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Edited by J. Ehlers, München, K. Hepp, Zürich
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Proceedings, Grenoble 1979

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PREFACE

The idea of Neutron Spin Echo was born in April 1972 at a red traffic light at the corner of Alagút street in Budapest. Within two weeks the basic points were experimentally verified at the reactor of the Budapest Central Research Institute for Physics. By the end of the year I was also able to demonstrate (this time at the Institut Laue-Langevin in Grenoble) that by this method one can really observe very small velocity changes of a neutron beam, independently of the velocity spread. Soon after, in January 1973, the ILL Council approved the construction of a proposed spin echo spectrometer (later to become known as IN11) for high resolution inelastic neutron scattering experiments.

The design of the new project was kept technically fairly simple and inexpensive, with a maximum of flexibility for tests. Nevertheless, the novel machine presented the ILL technical services with a number of unusual problems. By the end of the year 1973 John Hayter joined the project, and it was not until early 1977, after a large amount of work by many people, that real-life tests could begin. Routine user operation started in mid-1978 and the demand for beam-time has been increasing ever since.

There existed one uncertain point when the project was launched: how to produce a good polarized neutron flux. Fortunately, during 1976, Paul Dagleish and I succeeded in developing a new type of neutron polarizer, the "supermirror", which provides several times higher flux on IN11 than the next best solution. Without this development we would have had a lot fewer experimental results to talk about today. The problem of neutron flux in polarization analysis was, perhaps fortunately, not fully appreciated back in 1972 when I made the proposal to build IN11, and it remains the main experimental difficulty.

The present first workshop on Neutron Spin Echo, the organization of which was initiated by John White, took place at a time when there was enough "battlefield" experience with NSE to make a summary, especially intended to help future users who seem to be steadily increasing in number at the ILL. These proceedings were therefore made with the ambition of providing as complete as possible a reference manual for readers with just a little background in neutron scattering research, and also for specialists from other areas of neutron physics. For their convenience, the volume includes an appendix of facsimile reproductions of a number of original publications, which appear by the kind permission of the Copyright holders: Springer-Verlag (Appendices A and B), International Atomic Energy Agency (Appendix C), The Institute of Physics (Appendix D), The American Physical Society (Appendix E) and North-Holland Publishing Company (Appendices F and G), whose courtesy is gratefully acknowledged.

As the editor of this volume, I am indebted to the authors who accepted the burden of writing up their talks, often in extended form. The book has no monolithic structure. The papers appear, however, in the same logical order as they were presented at the workshop. They are essentially self-contained articles, in which the authors have freely expressed their own points of view and understanding of the subject. I also wish to thank Mmes. Wegener, Parisot and Volino in Grenoble and Miss Polgàr in Budapest for their careful typing of nearly all of the contributions and MM. Paul Dagleish and Harvey Shenker for their part in the proofreading.

To conclude I would like to express my very personal gratitude to all those whose help and collaboration marks the way from the original idea to the reality of this volume. They include many many people from the technical services at the ILL, numerous colleagues, particularly those who contributed to this book, and the successive directors of both the Institut Laue-Langevin and the Central Research Institute for Physics in Budapest, MM. Dreyfus, Jacrot, Joffrin, Lomer, Pàl, Springer, Szabò, White and especially Prof. Mössbauer. It has been the continuous interest, support and generous approach by these directors that have smoothed my way from that red traffic light onwards.

Budapest, March 1980 F. Mezei

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CHAPTER I:

The Neutron Spin Echo Method

THE PRINCIPLES OF NEUTRON SPIN ECHO

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INTRODUCTION

Neutron Spin Echo (NSE) is a particular experimental technique in inelastic neutron scattering. It is substantially different from the other, the "classical", methods both conceptually and technically. Conventionally, an inelastic neutron scattering experiment consists of two steps, viz. preparation of the incoming monochromatic beam and analysis of the scattered beam. The values of the measured energy and momentum transfer are then determined by taking the appropriate differences between the incoming and outgoing parameters measured in the two above steps. In NSE, both the incoming and outgoing velocity of a neutron (more precisely given components of these) are measured by making use of the Larmor precession of the neutron's spin. This kind of measurement could be called "internal" for each neutron, since the Larmor precession "spin clock" attached to each neutron produces a result stored on each neutron as the position of the spin vector serving like the hand of a clock. This is in contrast to the classical monochromatization or analysis, in which cases neutrons within a given velocity band are singled out "externally", i.e. by a selecting action measuring equipment. This difference is the technical one. In addition, since the Larmor precession information on the incoming velocity (component) of each neutron is stored on the neutron itself, it can be compared with the outgoing velocity (component) of one and the same neutron. Thus in NSE the velocity (component) change of the neutrons can be measured directly, in a single step, which is its conceptual novelty.

In this introductory paper the principles and the different types of applications of NSE are described. Although the presentation is self-contained, most technical and mathematical details are omitted here. These are extensively dealt with in the subsequent contributions and in the original papers reproduced in the Appendix of this volume, and the reader will be provided with ample references to these. In the first section the basic facts about Larmor precession in a polarized beam and the notion of the spin echo action are discussed. The second section is devoted to the introduction of the simplified principle of Neutron Spin Echo as a method of inelastic neutron scattering spectroscopy, applicable to quasi-elastic and non-dispersive inelastic scattering processes. The following section gives the generalization of the NSE principle for the study of dispersive elementary excitations; the final one describes the effect of sample magnetism introducing the notions of Paramagnetic, Ferromagnetic and Antiferromagnetic NSE.

1. LARMOR PRECESSION AND SPIN ECHO

To the best of my knowledge Larmor precession in a neutron beam traversing a magnetic field region was first observed by Drabkin et al.[1] as early as 1969. Unfortunately this work was not known to me until recently; it was in 1972 that I started to work on Larmor precession by introducing a simple new technique for turning the neutron spin direction in any desired direction with respect to the magnetic field direction[2] (see also the Appendix). This technique is described in the following paper by Otto Schärpf, together with more details about Larmor precessions. For the moment it is sufficient to recall that in a neutron beam travelling through a homogeneous magnetic field H_o and polarized originally parallel to the magnetic field direction $z \| H_o$, one can initiate Larmor precession by turning the polarization direction $\vec{P}$ perpendicular to the z axis, say into the x direction at a given point (surface) A along the trajectory (Fig. 1).

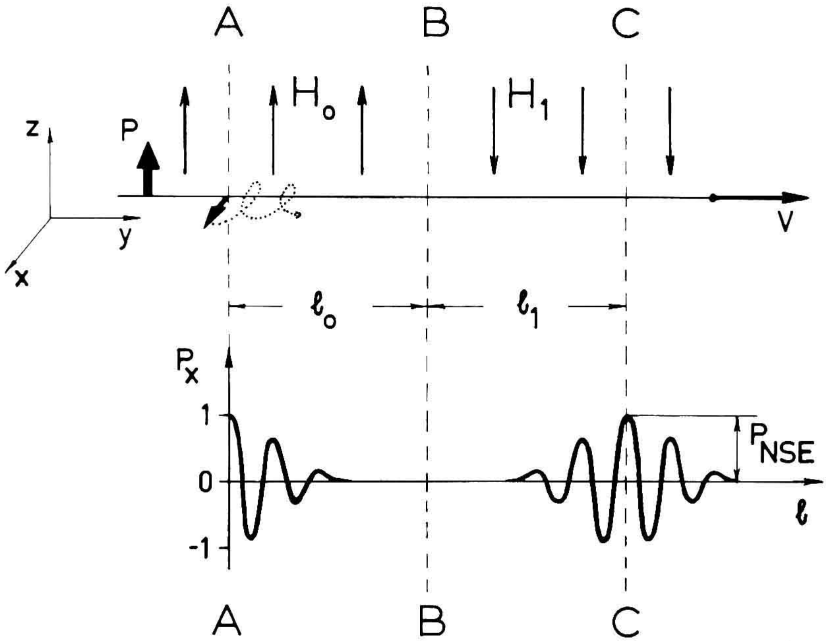


Fig. 1. Larmor spin precession of neutrons in a beam and the simple spin echo effect.

This $\frac{\pi}{2}$ turn initiates the Larmor precession which can be physically characterized, for example, by the x component of the neutron polarization - which obviously has a value of 1 at A. The basic fact about Larmor precessions in spin $\frac{1}{2}$ particle beams is that they can be exactly described classically except in situations where the Stern--Gerlach effect is appreciable, which only happens in very extreme cases with neutrons. This means that the particle beam will be described by a classical velocity distribution function f(v), and for each point-like particle the "classical" spin vector $\vec{S}$ follows the $d\vec{S}/dt=\gamma_L[\vec{S}x\vec{H}]$ classical equation of motion. A rigorous quantum mechanical proof of this theorem has been described recently by the author[(3)]. Thus the Larmor precession angle φ for a given neutron at a distance ℓ from A (Fig. 1) will be given as

$$\varphi = \gamma_L \frac{\ell H_o}{v} \quad , \qquad (1)$$

where γ_L=2.916 kHz/Øe. Since we measure φ with respect to the initial direction x, the polarization component P_x for the beam is given by the beam average

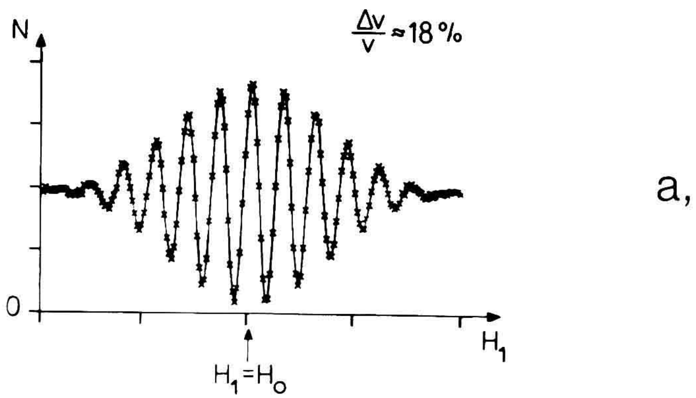
$$P_x = \langle\cos\varphi\rangle = \int f(v)\cos\left(\frac{\gamma_L \ell H_o}{v}\right)dv \qquad (2)$$

(Notice that here P_x is given as the Fourier transform of the distribution function for $\frac{1}{v}$, viz. $F(\frac{1}{v})=v^2 f(v)$, which is in fact the wavelength spectrum. This point is discussed in detail in the contribution of John Hayter; and also in the Appendix[(4)].) The behaviour of P_x with ℓ is easily seen from Eq.(2). As ℓ increases, the differences between φ's for different v's become bigger and bigger, i.e. the Larmor precessions for different neutrons become more and more out of phase. Consequently, the average $\langle\cos\varphi\rangle$ will tend to zero, and we obtain the characteristic behaviour of P_x shown in the lower part of Fig. 1 between A and B; this behaviour was observed by Drabkin et al. in 1969. The period of the damped oscillation is obviously related to the average beam velocity. Thus the observation of Larmor precessions is a simple way of measuring neutron velocities though it tends to be somewhat over-sensitive except for special high precision problems such as the one described by W. Weirauch et al. later in this volume. This sensitivity is illustrated by the large value of φ=1832 rad for H_o=100 Øe, ℓ=1 m and v=1000 m/sec (λ=4 Å).

In order to make more general use of the high sensitivity of Larmor precessions we have to eliminate this dephasing effect arising from the velocity distribution f(v). This is where the echo principle, common to various physical phenomena (one of which is described in the contribution of Badurek, Rauch and Zeilinger), becomes instrumental. In the present case it is realized by making the neutrons precess in the opposite sense after a certain time. This happens in section BC in Fig. 1, where field H_1 is opposite H_o. At point C

$$\varphi = \varphi_{AB} - \varphi_{BC} = \gamma_L (H_o \ell_o - H_1 \ell_1)/v \qquad (3)$$

and if the configuration is "symmetric", that is, $H_o \ell_o = H_1 \ell_1$, φ will be zero for all velocities v and thus $P_x = \langle\cos\varphi\rangle = 1$. Obviously, as is also illustrated in Fig. 1, P_x will show the same damped oscillation behaviour on both sides of C as that described for point A, since differences in φ build up in exactly the same way on moving away from C. It is clear from Eq.(3) that only the difference $H_o \ell_o - H_1 \ell_1$ is important, and in view of this the number of both the forward and the backward precessions, φ_{AB} and φ_{BC}, respectively, can be arbitrarily big (assuming that the fields H_o and H_1 are sufficiently stable and homogeneous). We will call this behaviour of the polarization P_x a "spin echo group" and the amplitude of the P_x oscillation at the symmetry position C will be called "spin echo signal", P_{NSE}. As has been pointed out, the spin echo group is the Fourier transform of the $\frac{1}{v}$ distribution function, $v^2 f(v)$, thus the narrower this distribution, the more oscillations are contained in the group, as shown by the measured curves in Fig. 2. Note that in practice one would change H_1 rather than ℓ_1; furthermore, H_o and H_1 will be parallel and the neutron spins are flipped at B instead, as in NMR spin echo (cf. Otto Schärpf's paper for details).



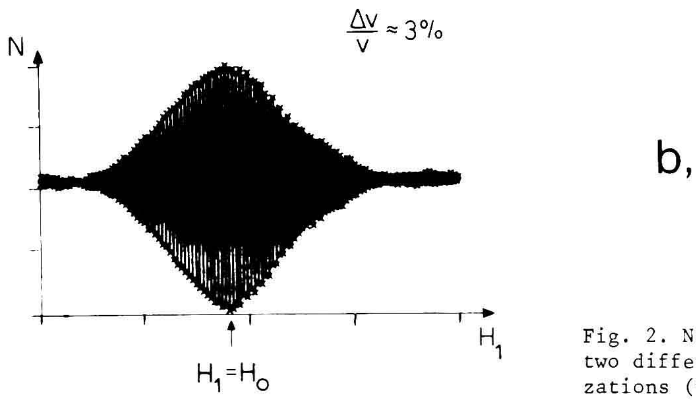


Fig. 2. NSE groups measured with two different beam monochromatizations (raw data).