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QUANTUM NUCLEONICS

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Quantum nucleonics: Status and prospects

L.A. Rivlin

Abstract. **It is pointed out that the use of long-lived nuclear isomers in modern quantum nucleonics is impeded by a large broadening of the gamma line of metastable nuclear states, which exceeds many times their natural radiative width. This broadening can be eliminated if atoms containing nuclei form a Bose – Einstein condensate.**

Keywords: *metastable states, Bose – Einstein condensate*.

1. Introduction

'Decay of Radium is a spontaneous event if the Radium atom is an isolated system. However, this decay can be stimulated by the gamma-radiation field identical in frequency to the gamma-rays emitted in the decay of Radium; the magnitude of this effect can be calculated by the Einstein formulae'.

This statement made by Arthur Eddington [1] a few decades before the harnessing of nuclear energy and the advent of lasers can be considered as the conceptual anticipation of quantum nucleonics – a modern field of science allowing one to extend the concepts and methods of optical quantum electronics from atoms to atomic nuclei, the photon energy being increased by four and more orders of magnitude. The essence of quantum nucleonics is that it uses radiative gamma transitions as an active factor for studying nuclear processes. The most developed directions in quantum nucleonics are the studies of stimulated emission of gamma quanta by nuclei (the development of different concepts of a nuclear gamma laser), controlled decay of the metastable states of nuclear isomers, etc. Note that the term quantum nucleonics was finally accepted in the scientific literature and international conferences beginning from 1995 [2], although the first conceptual proposals in this field were already made in 1961 – 1963 (Refs [3 – 6] and other references).

The aim of this paper is not to review in detail all the studies devoted to quantum nucleonics but to analyse briefly the main trends in these studies and the most general bottlenecks requiring the solution.

2. Stimulated emission of gamma quanta by nuclei (nuclear gamma laser)

As mentioned above, the principal possibility of stimulated emission of gamma quanta by nuclei follows directly from the general Einstein radiation laws. Therefore, although the observation of individual spontaneous radiation events detected by photon counting would be a spectacular experiment, it is unlikely that this experiment would allowed us to approach the construction of a scheme providing an increase in the flux of gamma quanta in a medium with excited nuclei. It is this problem that should be solved to create a nuclear gamma laser. It is known that the operation of this laser is determined by the gain of the photon flux

$$g = \sigma\left[n_2 - n_1\frac{2J_2+1}{2J_1+1}\right] - \chi n, \tag{1}$$

where n_2 and n_1 are the volume concentrations of radiators in the upper and lower states of the transition; J_2 and J_1 are their angular moments; $n \geqslant n_2 + n_1 + n_0$ is the total concentration of atoms, including the concentration n_0 of possible inactive impurities, for example, atoms of a crystal matrix; χ is the averaged total cross section for photon losses of all types;

$$\sigma = \frac{\lambda^2}{2\pi}\frac{1}{\Delta\omega_{\text{tot}}\tau_\gamma} \tag{2}$$

is the stimulated emission cross section depending on the emission wavelength λ, the radiative lifetime τ_γ of the excited state, and the total spectral linewidth $\Delta\omega_{\text{tot}}$ of the transition taking all the types of broadening into account. Under normal conditions, the cross section σ is very small due to a great value of $\Delta\omega_{\text{tot}}$.

Note, however, that in the limiting case of the absence of any additional types of spectral line broadening, except the uncertainty relation

$$\hbar\Delta\omega_\gamma\tau_\gamma \geqslant \hbar, \tag{3}$$

when

$$\Delta\omega_{\text{tot}} = \Delta\omega_\gamma, \tag{4}$$

the second factor in (2) turns to unity, and the stimulated emission cross section increases up to its maximum value

$$\sigma = \frac{\lambda^2}{2\pi}. \tag{5}$$

L.A. Rivlin Moscow State Institute of Radio Engineering, Electronics, and Automatics (Technical University), Laboratory of Applied Physics, prosp. Vernadskogo 78, 119454 Moscow, Russia;
e-mail: rivlin140322@mccinet.ru

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Therefore, the paramount problem is to increase σ by eliminating the possible sources of line broadening leading to an increase in the parameter

$$\beta \equiv \frac{\Delta\omega_{\gamma}}{\Delta\omega_{\text{tot}}} < \frac{1}{1+\alpha}, \tag{6}$$

entering the expression

$$\sigma = \frac{\lambda^2}{2\pi}\beta \tag{7}$$

(α is the internal electron conversion coefficient).

The problem of providing the conditions at which $\beta \to 1$ is solved differently in the most popular schemes:

(1) In the standard Mössbauer scheme with active nuclei embedded into a cooled crystal matrix (Refs [3–7] and other papers), it is proposed to use the zero-phonon transition with the natural width.

(2) The scheme based on the inversionless gain [8] also assumes the use of the zero-phonon transition in nuclei embedded into a cooled crystal matrix.

(3) The scheme with a nuclear medium represented by an ensemble of strongly cooled free atoms [9] assumes the elimination of the Doppler broadening of the line by preparing a monokinetic atomic ensemble using the known methods for laser manipulation of neutral atoms (see, for example, Ref. [10]).

Each of the above schemes has its own positive and negative features.

The use of the zero-phonon line with the natural width in standard Mössbauer scheme 1 is attractive due to the possibility of producing rather high concentrations of active nuclei in a solid; however, to achieve the threshold gain $g > 0$, the high degree of inversion is required:

$$\frac{n_2}{n_2+n_1} > \frac{Y+(\chi/\sigma)(1-n_0/n)^{-1}}{Y+1} \approx (1+Y^{-1})^{-1}. \tag{8}$$

This is caused by the fact that the emission and absorption lines are resonant with each other and also by the presence of inactive atoms of the matrix, resulting in the dependence on the multipolarity parameter

$$Y = \frac{2J_2+1}{2J_1+1}. \tag{9}$$

For $\beta \to 1$, usually $\chi/\sigma \ll 1$ (typically, $\sigma \approx 10^{-17}$ cm^2 and $\chi \approx 10^{-20}$ cm^2), and if the relative content of an inactive impurity is low, then the approximate equality is valid in (8). The tendency $\beta \to 1$ is bounded above by the excited-state lifetime (of the order of 10 μs), which determines the minimum achievable width of the zero-phonon line, so that the limiting narrowing δ of the zero-phonon line achieved in practice is of the order of $10^{-13} - 10^{-14}$. In addition, it seems that this approach does allow the use of the required pump intensities due to absorption of light in a matrix resulting in its heating and degradation, thereby violating the Mössbauer conditions.

Scheme 2 with the inversionless gain also uses the Mössbauer zero-phonon line. Therefore, this scheme has the same pluses and minuses as scheme 1, except strict requirement (8), which is replaced by a substantially milder condition

$$\frac{n_2}{n} > \frac{\chi}{\sigma}. \tag{10}$$

This scheme also does not contain an explicit dependence on the multipolarity parameter (9) because due to the quantum interference of the states (on which the inversionless gain is based), the population n_1 of the lower level of the transition is not involved in the photon absorption process. Estimates of the threshold value of $n_2/(n_2+n_1)$ by expression (8) can exceed estimates by expression (10) by a few orders of magnitude.

Elimination of the Doppler line broadening by deep cooling of ensembles of free nuclei by the methods of laser manipulation of neutral atoms in scheme 3 automatically leads to the so-called hidden inversion due to the mutual spectral shift of the emission and absorption lines of nuclei undergoing the recoil during radiative transitions. As in scheme 2, this reduces the requirement to the desired degree of inversion $n_2/(n_2+n_1)$ to condition (10) and removes the dependence of g on the parameter Y (9). However, scheme 3 imposes noticeable restrictions on the achievable total volume concentration of active nuclei. The value of the limiting relative narrowing of the line depends on the temperature T of the medium with atoms containing nuclei:

$$\delta = \left(8\ln 2\frac{kT}{Mc^2}\right)^{1/2} \approx 7\times10^{-10}\left(\frac{T}{A}\right)^{1/2}, \tag{11}$$

where k is the Boltzmann constant; M is the atom mass; c is the speed of light; A is the isotopic number of a nucleus; and the temperature T is in microkelvins. For example, for $A = 100$ and $T = 0.01$ μK, the parameter $\delta \approx 7\times10^{-12}$.

Therefore, the advantages of the hidden-inversion and inversionless schemes (schemes 3 and 2, respectively) over standard Mössbauer scheme (1) are first of all that the first term in expression (1) for the gain g for schemes 3 and 2 does not contain the resonance-absorption component, which removes the dependence of g on the multipolarity parameter Y and can appreciably reduce the requirements to the inversion degree $n_2/(n_2+n_1)$ needed to achieve the positive gain $g > 0$.

3. Preparation of a medium with excited nuclei (pumping)

The relatively low degree of inversion $n_2/(n_2+n_1) \approx 10^{-3}$ at which the threshold $g > 0$ is achieved in schemes 2 and 3 should not suggest the unjustified optimism because the absolute volume concentration of excited nuclei required for achieving the values of g providing an appreciable amplification of the photon flux proves to be rather high. For example, even for $\beta \to 1$ and $\sigma = 10^{-17}$ cm^2, to obtain $g = 0.1$ cm^{-1}, the concentration should be $n_2 = 10^{16}$ cm^{-3}. Such high absolute concentrations of excited nuclei require an extremely intense pumping of one or other type. It is for this reason that negative predictions have been made in fundamental paper [11]. The authors of this paper indicated the UV boundary for the frequency range of lasers, which is determined by a drastic increase in the spontaneous radiation energy with increasing frequency (proportionally to its fourth power) resulting in an extremely short lifetime of excited states, which prevents the achievement of the level population inversion.

However, the groundlessness of this statement as applied to atomic nuclei, among which isomers are known with lifetimes of excited metastable states of the order of hundreds and event thousands of years, was pointed out already in Refs [3, 7]. Therefore, the problem is to make a choice between the realisation of an extremely intense but nondestructive pumping of nuclei with rapidly relaxing excited states (it is this choice that has been made in the three schemes considered above, where nuclei with long-lived states cannot be employed for different reasons) and the use of long-lived isomers, which possibly do not required pumping at all, but are absolutely unsuitable for the realisation of the condition $\beta \rightarrow 1$ by the methods used in schemes 1, 2, and 3. The authors of comprehensive analytic reviews [12–14], where numerous sophisticated pumping schemes employing incoherent X-rays, neutron fluxes, etc. had been considered, concluded that the advance in the first direction offers no promise, while in Ref. [14] the insolubility of the so-called 'gamma-laser dilemma' was pointed out due directly to incompatibility of the intense pumping with other conditions required for the laser operation.

It seems that the most adequate attempt to take into account the features of this dilemma is made in scheme 3. This scheme does not contain a solid matrix degrading upon pumping, and pumping is performed by incoherent X-rays with an extremely high spectral brightness (in particular, generated by modern, most perfect sources of relativistic electrons) using a two-level scheme [9], in which the usual additional third level is not required due to the above-mentioned spectral shift between the emission and absorption gamma lines caused by the recoil of nuclei. Nevertheless, estimates [9] show that the spectral brightness of radiation of the stimulated nuclear process (which can be considered in fact as stimulated backward scattering of pump photons) is lower than that of the pump radiation and the conversion efficiency proves to be extremely low. Therefore, although the observation of stimulated nuclear gamma radiation in scheme 3 would be quite possible and interesting physical experiment, its pragmatic value is disputable.

Therefore, the possibility of using nuclear isomers, which eliminates the necessity of solving the gamma-laser dilemma and, which is more important, opens up the way for a direct use of the nuclear energy of long-lived metastable states, becomes especially attractive.

4. Controllable release of the nuclear isomer energy

There exist many long-lived nuclear isomers, both natural and artificial, with the specific energy content of excited metastable states exceeding tenths of megajoules per gram. The relative width δ of metastable states is extremely small: thus, for a state energy of 100 keV and $\tau_\gamma = 1$ h, it is $\sim 10^{-17}$. Numerous attempts to achieve a controllable decay of this states accompanied by the isomer energy release, beginning from papers [15, 16] (see also comprehensive references in Refs [17, 18]), have been mainly based on the use of the anti-Stokes (trigger) transition bypassing a strongly forbidden direct transition from the metastable state to a lower state. This process consists of two stages: a transition from the metastable level to an upper level with the absorption of the corresponding energy (usually, the energy of a soft X-ray photon) from an external source and a spontaneous transition to a lower level with the energy gain equal to the metastable-state energy.

If a part of the energy released in this way could be used to repeat such trigger transitions in new isomer nuclei, for example, by using the resonance part of the emission spectrum of a hot plasma, which is in turn heated by absorbing the released isomer energy, then, in the case of a positive energy balance of such a cycle, a self-sustained chain reaction of radiative transitions in metastable nuclei can appear [19, 20].

The existence of a long-lived metastable state of an isomer nucleus is usually caused by a great difference between the angular momenta of the metastable and lower (in particular, the ground) states and, therefore, by a high multipolarity of the radiative transition. This complicates the direct use of the trigger transition in the gamma-laser problem due to the obvious contradiction. Indeed, to solve this problem, the successive transitions at both stages should be sufficiently rapid, i.e., the difference of the angular momenta for these transitions should be small, but at the same time their sum should be equal to a great difference of the angular momenta for the forbidden direct transition from the metastable state.

Finally, leaving aside the bypass trigger manoeuvre, it is a great difference between the angular momenta and a high multipolarity of long-lived isomers that are usually considered as main obstacles to the direct transition from a metastable state to a lower state and the observation of the stimulated radiative processes at this strongly forbidden transition.

5. Effect of the atomic degrees of freedom on the gamma-line width

To elucidate the essence of the problem, recall that the relation between the Einstein coefficients for spontaneous (A_1) and stimulated ($B_{21} = B_{12}$) emission (absorption) of light at the frequency ω between levels $2 \leftrightarrow 1$

$$\hbar\omega \frac{2\omega^2}{\pi c^3} B_{21} = A_{21} = \frac{1}{\tau_\gamma} \tag{12}$$

is valid, due to the generality of the thermodynamic approach, for transitions of any types between the quantum states $2 \leftrightarrow 1$ radiators, irrespective of the multipolarity and the value of the transition matrix element. In fact, the effect of the matrix element and multipolarity on the probability of the $2 \leftrightarrow 1$ transition is completely determined by the value of the coefficient $A_{21} = \tau_\gamma^{-1}$, i.e., the inverse lifetime τ_γ of the upper state related to the spontaneous radiative transition. The value of τ_γ can be extremely large for high-multipolarity transitions.

Let us emphasise now that the stimulated emission cross section (2)

$$\sigma = \hbar\omega \frac{4B_{21}}{c\Delta\omega_{\text{tot}}} = \frac{A_{21}}{2\pi} \frac{\lambda^2}{\Delta\omega_{\text{tot}}} = \frac{\lambda^2}{2\pi} \frac{1}{\Delta\omega_{\text{tot}}\tau_\gamma} \tag{13}$$

is expressed in terms of the coefficients B_{21} and A_{21} and, hence, it follows from the same general thermodynamic considerations. Therefore, it is valid for transitions of any multipolarity with any values of matrix elements and any product $\Delta\omega_{\text{tot}}\tau_\gamma$. In this case, the probability of the spontaneous radiative transition remains invariable,

$A_{21} = \tau_\gamma^{-1}$, and it can be negligibly small for high-multipolarity transitions.

Therefore, returning to the analysis of elimination of all possible sources of the line broadening, note that the formulation of this problem is also justified for long-lived metastable states with high-multipolarity transitions. The only question is how much the ratio β can be increased and whether it is possible to approach experimentally the condition $\beta \to 1$.

The three above-mentioned schemes of a gamma laser use alternative approaches to solve the problem of the tendency $\beta \to 1$. The aim of both these approaches is in fact only the elimination of the sources of line broadening, which is restricted by various factors and is related to the atomic degrees of freedom of radiators: the chaotic motion of atoms containing nuclei, the effect of the phonon spectrum of a solid, the Doppler broadening of spectral lines of free nuclei, etc. The question arises of whether there exists at least the principal possibility to eliminate efficiently all the atomic sources of the gamma line broadening, thereby including isomer nuclei with long-lived metastable states into consideration. This would be of great interest for obtaining ultra-narrow gamma lines and, especially, as the 'internal pump' replacing the external pump of a gamma laser.

6. Elimination of atomic sources of gamma-line broadening in the Bose – Einstein condensate

It seems that this problem can be solved based on recent experimental observation of the Bose – Einstein condensate of strongly cooled ensembles of Bose atoms (i.e., nuclides with an even difference between the isotopic number A and the element number) [21, 22], when all the atoms have the zero moment, the de Broglie wavelength

$$\Lambda_{\mathrm{dB}} = \frac{2\pi\hbar}{(MkT)^{1/2}} \approx \frac{4.25 \times 10^{-4}}{(AT)^{1/2}} \qquad (14)$$

of the atom becomes comparable with the interatomic distance, and the atomic wave functions are overlapped [in (14) and below, T is in microkelvins, and Λ_{dB} is in centimetres), i.e., in the case of an ideal gas, when

$$n\Lambda_{\mathrm{dB}}^3 \geqslant 2.612. \qquad (15)$$

This corresponds to cooling below the degeneracy temperature T_0 (J is the angular momentum of the atom):

$$T < T_0 = 3.3\frac{\hbar^2}{Mk}\left(\frac{n}{2J+1}\right)^{2/3}. \qquad (16)$$

Equality (16) has the numerical form (T_0 is in microkelvins)

$$AT_0 \approx 5.8 \times 10^{-7}\left(\frac{n}{2J+1}\right)^{2/3}. \qquad (17)$$

Thus, $\Lambda_{\mathrm{dB}} = 4.25$ µm and $n \geqslant 3.4 \times 10^{14}\,\mathrm{cm}^{-3}$ for $A = 100$ and $T = 0.01$ µK.

All the atoms in such a condensate are in the same lowest quantum state and, hence, all sources of the gamma-line broadening related to the properties of the atomic medium containing nuclei prove to be absolutely eliminated in an ideal gas. This allows one to hope to achieve the condition $\beta \to 1$ for long-lived isomers and to obtain extremely narrow gamma lines, as well as to find new isomers promising for the observation of the stimulated radiation of nuclei.

Of course, the degree of approximation to the condition $\beta \to 1$ remains in fact unknown at present because many problems remain to be solved. These problems include the spatial and temporal quantum coherence that can be achieved in the condensate; analysis of the possible existence of sources of line broadening related to the degrees of freedom of nuclei in the unit quantum state of many atoms; the line broadening caused by the inhomogeneous spatial distribution of atoms with excited and unexcited nuclei; the realisation of condition (15) for a sufficiently great number of atoms of a nonideal gas; competition between the development of stimulated gamma emission (if it appears) and the destruction of the condensate caused by nuclear radiative processes; and many other problems.

Candidates (by no means optimal) for initial experiments can be such nuclides as the ${}^{81\mathrm{m}}_{37}\mathrm{Rb}$ and ${}^{135\mathrm{m}}_{55}\mathrm{Cs}$ isomers with the lifetimes and transition energies equal to 30.5 min and 86.3 keV, and 53 min and 846 keV, respectively. Both these nuclides are bosons (if the data [23] on the observation of a condensate of fermion atoms forming something like Cooper pairs are confirmed, then the list of possible candidates will expand significantly).

To observe the stimulated emission of long-lived isomers in the Bose – Einstein condensate, it is necessary to provide seed photons from external resonance sources because the intrinsic spontaneous photon background is virtually absent due to a low probability $A_{21} = \tau_\gamma^{-1}$ of the spontaneous radiative transition (see above). The advances in the manufacturing of efficient X-ray Bragg mirrors with the normal reflection coefficients above 80 % [24] allow one to hope to use a standard multi-pass scheme with a Fabry – Perot interferometer.

The experimental conditions, along with the known difficulties inherent in experiments with the Bose – Einstein condensate, are rather intricate. For example, the required elongation of the Bose – Einstein condensate shape in the case of an extremely narrow gamma line imposes severe requirements to its strictly horizontal orientation excluding the gravitational shift of the lines along the sample.

7. Conclusions

Note in summary that the successful solution of problems of quantum nucleonics considered above (development of a nuclear gamma laser, control of releasing energy of nuclear isomers, including the launching of an exothermal chain reaction, etc.) is determined by two factors: the necessity of a drastic narrowing of the emission line down to $\beta \to 1$ and the necessity of using long-lived excited metastable states as the energy sources for proceeding processes. The solution of these problems would result in the direct use of the energy of isomer nuclei and completely eliminate the problem of pumping and exclude the gamma-laser dilemma. This is possible because the stimulated emission cross section is independent of the spontaneous emission probability (however low the latter could be) under the condition that all the sources of the gamma-line broadening above its natural radiative width are eliminated.

At present it seems that such a narrowing of the lines of transitions from long-lived metastable isomer states is possible in nuclei in atoms forming the Bose – Einstein condensate, in which all the sources of the gamma-line perturbation related to the atomic degrees of freedom are absent. Apart from the solution of the above-mentioned problems of quantum nucleonics, the advances in ultrahigh-resolution gamma and optical spectroscopy are also possible here.

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