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Search for Neutron EDM Using Crystal Techniques

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Antisymmetric imaginary spin dependent scattering amplitudes related to atomic effects such as spin-orbit coupling, or nuclear effects such as parity violating weak forces or neutron EDM, generate particular spin rotations in perfect crystals. These effects are usually too small to be detected by normal neutron polarimetry. A new perfect crystal technique using Zeeman splitting as a polariser and termed Dual-Polarised-Beam polarimeter (DPB) with enhanced sensitivity, has been built and tested. The sensitivity of DPB to detect small spin rotations is about two orders of magnitudes better than classical polarisation techniques and it is only sensitive to antisymmetric effects. An extra gain arises from a specific enhancement effect close to the Bragg-edge directions. We have used this DPB technique in connection with a double crystal set-up to show that indeed effective electric fields up to 10^9 V/cm are accessible in suitable crystals by measuring the spin-orbit effect arising from this field. The conditions for EDM search are discussed.

KEYWORDS: neutron electric dipole moment, dual polarised beam, spin-orbit coupling

1. Introduction

EDM search is the most sensitive test yet devised to detect the breakdown of time reversal invariance. In an early search for neutron EDM, Shull[1] has used the strong Coulomb field in atoms. If the neutron had an EDM, he argued, the latter would interact with the atomic Coulomb field via an extra imaginary scattering amplitude. By a clever choice of the crystal used, he was able to considerably refine the possible upper limit for neutron EDM in the framework of a polarised neutron scattering experiment. His result, an upper limit of $d \leq + (2.4 \pm 3.9)$ 10^{-22} cm, was in fact better than the result published in parallel and obtained by the Ramsey free-neutron resonance-beam technique.[2] More recently only the latter technique was pursued to yield a present-day upper limit of $d \leq -(0.3 \pm 0.5)$ 10^{-25} cm, obtained with stored ultra-cold neutrons (UCN). The electric fields used in the resonance beam experiments are limited to a little more than 10^4 V/cm.

It has been demonstrated experimentally[3] that certain convenient crystals exhibit Coulomb fields much higher than this. A typical example is quartz with a measured usable field of 2.10^8 V/cm; certain more exotic crystals such as Bismuth germanate (BGO) yield electric fields up to several 10^9V/cm. This electric field is a weighted average value in a close to perfect crystal.

To efficiently use this very high field a simple polarised neutron scattering experiment to detect the extra imaginary scattering length arising from a possible EDM is not sufficient. In the Born approximation, the coherent spin scattering amplitudes arising from the electromagnetic (Schwinger or Spin-Orbit, S-O) interaction :

$$f_{\text{S-O}} = -2i\mu\hat{\sigma}(\boldsymbol{k} \times \boldsymbol{k}')(\hbar c)^{-1} e[Z - F_e(q)]q^{-2} \tag{1,1}$$

where $\hat{\sigma}$ is the spin matrix, $q = |\boldsymbol{k} - \boldsymbol{k}'|$, μ the neutron magnetic moment, and $[Z - F_e(q)]$ the screened atomic charge factor. $f_{\text{S-O}}$ is antisymmetric with respect to the exchange of $\boldsymbol{k}$ and $\boldsymbol{k}'$, the neutron momenta before and after scattering, and vanishes in the forward (no effect in the optical potential !) and backward directions. Similarly the Coulomb field-EDM interaction can be written as :

$$f_{\text{EDM}} = id\hat{\sigma}(\boldsymbol{k} - \boldsymbol{k}')2m\hbar^{-2} e[Z - F_e(q)]q^{-2} \tag{1.2}$$

where d is the neutron EDM (cm). This interaction is also antisymmetric with respect to the exchange of $\boldsymbol{k}$ and $\boldsymbol{k}'$, vanishes in the forward direction, and becomes maximum in backscattering. Both $f_{\text{S-O}}$ and f_{EDM} are so small (about 10^{-4} or less of the nuclear scattering lengths b for typical atoms) that their direct detection in the presence of normal nuclear scattering is normally impossible. Close to resonances, though, $f_{\text{S-O}}$ can be directly measurable.[4] As pointed out by Forte[5], imaginary scattering lengths such as $f_{\text{S-O}}$ and f_{EDM} give rise, in perfect or close to perfect non-centrosymmetrical crystal structures, to optical effects (spin rotations). When the Bragg geometry is considered, it can be shown that these spin rotations show strong amplification effects for certain, slightly off-Bragg directions. We shall further develop this theoretical point in the section on spin dependent dynamical theory. For the moment one should retain that optical spin rotation effects are far more sensitive to $f_{\text{S-O}}$ or f_{EDM} than direct polarised beam experiments.

To measure the above antisymmetric spin rotation effects efficiently we have developed and built a particular neutron polarimeter based on a Zeeman-splitted neutron beam (Dual Polarised Beam, DPB) which is capable to detect spin rotations with a sensitivity at least 100 times better than standard neutron polarisation techniques.[3] The DPB polarimeter is by its concept sensitive to antisymmetric spin rotations only. The details of this device will be described in section 3. It was used to measure spin rotations arising from $f_{\text{S-O}}$, the spin orbit effect, which is nothing else than the neutron spin coupling to the atomic Coulomb field, in different types of perfect crystals. These measurements have confirmed that the high electric field values quoted above are indeed available and give rise to the spin rotation enhancements predicted by spin dependent dynamical theory.[3)]

The effect of crystal imperfection can be taken into account by a simple convolution of theory with the measured Bragg profiles yielding a theory-to-experiment agreement without any adjustable parameter. Coulomb fields of 10^9 V/cm having been shown to be available in crystals, we can now discuss the potential of an EDM search based on this high electric field and the Dual Polarised Beam Polarimeter. The figure of merit commonly used to characterise the precision obtainable for a neutron EDM search is the quantity[6)]:

$$(E\cdot\tau\cdot\sqrt{N})^{-1}$$

where E is the electric field to which the neutron is exposed [in V/cm], τ the time of interaction (seconds), and N the number of events. τ depends essentially on the energy of the neutrons used, for UCN it can reach larger values than for crystal techniques as described here, the wavelength of the neutrons has to be of the order of $2d$ where d is the crystal lattice spacing. Hence, one is limited by the Bragg cut-off of the chosen crystal material. A very favourable crystal for this purpose is $Bi_{12}GeO_{40}$ for which $2d$ is of the order of 5Å. τ also depends on the crystal size which with some crystal growing effort could safely be increased to, say, 10cm, yielding τ values of several 10^{-4} seconds. The available neutron flux however is considerably larger for cold neutrons than for UCN.

Consequently crystal techniques are favourable for E and $\sqrt{N}$ but the $\lambda < 2d$ Bragg condition severely limits the interaction times. A suggestion by Fedorov[7)] to use Laue geometry does indeed allow larger τ's but has other drawbacks (see paragraph 4). Table 1 gives the values of $(E\cdot\tau\cdot\sqrt{N})^{-1}$ for different experimental situations. We consider this to be the starting point for the design of a DPB dedicated to the search for neutron EDM with a sensitivity expected to reach beyond existing techniques.

2. Spin Dependent Dynamical Theory : Antisymmetric Spin Rotations

Optical effects in perfect crystals arise from the presence of spin dependent imaginary scattering lengths such as $f_{S\text{-}O}$ or f_{EDM} described in the introduction. With the conventions of figure 1 relations (1.1) and (1.2) can be written as (θ is the scattering angle and $\lambda = 2\pi/k$, the neutron wavelength) :

$$f_{S\text{-}O} = -i\mu(\hbar c)^{-1}e[Z - F_e(q)]\cot\theta\,\sigma_3$$
$$\approx -i \times 1.5\times10^{-16}[Z - F_e(q)]\cot\theta\,\sigma_3 \ \text{[cm]}$$

and

$$f_{EDM} = id\frac{1}{2\pi}m\hbar^2 e[Z - F_e(q)]\lambda\csc\theta\,\sigma_2$$
$$\approx -i\times10^{-20}\lambda[Z - F_e(q)]\csc\theta\,\sigma_2 \ \text{[cm]}$$

(value corresponding to the present limit of d).

These equations show that if we take an initial polarisation along x_3, as for example in Figure 1, there will be no spin rotation due to the spin orbit coupling. The rotation α indicated in this figure would be due to f_{EDM} only.

The ratio between the two scattering amplitudes can be written as :

$$\frac{f_{EDM}}{f_{S\text{-}O}} \propto \lambda\frac{1}{\cos\theta},$$

which evidences the advantages of the Bragg geometry. Indeed close to backscattering ($\theta \to \pi/2$, impossible in Laue geometry) the above ratio increases, allowing a further separation of both effects.

In non-centro-symmetrical crystals the Friedel pair structure factors F and $\overline{F}$ are in general unequal. The

Table I. EDM detection by UCN and crystal techniques

	UCN storage present situation	**crystal diffraction** Quartz values	**crystal diffraction** suitable crystals
E (V/cm) usable electric field	10 - $16\cdot10^3$	$\sim 2\cdot10^8$ (quartz depending on reflection used)	10^9 possibly 10^{10} (limit)
τ (sec) storage time	70 (v = 5-6 m/sec)	$6\cdot10^{-5}$	$\sim 3\cdot10^{-4}$ (10 cm crystal , cold neutrons)
$E.\tau$	$\sim 1\cdot10^6$	$1.2\cdot10^4$	$3\cdot10^5$
N (neutrons/sec)	40 - 50	~ 500 (S21/ILL)	10^4 (ILL)
$(E\cdot\tau\cdot\sqrt{N})^{-1}$ $V^{-1}cm/sec^{-1/2}$. Figure of merit for fundamental limit of uncertainty	$\sim 2\cdot10^{-8}$ EDM < 1.1 x 10^{-25}e.cm	$\leq 10^{-7}$	$\leq 3\cdot10^{-10}$

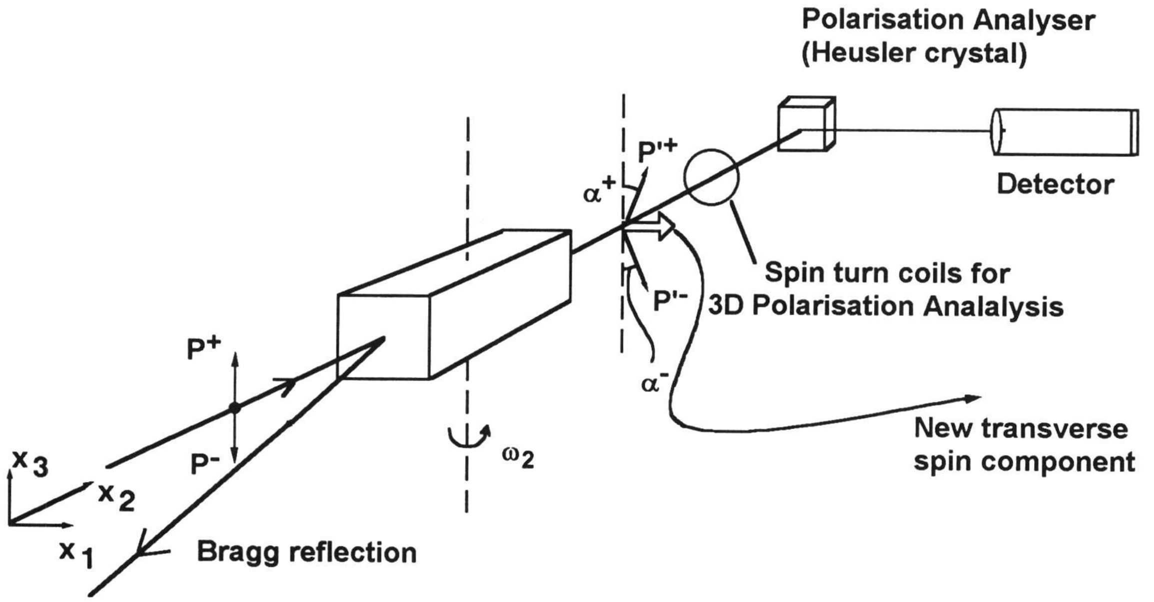

Fig. 1. Schematic representation of antisymmetric spin rotations α+ and α- of a dual polarised beam (P+,P-) observed in transmission of a perfect crystal slab.

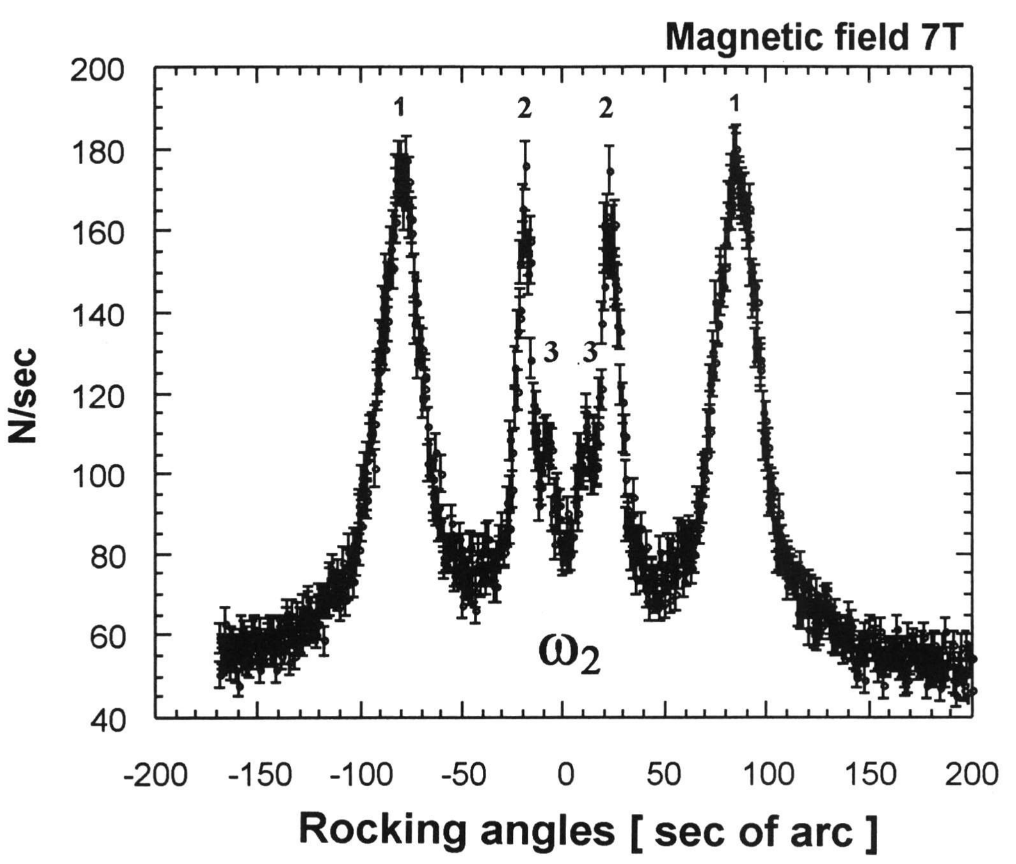

Fig. 2. Zeeman splitting of 4.85 Å neutrons (labeled 1) by a 7 Tesla magnetic field performed on the ILL S21 double crystal spectrometer. ω_2 is the rocking angle of the second crystal (Figure 1 and 3). The beam is unfiltered and the splitting of second (labeled 2) and third order neutrons (labeled 3) can also be seen.

presence of nonvanishing spin terms in $F\overline{F}$ essentially depends on the phase relation between the nuclear part F_n and the spin part, hence it is given by the crystal structure. For small spin dependent imaginary scattering as compared to the nuclear scattering F_n, which is the case here, we can separate the spin and non-spin dependent quantities in ($F\overline{F}$) by introducing the phase angles δ_n, $\delta_{S\text{-}O}$, and δ_{EDM}:

$$F = |F_n|\exp(i\delta_n) + i|F_{S\text{-}O}|\exp(i\delta_{S\text{-}O})\sigma_3 + i|F_{EDM}|\exp(i\delta_{EDM})\sigma_2 \, , \quad (2.1)$$

Because $|F_{EDM}|$ and $|F_{S\text{-}O}|$ << $|F_n|$, we can write for the product ($F\overline{F}$), after introducing the phase angles $\delta_\beta = \delta_n - \delta_{S\text{-}O}$ and $\delta_\alpha = \delta_n - \delta_{EDM}$, the following expression, to first order in F_{EDM} and $F_{S\text{-}O}$:

$$(F\overline{F}) \approx |F_n|^2 + 2|F_n||F_{S\text{-}O}|\sin(\delta_\beta)\sigma_3 + 2|F_n||F_{EDM}|\sin(\delta_\alpha)\sigma_2 \, . \quad (2.2)$$

Equation (2.2) is interesting because of the fact that the small values $|F_{S\text{-}O}|$ and $|F_{EDM}|$ are strongly enhanced by $|F_n|$. $F\overline{F}$ is the fundamental quantity entering dynamical theory. Using the formulation of Sears[8], the relevant parameter proportional to the Pendellösung frequency is given by:

$$W = \sqrt{X^2 - F\overline{F}} \, ,$$

where X is the deviation from the Bragg condition and is given by :

$$X = \frac{1}{2\pi N}(\boldsymbol{k} - \boldsymbol{k}') \cdot \boldsymbol{h} \, ,$$

where $\boldsymbol{h}$ is a reciprocal lattice vector and N the crystal unit cell density. Conventionally the normalised deviation from the Bragg condition $x = X/|F_n|$ is used. The total reflection domain (Darwin half-width) is then characterised by $|x| \le 1$. We can calculate the fundamental parameter $w = W/|F_n|$, the normalised Pendellösung frequency W of the theory. Without entering details one can show that w can again be separated in nuclear and spin terms in the following way :

$$w = w_n - \frac{|F_n|}{w_n}|F_{S\text{-}O}|\sin\delta_\beta\,\sigma_3 - \frac{|F_n|}{w_n}|F_{EDM}|\sin\delta_\alpha\,\sigma_2 \, .$$

Introducing this expression of the Pendellösung frequency in the phase velocity formula and evaluating the final transmitted polarisation for neutrons travelling close to a Bragg direction, one deduces an expression for the spin rotation α (due to EDM, S-O expression is similar) valid for small nuclear absorption and outside the Darwin range $|x| \le 1$.

The spin rotation α is a consequence of the transmission of a neutron wave initially polarised along x_3 (for EDM detection) and measured by the rotation around x_2 of the initial states P^+ and P^- to the final states P'^+ and P'^-. (Figure 1) The Pendellösung average of this spin rotation develops linearly in the crystal with an exit value for a perfect crystal of thickness t of :

$$\alpha(x) \approx \lambda N t\left(\frac{x}{w_n} + \frac{w_n}{x}\right) w_n^{-1} |F_{EDM}|\sin\delta_\alpha \, . \quad (2.3)$$

This spin rotation is antisymmetric with respect to the Bragg line centre and is enhanced as the Darwin half width, $|x| = 1$, is approached.

3. Dual Polarised Beam Polarimeter

In order to be sensitive to antisymmetric spin rotations only (with respect to the incident spin direction) one can produce a dual polarised neutron beam in such a way that exactly half of the neutrons have their spins aligned with the magnetic guide field vector, the other half having spins antiparallel to the guide field. Such a beam can be produced by passing a monochromatic neutron beam through a strong magnetic field area. If $\boldsymbol{B}$ is the magnetic induction vector and μ_B the neutron magnetic moment, then a Zeeman energy splitting of $\Delta E = 2\mu_B B$ (longitudinal Stern-Gerlach experiment) occurs in the beam. The result will be a separation into two polarised sub-beams, one polarised along $\boldsymbol{B}$ with energy $E_0 + \mu_B B$ and the other polarised antiparallel to $\boldsymbol{B}$ with energy $E_0 - \mu_B B$. By placing a crystal in the field area $\boldsymbol{B}$ and analysing the energy spectrum with an identical parallel perfect crystal (see Figure 2) the splitting $2\mu_B\boldsymbol{B}$ can be evidenced. Care must be taken to provide a convenient guide field along the neutron beam. A rocking scan ω_2 of the second crystal will then reveal a dual polarised beam structure as in Figure 3, the two spin up and down components which are propagating in slightly different directions, according to each Bragg angle $\theta_\pm$ as shown in Fig. 3.

$$\theta_\pm = \pm\arcsin\frac{\lambda^\pm}{2d}$$, where $\lambda^\pm = C(E_0 \pm \mu_B B)$-1/2 and $\lambda_0^{-1} = C(E_0)^{-1/2}$, E_0 is the incident neutron energy, C a constant. For $\lambda_0 = 4.85$Å neutrons, $\delta\theta = \theta_- - \theta_+$ is 0.11 mrad/T.

By rotating one of the two crystals, the Zeeman doublet can be resolved, provided the splitting is larger than the width of the rocking curve. To switch rocking from one peak of the doublet to the other makes spin-up and spin-down beams available without the necessity of a flipper. Figure 2 shows typical Zeeman splitting of 4.85Å neutrons by a 7 Tesla field. A 6-peak structure is observed with a white neutron beam, the outmost and most intense peaks corresponding to E_0 whereas the smaller innermost ones correspond to the second and third order (4 E_0 and 9 E_0) contamination of the incident beam produced by a broad mosaic pyrolytic graphite crystal. Provided that the incident spectrum around E_0 is sufficiently broad compared to the energy resolution of the double crystal set-up, the same result can be obtained by rocking the first crystal ω_1. The magnetic field is produced here by a superconducting coil and hence by changing the coil current any splitting up to the maximum field value can be adjusted.

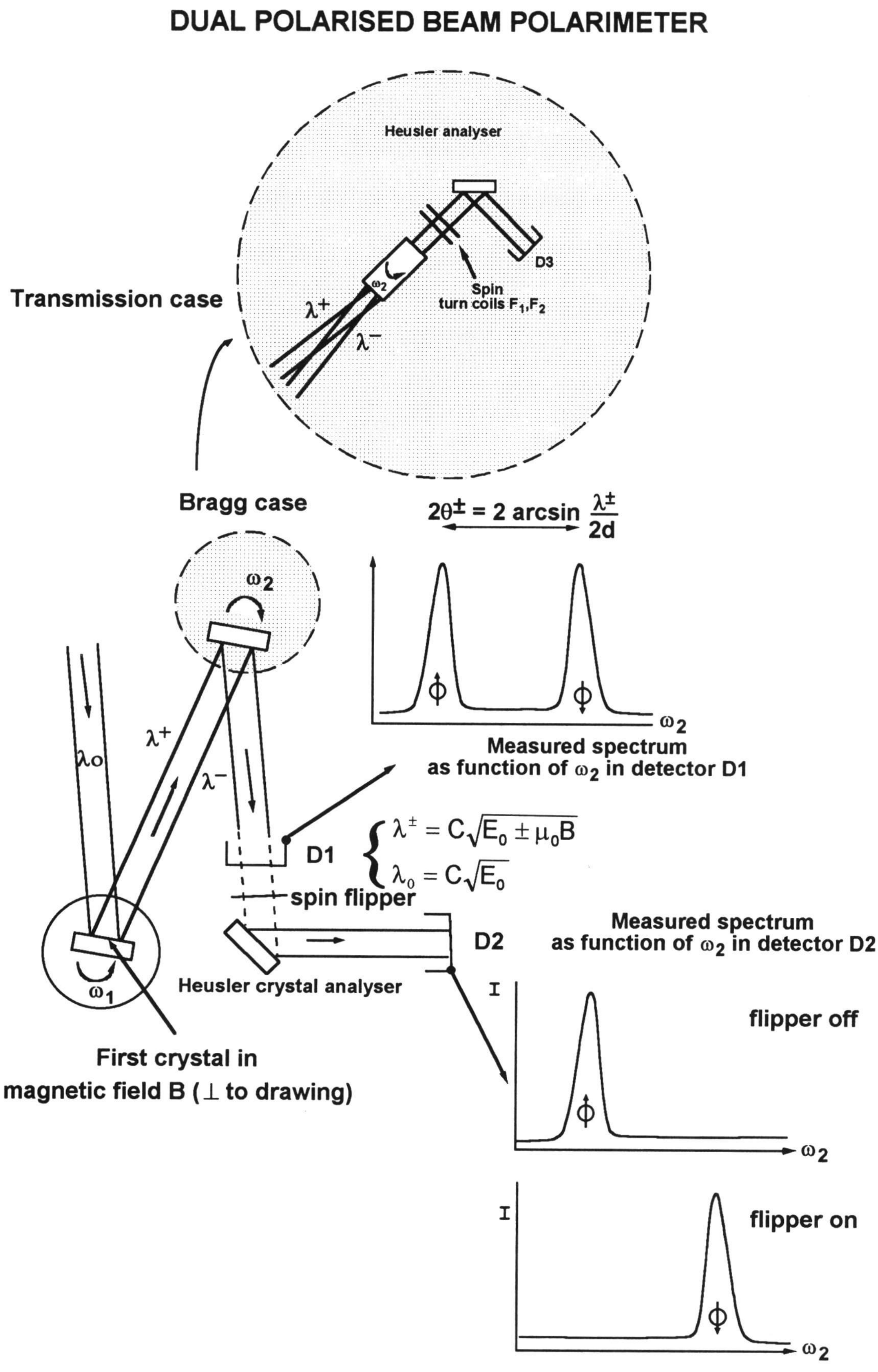

Fig. 3. The Dual Polarised Beam Polarimeter, the Bragg reflection case and the transmission case are shown.

For the observation of the S-O effect with the DPB technique, the two sub-beams are adjusted via $\boldsymbol{B}$ to travel in the x=±1 directions with respect to the second thick crystal. Spin rotations occurring in transmission of the second crystal can be observed as shown in Fig. 1, except that they occur in the x_1, x_2 plane. The spin direction of the neutrons transmitted by the second crystal is analysed with a system of spin turn and flipper coils and a Heusler analyser crystal. The neutrons are detected by D3 and the three different polarisation components are observed as a function of rotation angle ω_2.

The new transverse spin component appearing due to S-O antisymmetric spin rotations is measured by tuning the spin turn coils to be sensitive to this component only. The result can be directly compared, after deconvolution with the crystal reflection curve, to the spin rotation formula (2.3). This has been done for quartz crystals[3)] and BGO[9)].

To search for EDM, one has to adjust the DPB to a scattering angle providing sufficient suppression of S-O effect and with the initial polarisation P^+ and P^- along x_3 as in Figure 1.

4. Outlook

In this paper we have shown that the crystal Coulomb field can in principle be used to increase the sensitivity of the search for neutron EDM by two orders of magnitude as compared to the present lowest limit. This results from the very high effective Coulomb field in convenient perfect non-centro symmetrical crystals, despite the fact that the use of cold neutrons reduces the residence time of the neutrons in the crystal as compared to UCN storage techniques. We have used the S-O effect as an indicator in spin-rotation experiments to demonstrate that effective fields of up to 10^9 V/cm are indeed available in convenient materials. This in principle establishes the feasibility of EDM search experiments based on crystal fields and using antisymmetric spin rotations as an indicator for the existence of neutron EDM. The next step now is the detailed design of experimental conditions allowing a practical implementation of the ideas described in this paper.

Particular care has to be taken to eliminate any parasitic spin rotations arising from the Spin-Orbit effect. As expressions (1.1) and (1.2) show the ratio of $f_{S\text{-}O}/f_{EDM}$ vanishes in backscattering Bragg conditions. Hence the search experiments will have to be performed around backscattering. We think that this argument is the principal advantage of the Bragg geometry versus Laue geometry. Although Laue geometry has the advantage to increase the residence time τ of the neutrons in the crystal, its drawbacks are that only scattering angles around 45° are feasible and that the recording of the Pendellösung oscillations requires extremely good momentum resolution.

The present crystal field technique combined to the very sensitive polarimeter represents a new approach to neutron EDM. It could become complementary, together with the superfluid He and 3He technique proposed by Golub[8)], to the UCN techniques improved very successfully during the last two decades.

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1) C.G. Shull and R. Nathans, *Phys. Rev. Lett.* 19 (1967) 384.
2) P. D. Miller, W. B. Dress, J. K. Baird and N. F. Ramsey, *Phys. Rev. Lett.* 19 (1967) 336.
3) M. Forte and C.M.E. Zeyen, *Nucl. Inst. and Meth. in Phys. Research* A **284** (1989) 147-150 - Proceedings of The International Workshop on Fundamental Physics with Slow Neutrons, ILL, Grenoble, March 8-11, 1989.
4) P.J. Brown and J.B. Forsyth, *Acta Crysta.* A, in press.
5) M. Forte, *Lettere al Nuovo Cimento* 34 (1982) 296.
6) R. Golub and J.M. Pendlebury, *Contemp. Phys.* 13, 6 (1972) 519.
7) V.V. Fedorov et al., *preprint* 1644 (1991) LNPI Gatchina.
8) V.F. Sears, *Can. J. Phys.* 56 (1978) 1261.
9) Y. Otake, T. Tabaru and C.M.E. Zeyen, to be published.
10) Golub and S.K. Lamoreaux, *Phys. Rep.* 237, No. 1 (1994) 1-62.