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Crystal acceleration effect for cold neutrons in the vicinity of the Bragg resonance

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Abstract

A new mechanism of neutron acceleration is studied experimentally in detail for cold neutrons passing through the accelerated perfect crystal with the energies close to the Bragg one. The effect arises due to the following reason. The crystal refraction index (neutron–crystal interaction potential) for neutron in the vicinity of the Bragg resonance sharply depends on the parameter of deviation from the exact Bragg condition, i.e. on the crystal–neutron relative velocity. Therefore the neutrons enter into the accelerated crystal with one neutron–crystal interaction potential and exit with the other. Neutron kinetic energy cannot vary inside the crystal due to its homogeneity. So, after passage through such a crystal, neutrons will be accelerated or decelerated because of the different energy change at the entrance and exit crystal boundaries.

Keywords: Neutron acceleration; Perfect crystal; Neutron diffraction; Accelerated crystal.

1. Introduction

The possibility of controlling the energy of neutron beams is of great interest because of the wide neutron applications in various scientific fields from material science to nuclear physics, particle physics and astrophysics. The acceleration effect for neutrons scattered by excited isomeric nuclei was first predicted in 1959 [1] and was discovered experimentally in 1980 [2,3]. The acceleration of neutrons in an inversely populated medium [4,5] turned out to be very important in processes of stellar nucleosynthesis. In Ref. [6] acceleration of neutrons by vibrationally excited nitrogen molecules was observed.

Acceleration of neutrons in the uniform magnetic field by means of a radio-frequency flipper is well known and successfully used in physical experiments (see, e.g., Ref. [7]). The phenomenon of neutron acceleration in a strong alternating magnetic field (of amplitude ∼0.4 T) was observed in Ref. [8]. The acceleration of neutrons in a weak alternating magnetic

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field (of 0.1–1.0 mT) was measured using anomalous behaviour of the velocity dispersion for neutrons, moving in a crystal close to the Bragg directions [9]. The foundations of the neutron acceleration in a laser radiation field were considered in Ref. [10].

Also acceleration and deceleration of neutrons by reflection from moving mirror [11,12] or by Doppler-shifted Bragg diffraction from a moving crystal [13,14] are well-known and used in experiments with ultracold neutrons.

Recently a new interest has arisen in the acceleration of neutrons passing through accelerating media [15,16]. This effect was first observed by the authors of Ref. [17] and was described in detail in Ref. [18]. It was noted in Ref. [18] that "the observed effect was a manifestation of quite a general phenomenon – the accelerated medium effect (AME) inherent to waves and particles of different nature". In Ref. [19], the acceleration and deceleration of neutrons were observed by applying a specific time-of-flight method. In Ref. [20], some new special features of the effect for a birefringent medium were discussed with the applications to neutron spin optics and evolution of flavor states of neutrino, propagating through a free space. The acceleration of the samples in the mentioned experiments reached several tens of g units, and the value of the energy transfer ΔE_n to a neutron with energy E_n

$$(\Delta E_n \approx 2(\Delta v/v_n)E_n[(1 - -n)/n])$$

fell within the range of (2–6)·10^{-10} eV [18] for ultracold neutrons (UCN), so up to now AME was observed only for UCN and by only one research group (see Refs. [18,20]). Here v_n is a neutron velocity, Δv is a value of a relative neutron-matter velocity variation during the neutron time-of-flight through the sample, n is the refraction index for neutron.

In the present paper, a new much more effective mechanism of acceleration effect is proposed [21], which has been tested and confirmed experimentally for cold neutrons passing through the accelerated perfect crystal. An energy transfer to a neutron in this case can be at the level of ~4·10^{-8} eV. This value in contrast to AME is determined by the amplitude V_g of the corresponding harmonic of the nuclear neutron–crystal periodic potential, but not by the value of a relative neutron–crystal velocity variation during the neutron time-of-flight through the crystal. For cold neutron

$$[(1 - n)/n] \approx V_0/2E_{n,}$$

so AME in our case has an order

$$\Delta E_n \approx (\Delta v/v_n)V_0 \sim 10^{-5}, V_0 \sim 10^{-13}\text{eV}$$

that is negligible in further consideration (V_0 is zero harmonic of neutron–crystal interaction potential, i.e. averaged crystal potential).

The essence of the crystal acceleration effect is as follows. The crystal refraction index for neutrons in the vicinity of the Bragg resonance sharply depends on the crystal–neutron relative velocity (see further). The neutrons enter into accelerated crystal with one potential of a neutron–crystal interaction and exit with the other potential, so the kinetic energy change at the crystal boundaries will differ, and neutrons will be accelerated or decelerated after passage trough such a crystal, in this case the energy transfer to a neutron being at the level of ~4·10^{-8} eV.

Neutron wave function significantly modifies for neutrons moving through the crystal under conditions close to the Bragg ones. As a result neutrons concentrate on "nuclear" planes or between them [22,23]. We take the term "nuclear" planes to mean the positions of maxima of periodic nuclear potential for corresponding system of crystallographic planes. The neutron–crystal interaction potential can be written as a sum (the reciprocal lattice vectors expansion) of harmonic potentials (harmonics) corresponding to all nuclear plane systems described by reciprocal lattice vector $\mathbf{g}$ normal to the given plane system, $|\mathbf{g}| = 2\pi/d$(d is an interplanar distance):

$$V(\mathbf{r}) = \sum_g V_g e^{i\mathbf{gr}} = V_0 + \sum_{g>0} 2v_g \cos(\mathbf{gr} + \varphi_g). \quad (1)$$

Here V_g are the amplitudes of g-harmonics of the crystal nuclear potential, which are determined by neutron scattering amplitudes for crystal elementary cell (structural amplitudes). In general, V_g are complex values, i.e. $V_g = v_g \exp \varphi_g$.

However, if the crystal is nonabsorbing and centrosymmetric, all phases can be turned to zero at once, i.e. all V_g can be made real, by putting the coordinate origin at the centre of symmetry. When a neutron is moving through the crystal under conditions close to the Bragg ones for a plane system $\mathbf{g}$, only one harmonic with amplitude V_g will be essential and should be taken into account. That is due to a very narrow wavelength width for Bragg reflection of neutrons. For one harmonic, the origin of coordinates can be always placed at its maximum making the V_g amplitude real. Just the same can be done with the crystal electric potential. So for centrosymmetric crystals the positions of "nuclear" and "electric" planes always coincide.

But if the center of symmetry is absent, the maxima of electric potential for some crystallographic planes will be shifted relative to the nuclear maxima. That