On the width of γ-line and the photon structure

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Basis for additional consideration of the question about the natural width of the emission line of γ-quanta (photons) in the decay of excited states of nuclei

The suppression of low-energy EM transitions in nuclei inside metals was recently discovered [1]. It was shown that the suppression of such transitions occurs due to the suppression in the metal of zero-point oscillations of the EM field, which are resonant to the transition, and which stimulate the spontaneous emission of photons.

But as is generally known (see, for example, [2]), the natural width of the emission line is the smaller, the lower the decay rate of the excited state. Therefore, it could be expected that the width of the γ-line for emitting nuclei in a metal should decrease along with the rate of their decay.

Outline

- General points about the natural linewidth of γ-radiation.

- Reasons for the appearance of the width of the γ-line in Mössbaur experiments.

It will be shown here that the width of the γ line is determined not only by the half-life of the emitting state of the nucleus, but also by its age and the time of irradiation of the absorbing nucleus..

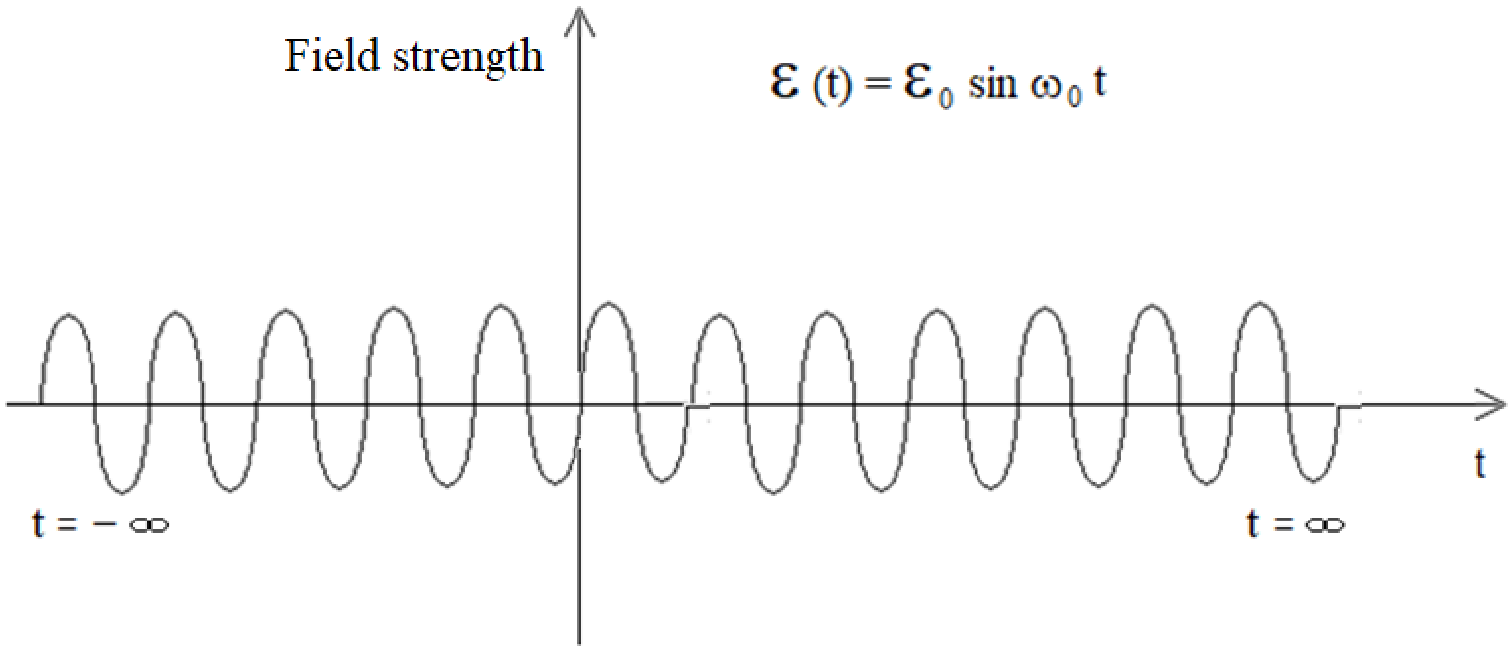
- To explain the properties of the width of the γ-line, the formulation of a hypothesis about the structure of a photon, including a new type of electromagnetic wave that does not have energy (0-wave) and an energy quantum on the “tail” of this 0-wave. This hypothesis is the central point of this work.

- On the possibility of detecting 0-waves and prospects for their practical application.

General information about the natural width of the γ-line

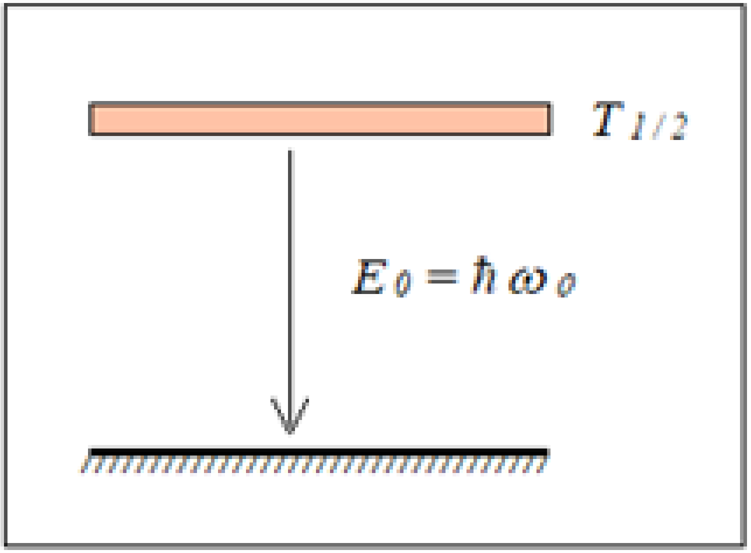
Definition of γ-quantum (photon) from the procedure of second quantization of the EM field:

- A photon is a sinusoidal wave of the EM field with a frequency ω_o that is infinite in time and is a solution of Maxwell's equation in free space.
- Just to such an infinite wave the energy of the γ-quantum $\hbar\omega_o$ is corresponded.

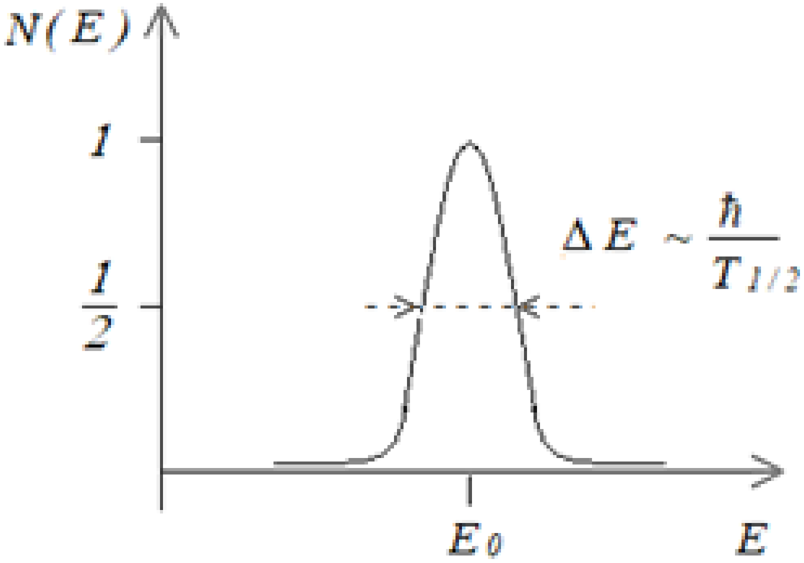


The γ-line width can be measured using the Mössbauer effect

In reality, nuclei do not emit monochromatic γ-quanta (photons). The radiation process has a finite duration in time and photons have a spread in energy ΔE, which corresponds to a spread in radiation frequency $\Delta\omega = \Delta E / \hbar$.



Nuclear transition scheme.



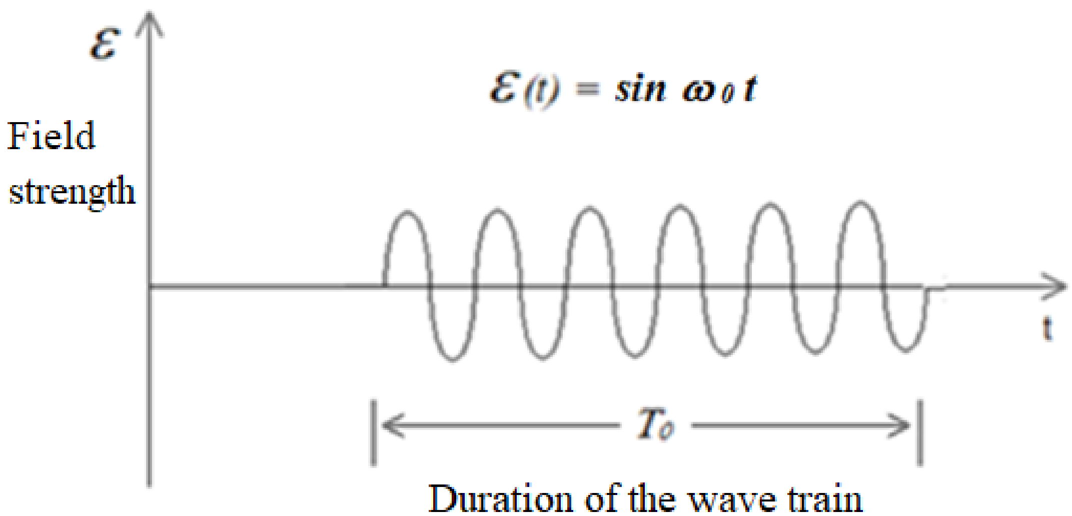
Energy distribution of photons in a conventional Mössbaur experiment.

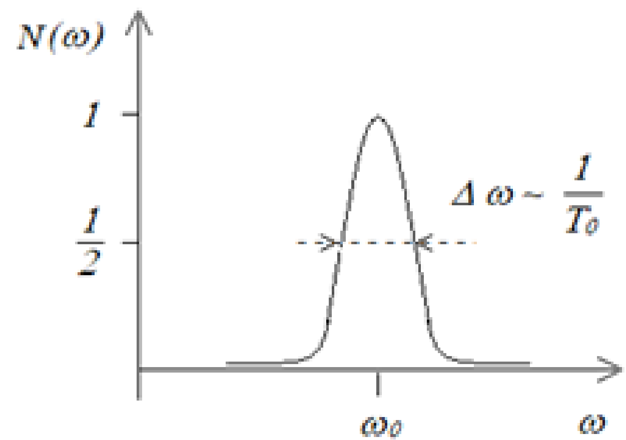
A feature of measurements is that one nucleus emits a photon, the other nucleus absorbs a photon. It's not obvious who creates the γ-width, the emitter or the absorber, or both?

Relationship between the spectral width of the EM pulse and its duration

- The relationship between the spectral width and the duration of radiation is seen from the Fourier transform of the wave fragment of the EM field strength.
- The width of the spectral distribution of photons is determined by the duration of the EM wave train.

$$N(\omega) \propto \frac{1/T_0}{\left(1/T_0\right)^2 + (\omega_0 - \omega)^2}$$

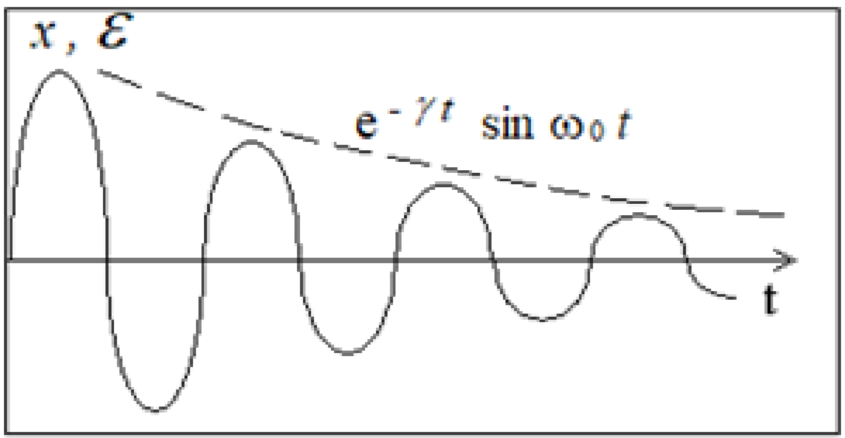


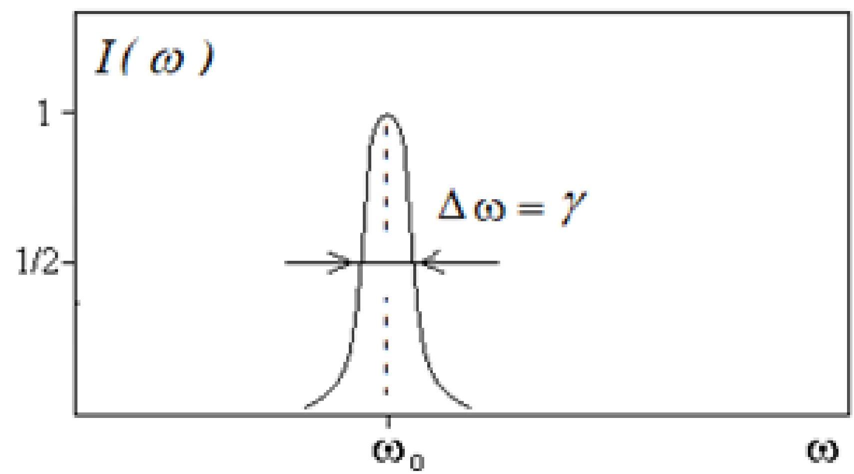


Sinusoidal train of waves and the corresponding frequency spectrum of photons.

Emission line width in classical electrodynamic

- With sinusoidal oscillations of an electric charge with a damped amplitude x, the amplitude ε of the intensity of the radiated EM field also decreases with time.
- Because of this, the distribution of the radiation intensity over frequencies acquires a width, which is determined by the decay time of the oscillation amplitude.

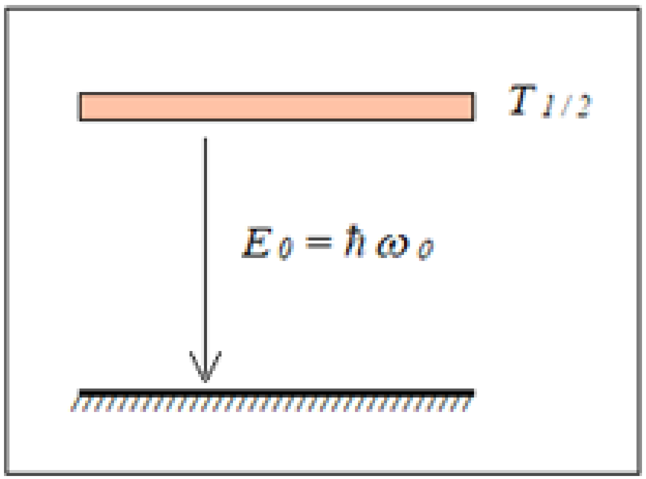


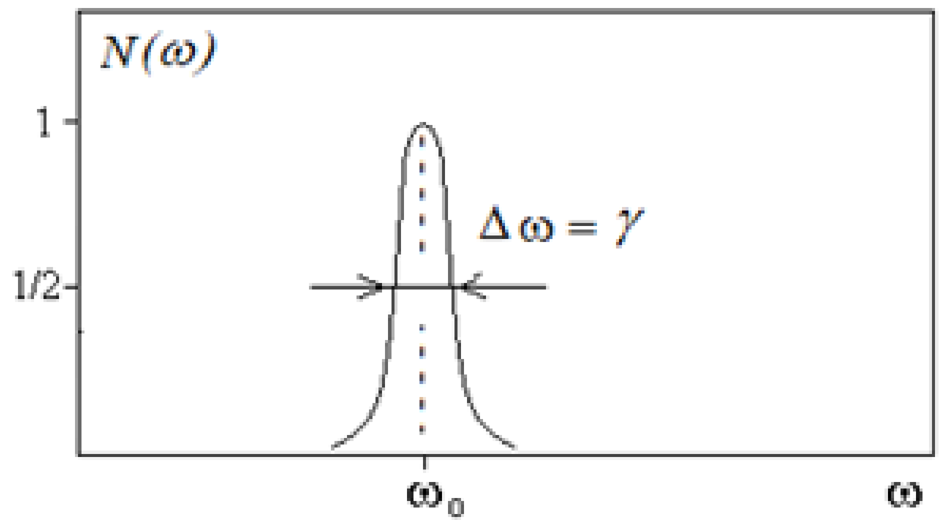


Decreasing in time the amplitude of oscillator x and the amplitude of the radiation field strength. Spectral width of radiation intensity $I(\omega)$.

Emission linewidth in quantum mechanics

Based on the nonrelativistic perturbation theory, which initially included the exponential decay of the radiating state, Weiskopf and Wigner (1930, [3]) obtained the spectral distribution of photons emitted during the decay of an excited state.





Decay constant $2\gamma = \ln 2 / T_{1/2}$

$$N(\omega) \propto \frac{1}{\left[(\omega - \omega_o)^2 + \gamma^2 \right]}$$

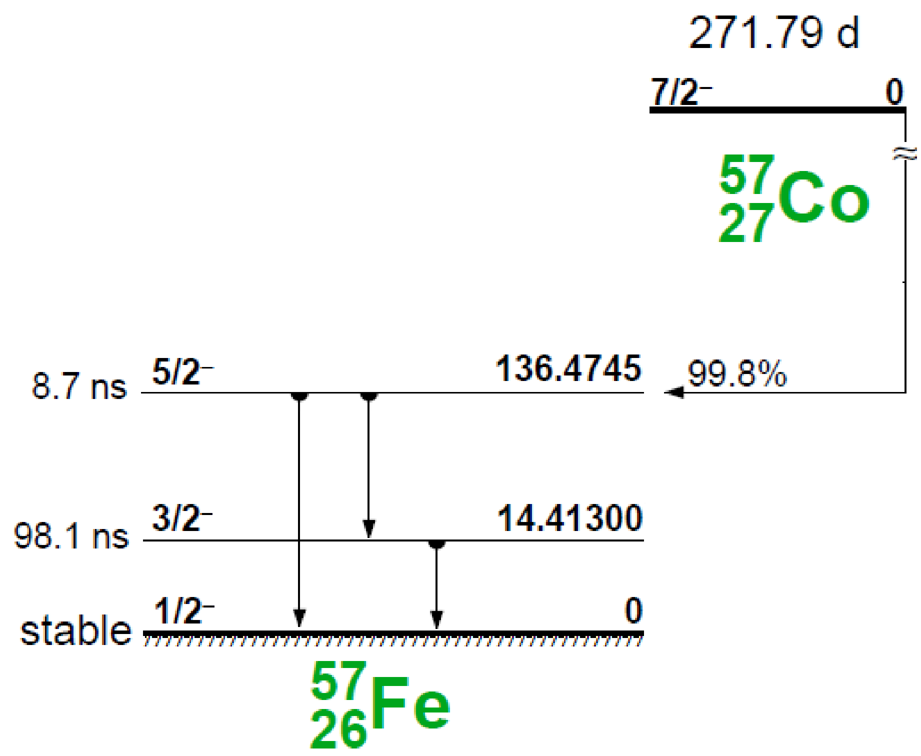
Decrease in the γ-line width with the age of the excited state

In Mössbaur experiments:

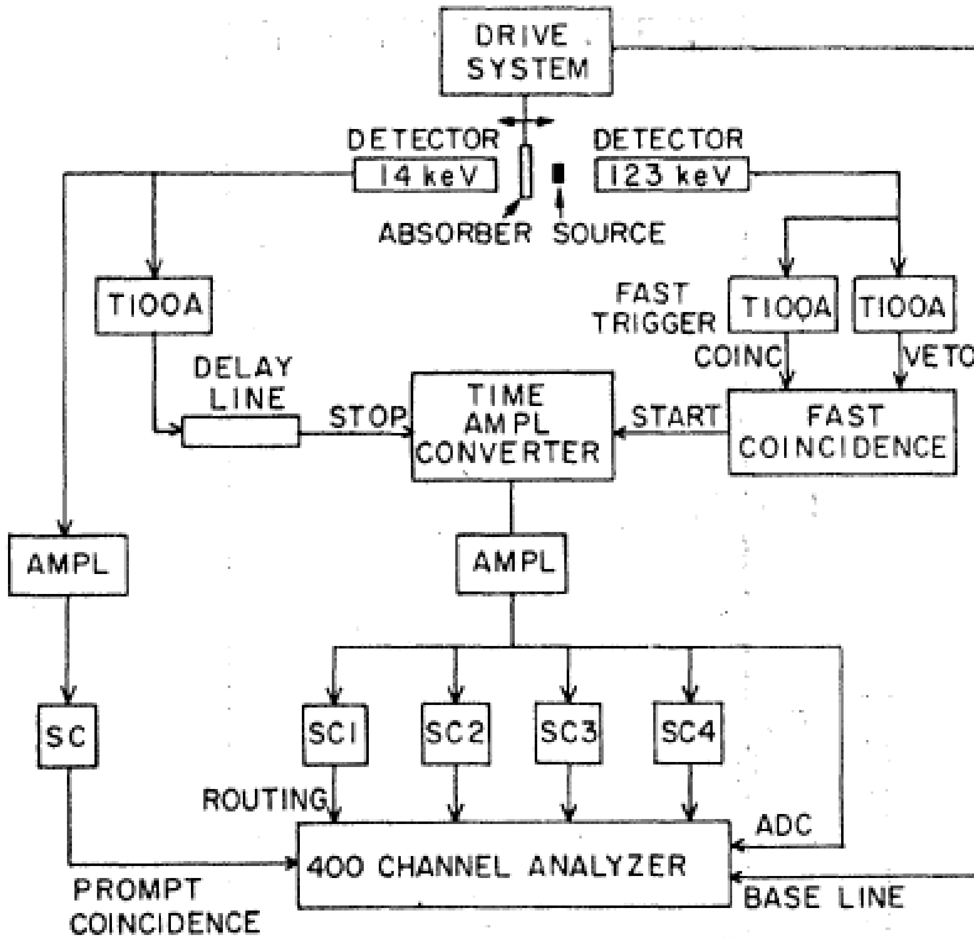
- the moment of population of the emitting level can be measured from the accompanying radiation;
- the moment of emission can be fixed by the time of detection of the γ-quantum.

So, it is possible to measure the age of the emitting level for a particular photon.

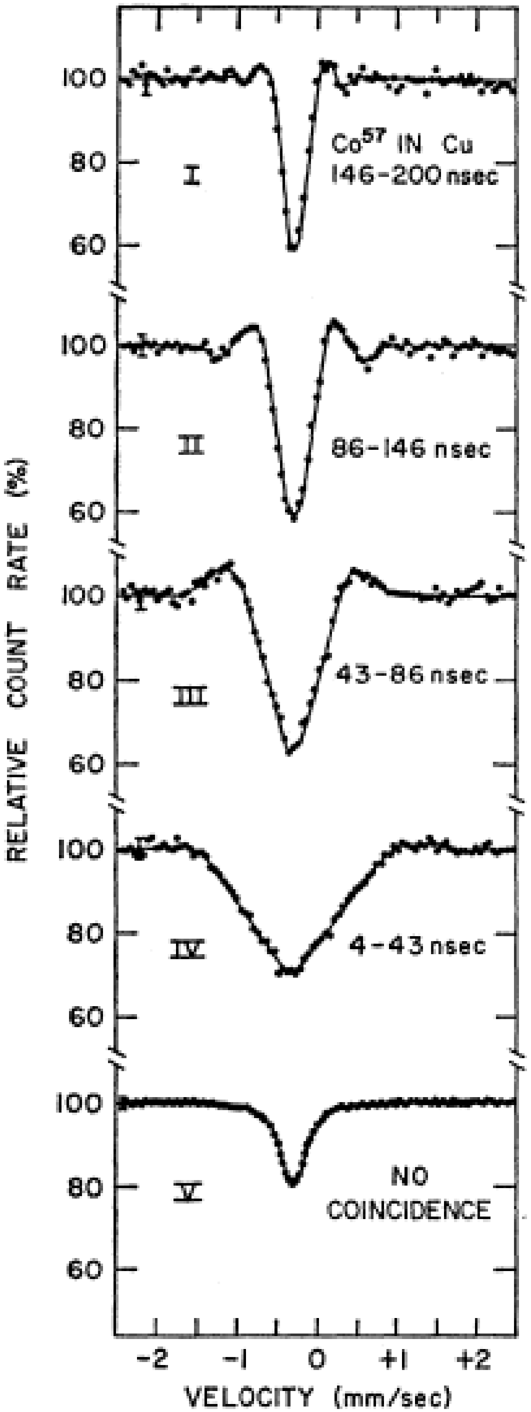
Even in early Mössbauer experiments with the ^{57m}Fe isomer, a decrease in the linewidth with increasing age of the emitting level was observed in this way (see, for example, [4]).



Scheme of the experiment with ^{57}Fe using the delayed coincidence method

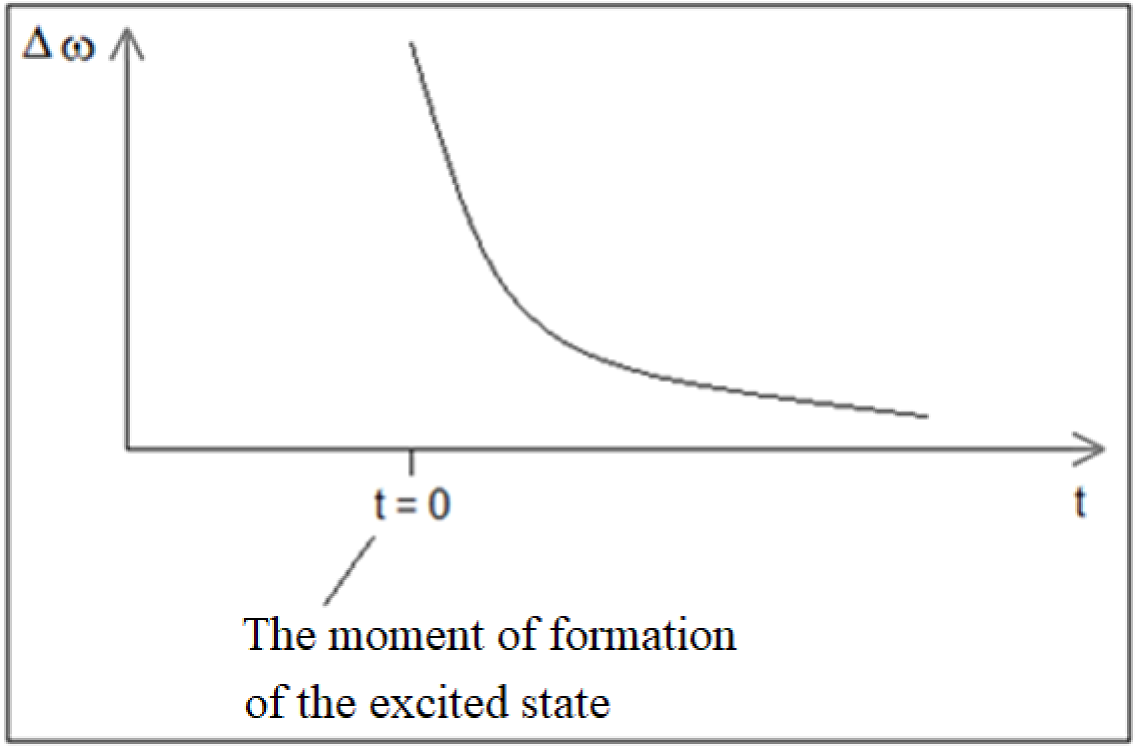


Schematic diagram of the fast-slow coincidence system used in the two-dimensional Mossbauer spectrometer [4]. The T100A units are fast discriminators, those designated AMPL are slow pulse amplifiers, and those designated SC are single channel pulse-height analyzers. Four 100-channel Mossbauer spectra can be determined simultaneously, corresponding to four delay time intervals.



Delayed coincidence Mossbauer spectra using a source of ^{57}Co in Cu-metal and an absorber of potassium ferrocyanide [4].

The time range for the age of the emitting level is indicated on the spectra.



The spectral width of 14 keV photons decreases with age of the ^{57m}Fe isomer.

Decrease in the g-line width with the age of the emitting level (Theory).

- In quantum electrodynamics, the interaction of charged particles is described by perturbation theory - the Hamiltonian of particles and EM field is divided into the Hamiltonian of free particles and field and the interaction energy operator between them.

- Then it turns out (Weiskopf and Wigner, 1930 [3, 5]) that the spontaneous emission of a photon by a system of particles is stimulated by zero point fluctuations of the EM field.

- Dependence of the matrix element of spontaneous emission of a photon of frequency ω0 on the time t of photon emission ($t = 0$ is the moment of emitting level formation):

$$S_{fi}^{(1)}(t) = \int_0^\infty d\omega A(\omega) \int_0^t dt_1\, e^{iE_2 t_1/\hbar - \gamma t}\, e^{-i\omega t_1}\, e^{-iE_1 t_1/\hbar}$$

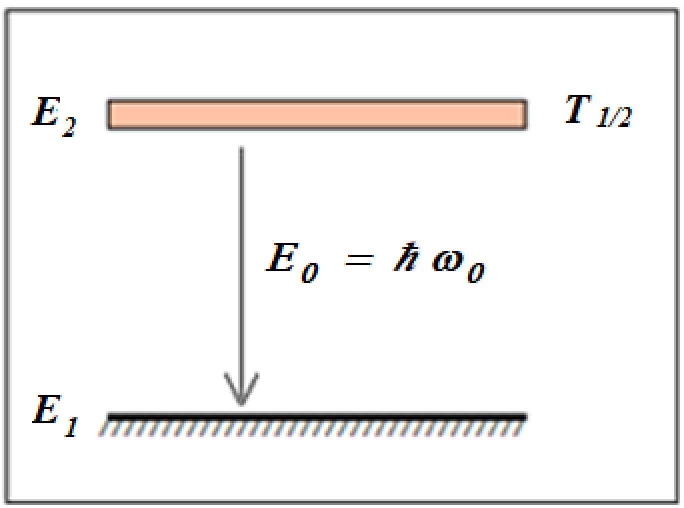
This kind of matrix element leads to the following dependence of the number of emitted photons $N(\omega, t)$ on their frequency ω and the age t of the emitting level

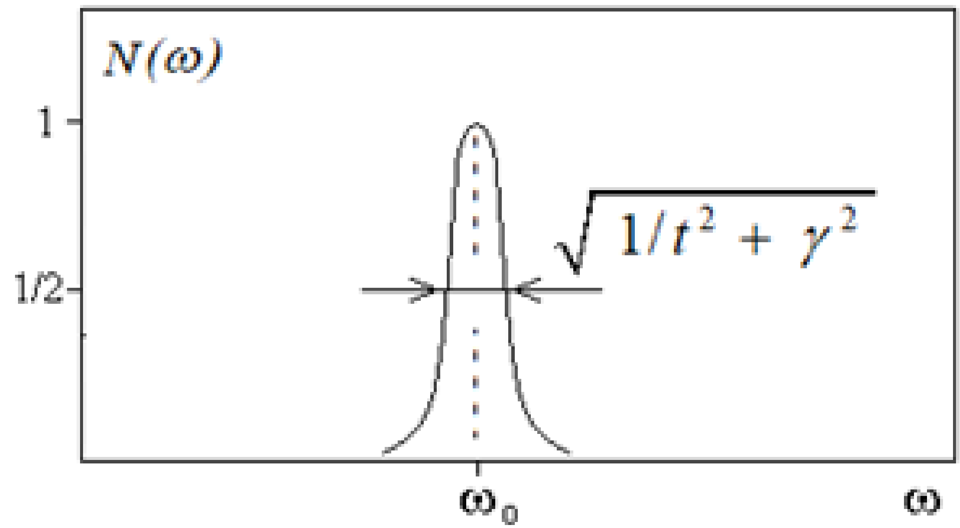
$$N(\omega, t) \propto \frac{1}{(1/t^2 + \gamma^2) + (\omega_0 - \omega)^2} \qquad \Delta\omega = \sqrt{1/t^2 + \gamma^2}$$

Frequency distribution of photons depending on the age of the emitting level

$$N(\omega, t) \propto \frac{1}{(1/t^2 + \gamma^2) + (\omega_0 - \omega)^2}$$

t is emitting level age.





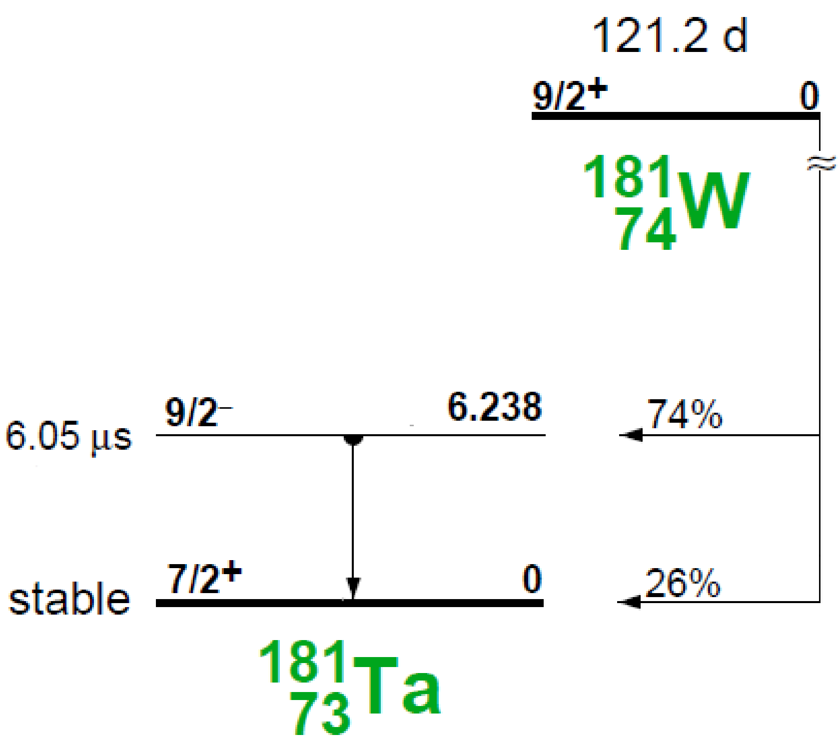
Decay constant $2\gamma = \ln 2 / T_{1/2}$

Frequency distribution of photons for the age *t* of the emitting level.

Increasing the width of the γ-line with the shortening of the wave train

The narrowing of the γ-line cannot be associated only with a decrease in the width of the emitting level. This was shown by the experiment of Voitovetsky et al. [6] with the ^{181m}Ta isomer .

When the absorber was shaded from the source by a shutter that opened their mutual visibility for a time of $\tau \approx 1.0$ μs, a broadening of the 6.2 keV γ-line from $\Delta\omega \approx 1/T_{1/2}$ to $\Delta\omega \approx 1/\tau$ was observed.



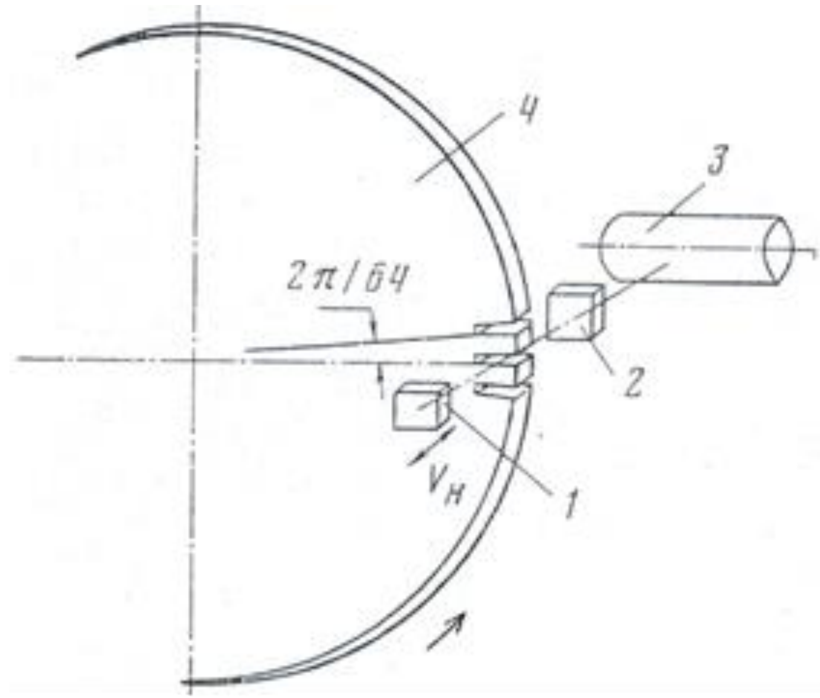
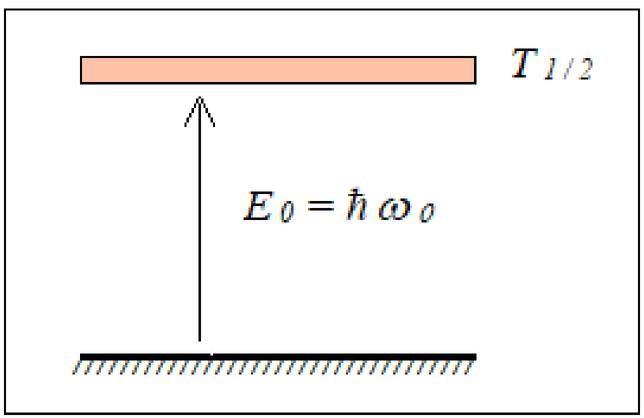


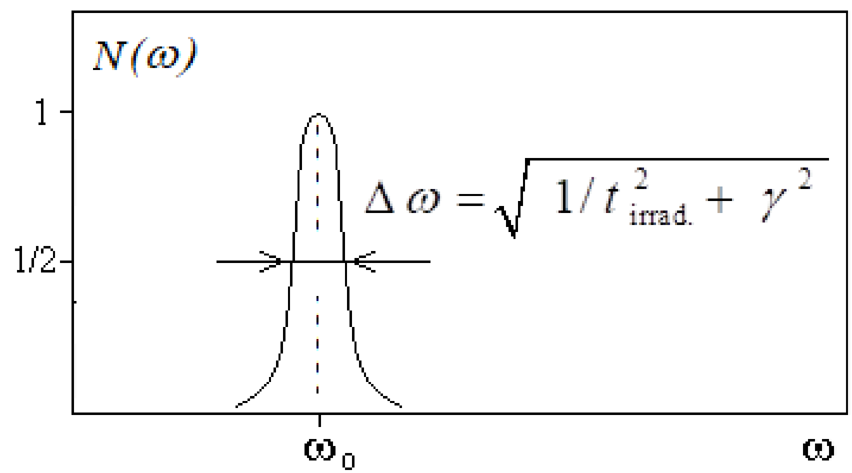
Схема эксперимента [6].

An increase in the γ-line width with a shortening of the wave train (Theory)

From Voitovetsky's experiment it turns out that the width of the γ-line is determined not only by the emitter, but also by the absorber, which, as it were, is tuned to the resonant absorption of the γ-quantum by the currently unknown radiation preceding the emission of the photon energy quantum.

In QED, the absorption of a photon is described by the same matrix element as the emission of a photon. The spectral width of the absorption line is $\Delta\omega = \sqrt{1/t^2_{irrad.} + \gamma^2}$

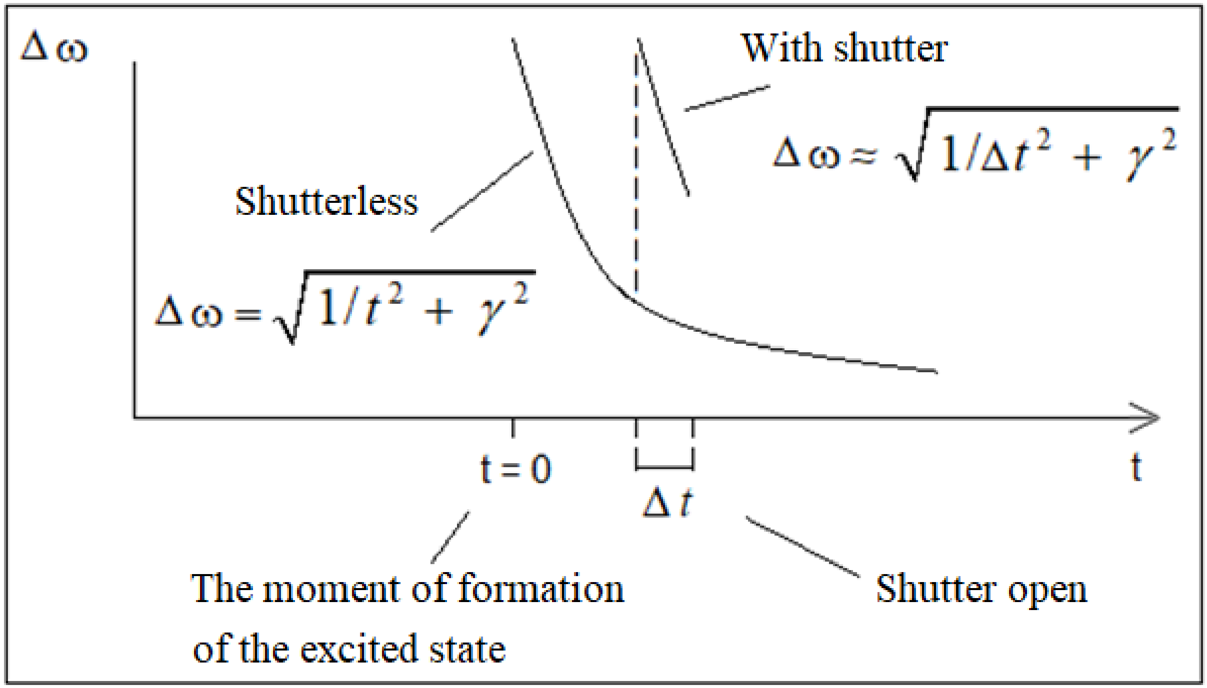




Spectral distribution of resonantly absorbed photons. Decay constant $2\gamma = \ln 2 / T_{1/2}$,

$t_{irrad.}$ is the time of irradiation of the nucleus before its excitation.

General view of the γ-line width in the Mössbaur experiment



- The dependence $\Delta\omega(t)$ without a shutter is from the experiment [4].

- Voitovetsky's experiment [6] showed an increase in the width $\Delta\omega$ when using a shutter between the emitter and the absorber, which opens the emitter only for a short time.

- This effect resembles the collision broadening of spectral lines in plasma due to the shortening of the length of the coherent wave train during the emission of photons.

Hypothesis about the structure of the photon

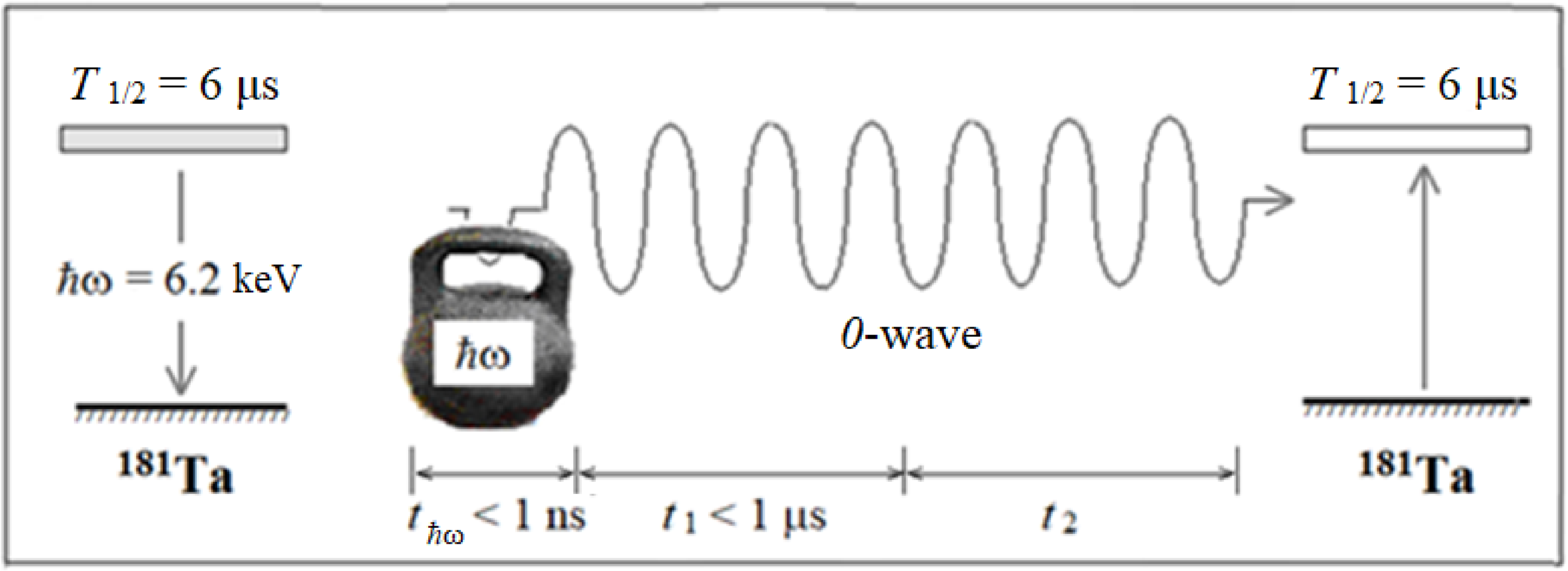
The half-life of the emitting state is much longer than the energy quantum emission time $t_{\hbar\omega}$, which is less than the duration of the g-signal in the detector ($t_{\hbar\omega}$ < 1 ns)..

Then we have to assume the following scheme of photon emission.

- Immediately after the formation of an excited state, the nucleus begins to emit an "empty" EM wave that does not carry energy - abbreviated as a 0-wave. The duration of this 0-wave, together with the decay constant of the radiating level, determines the spectral width $\Delta\omega$ of the radiation.
- The energy quantum $\hbar\omega$ is emitted at the end of the 0-wave.
- The absorber nucleus is irradiated with a 0-wave, and the spectral distribution of resonantly absorbed photons depends on the decay constant of the excited level and the duration of irradiation of the absorber nucleus.

This hypothesis helps to understand the photon wave-particle duality.

Voitovetsky's experiment according to the photon structure hypothesis



Scheme of photon emission by the ^{181m}Ta isomer in Voitovetsky's experiment [6]. After the formation of the radiating level, the nucleus immediately begins to radiate a 0-wave of frequency ω. t_1 is the part of the 0-wave train that can be seen by the absorber through the open shutter; t_2 is the initial part of the 0-wave, it is cut off by the shutter and the absorber does not see it. The energy quantum is emitted "on the tail" of the 0-wave during the time $t_{\hbar\omega}$.

$\mathit{0}$-wave properties

- A train of 0-waves is emitted all the time after the formation of an excited state. It can be assumed that 0-waves propagate at the speed of light. Then, for example, for the emission of the ^{107m}Ag isomer with $T_{1/2}$ = 44 s, the train length is about 10^9 m.

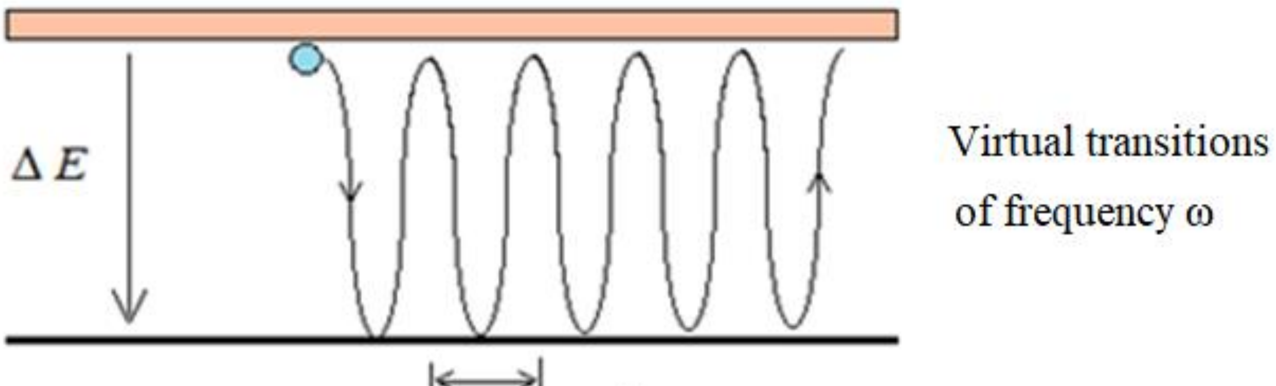
- The question arises about the nature of 0-waves. In terms of reflection and interference, the properties of 0-waves are apparently the same as those of known EM waves. For example, these waves are not transmitted by the shutter in Voitovetsky's experiment [6]. But these are not ordinary EM waves, since they do not carry the energy $\hbar\omega$.

- After the formation of the radiating state, the 0-wave will begin to be emitted, but the energy quantum itself may not be emitted if the decay occurs through some other channel and then the 0-wave will exist on its own, without an energy quantum.

- A 0-wave with an energy quantum $\hbar\omega$ “on its tail” resembles a pilot wave introduced by De Broglie to explain the wave-particle duality of electrons [7].

Possible source of 0-waves

- A possible source of the 0-wave is the virtual transitions from the excited level to the ground state of the nucleus and back before the emission of an energy quantum.
- With this assumption, it would be possible to understand the frequency of which process appears in the formula for the transition energy $\Delta E = \hbar\omega$.
- According to quantum mechanics, energy fluctuation by ΔE in virtual transitions is possible for a time $\Delta T \sim \hbar / \Delta E$. Accordingly, the frequency of virtual transitions $\omega = 1 / \Delta T \sim \Delta E / \hbar$.



$$\Delta T \sim \frac{\hbar}{\Delta E} \Longrightarrow \omega = 1 / \Delta T \sim \Delta E / \hbar$$

Possible experiments on direct observation of 0-waves

It would be interesting to find a way to detect 0-waves and explore their properties in more detail. For example, it would be worth to clarify the influence of 0-waves on absorbing nuclei. In particular, according to the scheme of the Voitovetsky experiment [6], it is possible to search for the modulation of the γ-line width with additional illumination of the absorber by resonant 0-waves.

Perhaps 0-waves can be used in practice

- For example, by detecting a 0-wave, one can detect an excited object and predict its future decay.
- It is also interesting to study the possibility of transmitting information using 0-waves.

References

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Thanks !