On the physical nature of the diffusion laser cooling phenomenon

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The physical nature of the phenomenon of diffusion laser cooling is discussed. Sub-Doppler cooling in this case is achieved due to the phenomenon of anisotropic light scattering. Once again, it is proposed to carry out simple experiments to test the proposed physical explanation.

Laser cooling studies developed rapidly in the 70-90s. Outstanding results were obtained. To cool neutral atoms, the so-called Doppler approach was first successfully developed [1, 2]. The experimenters then discovered that the observed cooling depth of the atoms significantly exceeded the Doppler cooling limit. To explain this phenomenon, some sophisticated physical mechanisms like Sisyphus cooling, Velocity Selective Coherent Population Trapping, Polarization gradient cooling, Resolved sideband cooling, Raman sideband cooling have been proposed.

However, the most popular explanation today for the capture, cooling and holding of atoms and particles by laser radiation is, probably, the idea of an optical dipole trap [3]. The idea was that atoms could be polarized. Due to this polarizability, under conditions of a large gradient of laser radiation intensity, its should be drawn into the laser beam. Such conditions exist in optical tweezers [4]. Moreover, it is assumed that below an atomic resonance ("red" detuning) the dipole potential is negative and the interaction thus attracts atoms into the light field. But, above resonance ("blue" detuning) the dipole interaction repels atoms out of the field. According to this distinction, dipole traps can be divided into two main classes, red-detuned traps and blue-detuned traps. Under the conditions of such a dipole trap, atoms can be captured and cooled in a vacuum for a long time.

In the huge stream of publications on laser cooling of atoms, molecules, ions, particles, and mechanical resonators, it is easy to overlook the amazing result of the so-called diffusion laser cooling [5 - 7]. There are no nudes and antinodes, there are no gradients of laser radiation intensity. It turns out that under conditions of completely isotropic irradiation, atoms are cooled no less efficiently than in sophisticated optical trap schemes. It is obvious that the Doppler mechanism of atomic cooling is at work here. It is characterized by a red-tuning of the laser radiation frequency relative to the resonance of the optical transition. However, the sub-Doppler temperature is also easily reached here. The authors do not provide any clear explanation of the physical nature of the phenomenon of sub-Doppler diffusion laser cooling.

However, such a physical explanation exists. It was discussed in [8]. We are talking about spatially asymmetric (nonisotropic) scattering of laser radiation during nonresonant irradiation of cold atoms. When the laser is tuned to the resonance of the absorption line, the atom that has absorbed the photon can be in an excited state for tens of nanoseconds. Then the spontaneous emission of a photon occurs. This spontaneous emission is predominantly isotropic [9]. When the laser is detuned from resonance, photon scattering occurs close to the Raman regime. Here the lifetime of the excited state can be negligibly small. In this case, non-isotropic scattering plays a predominant role.

This mechanism is most clearly manifested in the long-known Bloch oscillations of cold atoms in a vertical optical lattice [10, 11]. The scheme of a typical experiment is shown in Figure1. Here, the laser radiation is directed from bottom to top. At the top, it is reflected by a mirror. As a result, the so-called vertical optical lattice is formed. A cold atom falling freely in a vacuum under these conditions performs stable oscillations [12]. A detailed mathematical description of the process of these oscillations has been created, but any clear physical explanation of this phenomenon is absent in the literature [13].

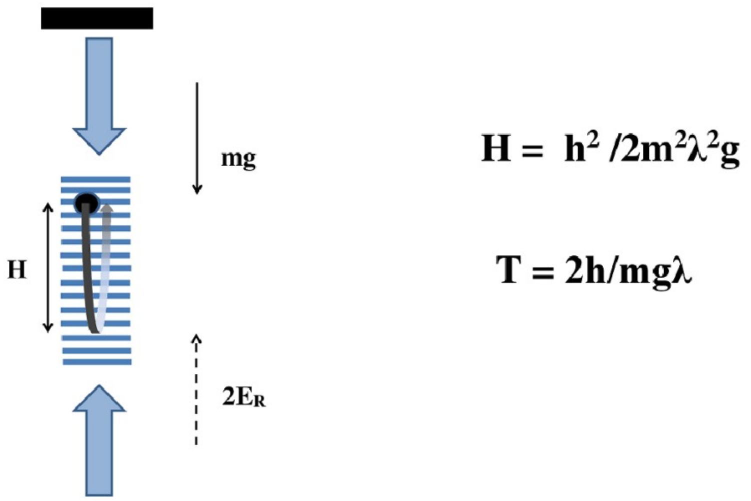

Fig. 1 Scheme of the Bloch oscillations of cold atoms in a vertical optical lattice.

The concept of anisotropic scattering explains the physics of this phenomenon easily and naturally. At a certain time and at a certain point in space, nonisotropic scattering of light occurs: an atom absorbs a photon from an upward laser beam and emits a scattered photon in the opposite direction. As a result, the atom receives double the recoil momentum and returns to its original point in space.

At the same time, according to a well-established point of view in the literature, dipole forces should play the main role in vertical Bloch oscillations [13]. Although, it is difficult to understand how these dipole forces can explain the basic properties of oscillations (amplitude and frequency).

It is quite simple experimentally to verify which of these alternative explanations of the physical nature of vertical Bloch oscillations is correct. We need to remove the top mirror. Will the Bloch oscillations persist? In this case, the vertical optical lattice will disappear. If vertical Bloch oscillations disappear, then the concept of dipole forces is correct. If vertical Bloch oscillations persist, then the concept of non-isotropic scattering is correct. For it, the presence of an upper mirror is not a fundamental necessity.

Surprisingly, such a simple and obvious experiment has not yet been carried out. On the other hand, the answer to this question has existed for quite some years in the form of the title of the experimental article [14]: “Bloch oscillations in the absence of a lattice”. There, the authors observed vertical Bloch oscillations in conditions where there was no vertical laser beam at all. Only scattered photons could be present.

With a certain amount of skill (ingenuity) from experimenters, the mechanism of anisotropic scattering can be used to achieve a sub-recoil cooling regime for atoms. For this to happen, the resulting recoil momentum of the two photons must be less than each of them. The recoil pulses from the absorbed and scattered photons should have opposite directions. Figure 2 illustrates this approach.

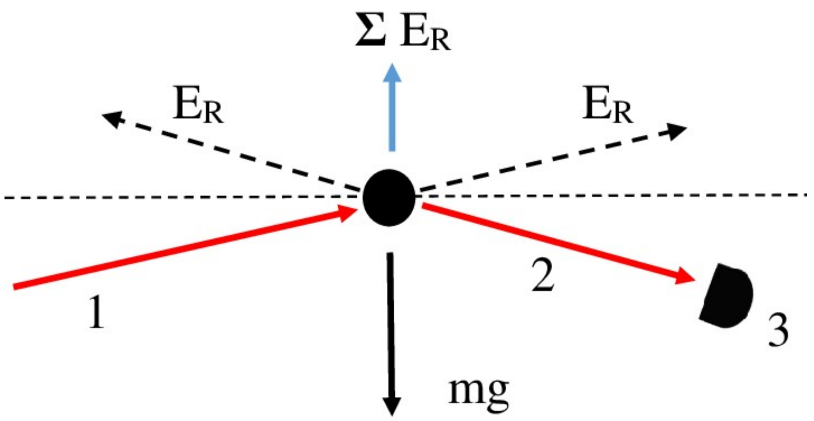

Fig. **2** Scheme of demonstration experiments for sub-recoil cooling of atoms through nonisotropic photon scattering. 1 – laser photons, 2 – nonisotropically scattered photons,
3 – scattered photon detector.

Here, a cold atom falls freely in a vacuum under the influence of gravity. This atom is affected by non-resonant laser radiation at a small angle to the horizontal direction. An anisotropically scattered photon is directed specularly to the detector. The resulting recoil momentum is directed upward. The closer the angle between the laser and scattered photons is to 180^0, the smaller the resulting recoil pulse. Obviously, under these conditions, vertical Bloch oscillations can also be observed, but with a small amplitude.

The authors of [15, 16] came close to demonstrating such a cooling regime. Unfortunately, this experiments were not brought to their logical conclusion. A vertical resonator formed by two mirrors was used there. Inside the resonator, a cloud of cold atoms freely falls in a vacuum under the influence of gravity. The falling atoms are exposed to horizontally directed laser radiation. In this case, scattered radiation appears in the vertical resonator and the falling atoms slow down. This is the initial stage of the emergence of vertical Bloch oscillations.

If the slowing down of atoms is due to the scattering of photons, then it is intuitively clear, that the downward scattering of photons should prevail. However, this information is hidden (erased) by the presence of a vertical resonator. Thus, these experiments should be repeated and continued without vertical resonator mirrors at different detuning of laser radiation from the optical transition frequency. It is important to measure the amplitude of vertical Bloch oscillations at different directions of the laser beam and to register the direction of anisotropically scattered photons.

Conclusion

Thus, the sub-Doppler cooling of atoms under nonresonant diffusion laser irradiation occurs due to the phenomenon of non-isotropic photon scattering. This spatially asymmetric scattering itself is a rather direct manifestation of a fundamental property of quantum physics – the nonequivalence of forward and reversed quantum processes [17]. An even more direct and obvious manifestation of this property is the well-known phenomenon of Bloch oscillations of cold atoms in a vertical optical lattice [8].

We have sufficient direct and indirect experimental evidence of such nonequivalence [17]. It is difficult to understand how long our physicists will persist in ignoring this already quite obvious experimental fact [18].

There are a large number of experimenters who have all the necessary equipment for such experiments. We once again encourage them to carry out these important, interesting and simple experiments.

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