei, which are cooled down to a sufficiently low temperature T, for example, by known methods of laser cooling. The velocity distribution of the atoms exhibits a narrow peak at a common transfer velocity v_0 with the root-mean-square random velocity (in metres per second)

$$\bar{v} \approx 150\left(\frac{T}{A}\right)^{1/2}, \tag{1}$$

where A is the isotopic number and T is temperature in kelvins (in particular, $v_0 = 0$). The nuclei are excited by a weakly divergent incoherent X-ray beam propagating along the z axis.

It is known that any radiative gamma transition with the energy E_0 (in kiloelectronvolts) in a free nucleus is accompanied by transfer of the recoil kinetic energy (in millielectronvolts)

$$E_{\mathrm{rec}} \approx 0.53\frac{E_0^2}{A} \tag{2}$$

to the nucleus and by the increase

$$\Delta v_z \approx 300\frac{E_0}{A}. \tag{3}$$

in the nucleus velocity (in metres per second), which is collinear to the wave vector of a gamma quantum.

Due to excitation of the nuclei, the second peak appears at the velocity $v_0 + \Delta v_z$ in the distribution of the atoms over the component of the velocity. These two peaks can be reliably resolved if the ratio of concentrations of excited (n_2) and unexcited (n_1) nuclei exceeds a critical value:

$$\frac{n_2}{n_1} > \exp\left(-6.15\frac{E_0^2}{AT}\right). \tag{4}$$

Inequality (4) means that the wing of a Maxwell distribution of atoms with unexcited nuclei does not overlap the maximum of the second velocity peak of atoms with excited nuclei. This inequality is valid if the ratio β of the natural linewidth to the Doppler linewidth is small ($\beta < 1$). If, however, $\beta \to 1$, then the natural Lorentzian linewidth $\Gamma_{\gamma\alpha}$ should be also taken into account, and we have

$$\frac{n_2}{n_1} > 0.22\left(\frac{A\Gamma_{\gamma\alpha}}{E_0^2}\right)^2, \tag{5}$$

where $\Gamma_{\gamma\alpha}$ is in millielectronvolts. However, because we consider a state of a nuclear medium below the lasing threshold, when there is no need to obtain the condition

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$\beta \to 1$, which provides the maximum amplification of the gamma-quantum flux, we can use the criterion (4).

Moreover, neither inequality (4) nor (5) impose in fact any experimental restrictions since the ratio n_2/n_1 of concentrations cannot be chosen so low as admitted by these inequalities because the number of atoms with excited nuclei should be sufficient for their reliable detection. A simpler and more obvious condition of a reliable resolution of the two peaks in the velocity distribution of atoms is the inequality

$$\Delta v_z \gg \bar{v} \tag{6}$$

between the velocity increase (3) and the mean random velocity (1) of an atomic ensemble. This gives the condition for the ensemble temperature (in kelvins)

$$\sqrt{T} \ll 2\frac{E_0}{\sqrt{A}}. \tag{7}$$

Thus, the observation and reliable resolution of the second peak in the velocity distribution of atoms, which appears after absorption of an X-ray quantum by nuclei, is an experimental confirmation of the presence of hidden nuclear population inversion, which can be achieved even when $n_2 < n_1$.

The second peak can be observed in the velocity distribution of atoms containing nuclei by purely optical methods because (along with the shift of the nuclear-transition energy) the frequencies of optical transitions in the atoms observed along the z axis are also shifted by

$$\Delta\nu_{\text{opt}} = \pm\frac{\Delta v_z}{\psi}\nu_{\text{opt}} \tag{8}$$

(where ν_{opt} is the transition frequency in an atom at rest and c is the velocity of light) due to a linear Doppler effect. Leaving aside the methods of sub-Doppler laser spectroscopy, we can claim that the above optical frequency shift $\Delta\nu_{\text{opt}}$ can be measured if

$$\Delta\nu_{\text{opt}} \gg \Delta\nu_T \equiv 7 \times 10^{-7}\nu_{\text{opt}}\left(\frac{T}{A}\right)^{1/2}, \tag{9}$$

where $\Delta\nu_T$ is the Doppler width of an optical line of atoms. Taking into account (8), this imposes the restriction on the temperature of atoms:

$$\sqrt{T} \ll 1.4\frac{E_0}{\sqrt{A}}, \tag{10}$$

which coincides in fact with (7).

The narrow peak in the velocity distribution of atoms, which appears due to excitation of nuclei, is broadening in time because of the isotropic recoil during spontaneous radiative decay of the excited states. Although in this case the nuclei are obviously no longer belong to the group of excited nuclei, their atoms still belong to a velocity group shifted by Δv_z and cannot be distinguished upon optical detection from the atoms containing excited nuclei. To minimise the undesirable broadening of the narrow peak belonging to the excited nuclei, we should restrict the time Δt of subsequent optical measurements by the interval that is small compared to the excited-state lifetime τ of nuclei:

$$\Delta t \ll \tau. \tag{11}$$

The same reasoning imposes the restriction on the time Δt_{x} of incoherent pulsed X-ray excitation of nuclei:

$$\Delta t_{\text{x}} \ll \tau. \tag{12}$$

In the case of pulsed excitation, the achievable ratio of concentrations of excited and unexcited nuclei is

$$\frac{n_2}{n_1} \approx \lambda^2\frac{2J_2+1}{2J_1+1}j_{\text{x}}\frac{\Delta t_{\text{x}}}{\tau}. \tag{13}$$

Here, λ is the resonance wavelength of a nuclear transition; J_2 and J_1 are the angular momenta of the upper and lower nuclear states; and j_{x} is the spectral brightness of an incoherent X-ray source. One can see that the latter should be comparatively high. For example, for obtaining $n_2/n_1 \approx 10^{-9}$ for $\lambda = 10^{-8}$ cm, and $\Delta t_{\text{x}}/\tau = 0.2$, we should have $j_{\text{x}} \approx 10^8$ photon cm^{-2}; in this case, inequality (4) is satisfied with a large margin already at $T = 10$ mK.

Optical spectral measurements should be performed during the lifetime Δt (11) of the observable hidden inversion. Taking into account that the typical lifetime of optical luminescence is $\Delta t_{\text{lum}} \approx 10$ ns, it is reasonable to set $\Delta t \gg \Delta t_{\text{lum}}$. Because

$$\tau \gg \Delta t \gg \Delta t_{\text{lum}} \approx 10 \text{ ns}, \tag{14}$$

the desirable lifetime of an excited nuclear state can be estimated as 1 μs or even longer. Such long nuclear lifetimes are not acceptable for a gamma-laser experiment but they are quite admissible in experiments performed below the lasing threshold when there is no need to provide a very narrow emission line.

The estimates performed using the above relations show that the required optical resolution lies in the range of a few hundreds of megahertz, i.e., it corresponds to the possibilities of modern spectroscopy. However, one should take into account that luminescence should be measured in experiments only within a small solid angle around the z axis because the Doppler shift should be detected in this direction. This means that the intensity of the measured photon flux can be certainly very low.

A more efficient approach involves excitation of atoms by a beam from a tunable optical laser, which is directed along the z axis, and detection of the isotropic 4π luminescence with photodetectors surrounding the nuclear medium. A tunable laser with the emission linewidth that is narrow compared to $\Delta\nu_T$ serves in fact as a spectrum analyser.

Finally, we present an example, which is not claimed to be optimal. Consider the $^{179}_{73}$Ta isotope with $E_0 = 30.7$ keV, $\tau = 1.42$ μs, the internal electron conversion coefficient equal to 4.6, the transition multipolarity E1, E_{rec}=2.8 meV, and $\Delta v_z = 50$ m s^{-1}. By assuming that $T = 10$ mK, we have $\Delta v_z \gg \bar{v} = 1.1$ m s^{-1}, and inequality (7) is satisfied with a large margin. Then, we can set $\Delta t = \Delta t_{\text{x}} = 150$ ns $\ll \tau =$ 1420 ns, and we will have $n_2/n_1 = 10^{-11}$ for $j_{\text{x}} = 10^7$ cm^{-2} and $|\Delta\nu_{\text{opt}}| \approx 50$ MHz, which exceeds $\Delta\nu_T$ by a factor of 32. Assuming that the detection sensitivity is of about 100 atoms cm^{-3}, we obtain that the above concentration ratio corresponds to the initial atomic concentration equal to 10^{13} cm^{-3}.

Thus, it seems that the optical method of observation of the hidden nuclear inversion can be successfully realised experimentally.

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