

CRYSTAL-BASED SPIN ANALYZER FOR FAST NEUTRON BEAMS

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Abstract

Possibility of construction of a spin analyzer for fast neutron beams is discussed, based on the conception that inter-crystal electric fields may act upon passing neutron via its magnetic moment. Such an influence might be substantial provided that proper crystal orientation is held and coherence conditions are organized. Numerical estimates of the beam and target parameters are performed, confirming possibility of realizing this technique under the condition of the incident beam high collimation degree.

INTRODUCTION

In modern experimental particle physics fast neutron beams are classified as a rather special experimental tool. The need in them is largely suppressed due to use of protons, which have all strong interaction properties almost identical with that of neutrons, but are advantageous technically, allowing for beam operation by means of external electromagnetic fields. Problems, for which use of neutron beams can not be avoided (apart from material research, where rather cold neutrons are proper), are investigation of spatial structure of nuclei and inter-nucleus forces [1], T-invariance precision tests [2] etc. As a whole, today fast neutron experimental physics is a progressing field, with beam quality and particle energies gradually raising.

Parameters of neutron beams available today in general depend on method of the neutron production, which may be basically of two kinds: knock-out reactions caused by fast protons or electrons on neutron-rich nuclei, and diffractive dissociation of neutron-rich light nuclei (D, T). Typical neutron energies achieved by both of the methods are of order 100 MeV. The advantage of knock-out reactions is a high outcoming neutron intensity in a pulsed regime, while the diffractive dissociation provides a better beam quality at high energy, since this process is closer to elastic and its differential cross-section is naturally peaked near the forward direction.

Additional difficulties arise at preparation of polarized fast neutron beams. In knock-out reaction methods a neutron polarization may be obtained by registering the outcoming particles at wide angles, while in diffractive dissociation – by polarization transfer from polarized initial deuterons. Measurement of fast neutron polarization degree is usually performed via measuring their attenuation asymmetry in cryogenically nuclear-spin-aligned targets. Typical polarizations achieved by those methods are of order 0.25.

In the present contribution we describe an alternative method for polarized neutron beam formation under conditions when a good unpolarized primary neutron beam is available. The method bases on the coherent amplification of the electromagnetic interaction at

passage of fast particles near crystal axes or planes. This effect is often exploited in experimental high-energy physics for conversion of charged particle beams. As for neutron, despite its electric neutrality, it possesses a non-vanishing magnetic moment, and thus its interaction with atomic fields is not zero and might be amplified through the coherent mechanism.

MECHANISM

Imagine a neutron with a definite momentum p , impact onto a finite-thickness mono-crystal, whose some strong crystallographic plane is aligned precisely parallel to the neutron initial momentum (z direction). Suppose that the neutron is fast enough as to scatter only through small angles under typical momentum transfers supplied by atomic fields. So, within the crystal the neutron moves approximately straight along a crystal plane. At that, the major impact on the neutron comes from an average electrostatic potential $\Phi(x)$, which depends only on the coordinate x , orthogonal to the oriented crystal planes.

Potential energy of the neutron in such a field depends on the sign of the neutron spin projection $\sigma_y = \pm 1$ on the y axis, the latter thus playing role of a quantization axis:

$$H_\mu = \mu v \sigma_y \frac{\partial}{\partial x} \Phi(x) \quad (1)$$

($\mu = -1.9|e|/2M$, M is the neutron mass, v its velocity). Accordingly, a quantum-mechanical phase, acquired by the neutron after passage through the crystal along a line at an impact parameter x , equals

$$S(x) = -\frac{L}{v} H_\mu(x), \quad (2)$$

where L is the crystal thickness. The scattering amplitude with a momentum transfer q reads

$$a = \frac{P}{2\pi i} \int dx e^{iqx} e^{iS(x)} \quad (3)$$

(we include the initial wave to consideration, too).

In view of identity of all the inter-plane intervals, constituting the crystal, this expression splits into two factors: the Bragg factor

$$F_B = \frac{\sin N_x qd}{\sin qd} \approx \frac{\pi}{d} \sum_n (-1)^n \delta\left(q - \frac{\pi n}{d}\right), \quad N_x \gg 1 \quad (4)$$

(d – the inter-plane distance, N_x – the number of planes, constituting the crystal) and the cell eikonal structure factor

$$F_c = \int_{-d/2}^{d/2} dx e^{iqx} e^{iS(x)}. \quad (5)$$

For a qualitative illustration, let the inter-plane potential $\Phi(x)$ be approximated by a quadratic function

$$\Phi(x) \approx \frac{2\pi\rho Ze}{d} x^2, \quad -\frac{d}{2} \leq x \leq \frac{d}{2}, \quad \Phi(x+d) = \Phi(x) \quad (6)$$

where ρ is the density of nuclei with the charge Z belonging to the chosen crystal plane. With the potential (6) the eikonal scattering phase (2) exhibits a “saw” structure

$$S(x) = \alpha x, \quad -\frac{d}{2} \leq x \leq \frac{d}{2}, \quad S(x+d) = S(x) \quad (7)$$

$$\alpha = \frac{4\pi\rho Ze\mu L}{d} \sigma_y$$

with the sign depending on the σ_y , and the cell structure factor is

$$F_c = \frac{2}{q+\alpha} \sin \frac{(q+\alpha)d}{2}.$$

This is a function with a dominant maximum at $q = -\alpha$. And in order to attain the largest positive effect and sharpness in the total amplitude and the cross-section $d\sigma/d\omega = |a|^2$, obviously, it is profitable to make the main maximum of F_c coincide with one of the maxima of F_B , distinct from the zeroth (cf. Fig. 1).

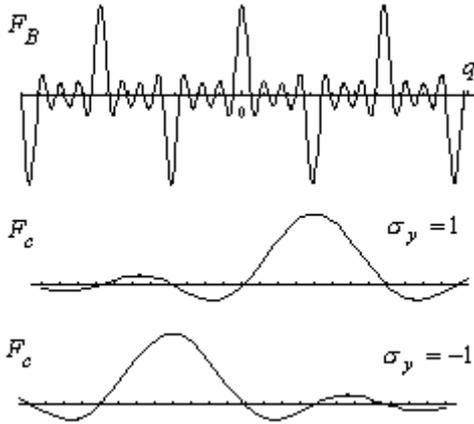


Fig.1 Schematics of Bragg and cell structure factors fitting.

Now let us turn to numerical estimates, which would help us decide, whether the given scheme is realizable and indeed efficient.

ESTIMATES

Let us start from estimating the target parameters and the beam energy, at which the best observable effect may be foreseen.

First, by choosing the F_c main maximum coincide with the first Bragg maximum, we come to the condition $\alpha = \pi/d$, which through (7), $L = N_z d$ determines the crystal thickness:

$$N_z = \frac{L}{d} \approx \frac{M}{4\rho d Ze^2}. \quad (8)$$

As we shall see below, it is advantageous to use materials with large Z , in order to achieve the desired effect at a shorter distance, before any negative effects can evolve.

At $Ze^2 \sim 1$, $\rho \sim 1/d^2$ (8) roughly means

$$N_z \sim 10^5, \quad L \sim 0.1 \mu\text{m}. \quad (9)$$

So, quite a thin (though macroscopic) monocrystal target is required here, and certain subtleties in preparation and setup must be expected. At such a thickness, of course, the target will be transparent to the beam, in the sense that shadows from atomic nuclei are negligible. The effect of the target influence, thus, indeed practically reduces to a pure elastic scattering (through small angles).

Next, the assumed mode of a nearly straight-line passage is dynamically sustainable if

$$p > \frac{N_z}{d}. \quad (10)$$

This entails a lower bound for the energy, which at $Ze^2 \sim 1$ proves to be non-relativistic:

$$E > \frac{(N_z/d)^2}{2M} \sim \frac{1}{2} M \left(\frac{1}{4Ze^2} \right)^2 \sim 30 \text{MeV}. \quad (11)$$

So, the energies required here are quite accessible with modern neutron facilities. (11) also confirms that larger Z are more appropriate here.

Sensitivity to changes of the energy and the incident angle in the described pattern is not strong. As follows from (2) through (1), the eikonal phase, even in a non-relativistic regime, basically does not depend on velocity. This guarantees that the same grid shall work equally well at all energies. The pattern also does not alter substantially under a non-zero (but small) incident angle between the neutron velocity and crystal planes, even if neutron crosses a few planes in course of its passage – because the “saw” structure of the eikonal phase is conserved.

But a most severe physical condition comes from the notion that under the typical scattering angles being of the order

$$\theta = \frac{q}{p} \sim \frac{1}{pd} < \frac{1}{N_z} \sim 10^{-5}$$

collimation of the beam in x direction must be better or about such a degree. This is not an insuperable difficulty, say, if use a 0.1 mm aperture at a 10 m distance from the neutron source. The reduction of intensity may be compensated by augmentation of the collimating slit length in y direction. Nonetheless, it must be recognized that there are no beams with such a quality of collimation at present – probably because there was no sensible motivation for that so far.

SUMMARY

As we have shown in the present contribution, at certain conditions a thin oriented monocrystal can split a monochromatic neutron beam into two parts, each being completely or almost completely polarized. In this sense the action of the crystal is equivalent to that of the renowned Stern-Gerlach apparatus (which in its conventional construction can not essentially manage with neutrons, since magnetic fields are not strong enough for that). Accordingly, the experiment described by us may also be suggested as a spin analyzer with the same advantages – polarization degree close to 1 and basically conservation of all the primary beam properties.

A salient feature of the oriented-crystal-based neutron spin analyzer, however, is the requirement of quite a high collimation degree for the incident neutron beam. Such a collimation may be planned in itself only in case of precision measurements. Possibility of moderating this

requirement needs more involved theoretical analysis and computer simulations. Tentatively, one may expect one order of magnitude to be reduced. Then the suggested method might be enough easily introduced to practice at existing fast neutron facilities, such as ORELA at ORNL and TSL at Uppsala, or the forthcoming SNS.

ACKNOWLEDGEMENT

Partial support by STCU-1746 grant is acknowledged.

REFERENCES

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