# Interference coherent excitation in two crystals

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(Submitted 12 September 1995; resubmitted 1 November 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 12, 895–899 (25 December 1995)

An application of the coherent excitation of particles traveling through a crystal in fundamental research is presented: A new modification of a coherent-excitation experiment employing two spatially separated crystals is proposed. This method increases the sensitivity of an experiment to a change in the energy of the particles excited in crystals and at the same time decreases the influence of stopping losses. © *1995 American Institute of Physics.*

Coherent excitation of nuclei and atoms traveling through a crystal was predicted in Refs. 1 and 2. The physics of this phenomenon consists of a sharp increase in the probability for the excitation of a discrete level of a nucleus (or atom) as it travels through the periodic field of a crystal with a velocity at which the collision frequency $\nu_{\text{coll}}=V/a_0$ of the traveling particle with the crystal atoms is equal to or is an integer number of times less than the frequency necessary to excite a level of the particle $\nu_{\text{exc}}=E/h$:

$$\nu_{\text{coll}}=\frac{V}{a_0}=\frac{1}{m}\nu_{\text{exc}}=\frac{1}{m}\frac{\Delta E}{h},$$

where $V$ is the velocity of the transmitted nucleus (atom), $a_0$ is the distance between the atoms in the crystal, $\Delta E$ is the energy of a level of the nucleus (atom), and $m=1, 2, 3,\ldots$ .

The first experimental results indicating the existence of coherent excitation of $He^+$ atoms traveling through a single-crystal film of silver were obtained in Ref. 3 .

Despite the fact that coherent excitation of atoms has been studied extensively, both experimentally[4–8] and theoretically[9–14] during the past decade, I believe that this work is moving in a direction in which the possibilities of coherent excitation in fundamental research are not completely utilized. I shall list some of these possibilities.

Experimental studies of the coherent excitation of atoms traveling through a crystal shed light on physical phenomena such as the formation time of an excited state of atoms inside a crystal, the shift of the energy levels of electrons in atoms traveling inside a crystal, the coherent interaction length of an ion with the periodic field of the crystal, and other phenomena. At present, these phenomena apparently cannot be investigated by other methods. However, the fundamental prospects for the application of coherent excitation lie not only in atomic physics, which already has been unequivocally demonstrated, in my opinion, in experiments where this phenomenon is investigated for atoms, for example, Refs. 4–6 , but also in nuclear physics at relativistic and ultrarelativistic energies.

  

a) The experimental confirmation of the existence of coherent excitation of nuclear energy levels will actually mean the discovery of a new type of nuclear reaction occurring not in single collisions of two nuclei but rather as a result of the collective interaction of nuclei traveling through a crystal with the crystal atoms. The probability of this reaction should be much higher than that of a reaction with the standard Coulomb excitation of nuclei traveling through an isotropic target, and it exhibits a specific resonance dependence on the energy of the nucleus (the half-width $\Delta E/E$ of the resonance can be made to reach $\sim 10^{-5}$), which gives rise to many promising applications of the effect in the physics of relativistic and ultrarelativistic energies.

b) A secondary effect of an experiment on the coherent excitation of nuclear energy levels is an accurate ($\sim 10^{-5}$) check of the time dilation effect with a relative velocity of the coordinate systems which correspond to the Lorentz factor $\gamma \sim 100-150$.

c) The results of the general theory of relativity concerning the change in the passage of time in accelerated coordinate systems can be checked in the same experiment. This possibility is connected with the fact that a nucleus traveling through a crystal is subjected to colossal accelerations, $\sim 10^{20}$ cm/s$^2$, as a result of ionization losses. According to the principle of equivalence, such an acceleration changes the passage of time in a coordinate system moving together with the nucleus and thereby shifts the energy levels of the nucleus.

d) It is possible to perform an experiment on the coherent production of $\Sigma^+$ hyperons by ultrarelativistic protons in a crystal; i.e., it is possible to observe a reaction that is the inverse of the two-particle decay reaction[15] $\Sigma^+ \rightarrow p + \gamma$.

In the present paper I call attention to one of the many possible applications of coherent excitation in fundamental research.

One would think that to realize the main advantages of the coherent excitation of particles traveling through a crystal — a) high resolution ($\Delta E/E \sim 1/n$) and b) increase in the excitation probability ($W \sim n^2$) — it would be advantageous to use thick crystals (the number of layers $n \sim 10^5-10^6$). However, the fundamentally unavoidable stopping losses of fast particles in matter limit the use of thick crystals.

The effect of the stopping losses on the excitation of fast particles in a crystal is analyzed in detail in Ref. 16. This effect limits the so-called coherence length, i.e., the thickness of the crystal, within which the contributions of single interactions of the traveling particles with crystal atoms sum coherently. The phase shift due to the stopping of fast particles in matter (ionization losses) results in weak frequency modulation of the time-periodic interaction of the traveling particle with the atoms in the crystal. This, in turn, limits the growth (proportional to the number of layers in a crystal) of the amplitude of the harmonics in the Fourier spectrum.[1] Ultimately, the excitation probability increases as the squared number $n$ of layers in the crystal up to some value $n_{\text{eff}}$, which was estimated in Ref. 16 as

$$n_{\text{eff}} = \sqrt{E/\Delta E},$$

where $E$ is the kinetic energy of the particle, and $\Delta E$ are the energy losses over the interatomic distance $a_0$. This limitation has only a weak effect in experiments on the coherent excitation of atomic energy levels in the case of ions traveling through thin

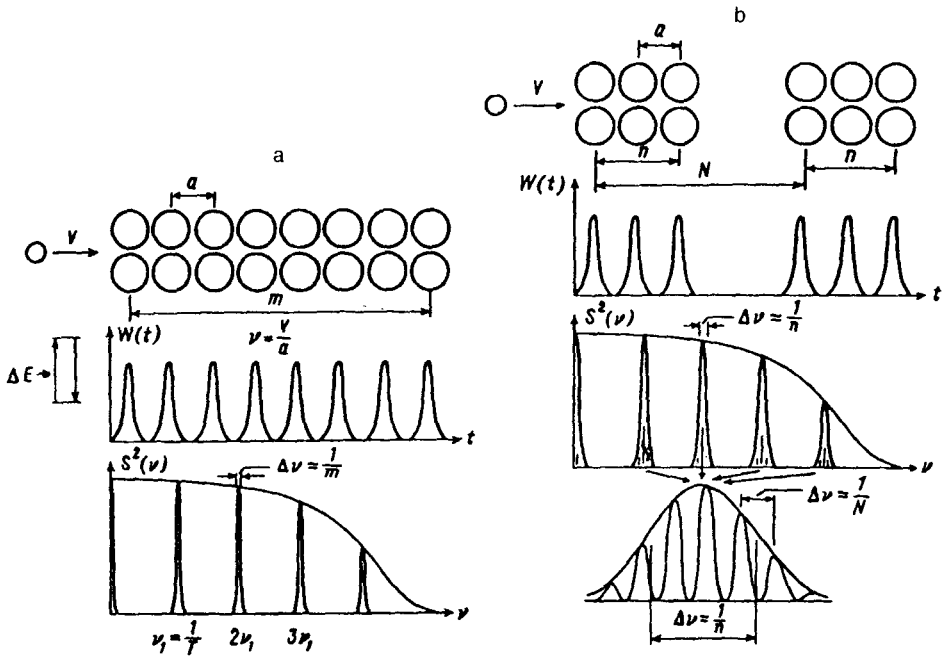


FIG. 1. Condition of coherent Coulomb excitation $\nu_{per} = \Delta E/h = kv/a = k\nu_1$, where $k = 1, 2, 3, \ldots$; a) $S_\Sigma^2(\omega) = S_0^2(\omega) \sin^2(\omega mT/2)/\sin^2(\omega T/2)$; b) $S_\Sigma^2(\omega) = S_0^2(\omega)[\sin^2(\omega nT/2)/\sin^2(\omega T/2)]2\cos^2(\omega nT/2)$.

single-crystal films,[3-6] but it must be taken into account in experiments on the coherent excitation of nuclear energy levels when thick crystals ($\sim 1-5$ mm), for which the stopping effects are important, must be used in order to increase the excitation probability.

It could be that some experiments will require a high sensitivity, rather than a high resolution, in the measurement of the changes in the energy of a beam. In this case the experiment must be modified so as to reduce to a minimum the influence of stopping losses, where the minimum is associated with an increase in the characteristic spread in the energy of the beam of particles traveling through the crystal; i.e., it is associated with the difference in the beam at the entrance and exit of the crystal. A modification of an experiment with these specific properties, which in the future could apparently expand the applications of this effect in fundamental research, is described below.

Let us consider how the physics of the coherent excitation changes when the atom travels successively through two crystals, each of which contains $n$ layers. The distance between the front planes of these crystals is equal to an integer number $N$ of interatomic distances (see Fig. 1b). The dependence of the excitation energy $W(t)$ between the traveling atom and the crystal atoms in this case has the form of two periodic sequences of single spikes, each of which is due to the interaction of the traveling atom with the crystal atoms. The qualitative character of the coherent excitation of the atom traveling through two crystals can be easily understood by analyzing the Fourier spectrum of the

perturbation experienced by the atom in the process of successive interaction with two crystals:

$$S_2^2(\omega)=S_0^2(\omega)\frac{\sin^2(\omega nT/2)}{\sin^2(\omega T/2)}\times 2\cos^2\frac{\omega NT}{2},$$

where $S_0^2(\omega)$ is the spectrum of a single interaction. For comparison, a diagram of the interaction of an atom traveling through one crystal that has $m$ layers is shown in Fig. 1a (Ref. 1). The difference is in the factor $\cos^2(\omega NT/2)$, which appears as a result of the interference of the two spectra generated by each crystal. In this case each harmonic (whose width $\Delta\nu_1\sim 1/n$ is now due to the small $n$) which is separated by the crystals is chopped up by the oscillating factor $\cos^2(\omega NT/2)$, whose half-wave is much smaller than the width of the harmonics, $\Delta\nu_2\sim 1/N$.

If the velocity of the atom traveling through the crystal is now allowed to vary continuously, the probability for the excitation of the traveling atom will have the same form as the Fourier spectrum which is shown in Fig. 1b, since the probability that the traveling atom will be in the excited state is determined by the Fourier component of this spectrum at the excitation frequency $\nu_{\text{exc}}=\Delta E/h$.

It is easy to see that the ionization losses in the two thin crystals, which first separate the harmonics at the frequencies $\nu_1\sim 1/T$, $\nu_2\sim 2/T$, $\nu_3\sim 3/T$, etc., are determined by the thickness $n$ of the thin crystals, and that the sensitivity to the energy of the incident beam is determined by the width of the half-wave of the oscillating factor which is proportional to $\Delta\nu_2\sim 1/N$, which can be 2–3 orders of magnitude smaller ($N\sim 10^2-10^3 n$). The effect of the ionization losses with respect to one crystal, whose sensitivity to the beam energy is the same, thus decreases by 2–3 orders of magnitude.

The two-crystal method of coherent excitation, which is described above, resembles the well-known method of separate oscillating Ramsey fields in molecular-beam physics.[17] In this method transitions in molecules are initiated by rf fields, arranged in spatially separated static magnetic fields through which the molecules being investigated travel in succession.

It is obvious that the interference excitation of an energy level of the traveling particle in two crystals is realized only when the lifetime of the level, $\tau_{\text{level}}$, is much longer than the travel time of the excited particle (a similar condition is also characteristic of Ramsey's method mentioned above) between the crystals: $\tau_{\text{level}}\gg T=a_0N/V$. In most cases this condition is satisfied comparatively easily.

To perform an experiment on the proposed interference coherent excitation on two crystals, we must satisfy at least two conditions.

1) The spread in the energy of the beam of experimental particles and its stability $\Delta E/E$ must be less than $1/N$.

2) The deviation of the planes of the two single-crystal films, which are perpendicular to the beam axis, from a parallel arrangement on an area equal to the size of the beam must be less than the interatomic distance $a$ in the crystal.

The first condition $\Delta E/E\sim 10^{-5}-10^{-6}$ can be satisfied in some special cases. The second condition apparently entails great experimental difficulties and it places the

method of two-crystal excitation at the limit of modern experimental capabilities.

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Translated by M. E. Alferieff