PROGRESS IN PHYSICS WITH NEUTRONS AT LOW AND MEDIUM FLUX RESEARCH REACTORS

A. Zeilinger

Department of Physics

Massachusetts Institute of Technology

Cambridge, MA 02139, U.S.A.

and

Atominstitut der Oesterreichischen Universitaeten

Schuettelstrasse 115, A-1020 Wien, Austria

ABSTRACT

Besides their key role in early neutron physics, low and medium flux reactors are continuing to make contributions to that field. As examples of work where a method or idea was first tested at a low-flux reactor and then transferred to a high-flux facility, the first tests of the spin echo method by Mezei and the development of perfect-crystal interferometry by Rauch and co-workers are discussed. Koester's gravity refractometer work and its application to equivalence principle questions is an example of a complete research program carried out at a medium-flux facility. Finally, we present the neutron physics program at MITR-II which covered neutron interferometry and fundamental diffraction experimentation: development of interferometers, searches for Aharonov-Bohm effects, linearity of the Schrödinger equation, neutron drift motion in crystals, study of mirror reflection and simultaneous Bragg diffraction, spherical wave diffraction, longitudinal Stern-Gerlach effect and the neutron effective mass.

INTRODUCTION

In the present paper I will discuss a few experiments done at lower flux facilities and I will try to convey the impression that their common feature is a high level of scientific novelty. After general examples I will present and discuss as a specific case the neutron physics research program carried out at the MITR-II reactor since its upgrading in the mid 70's.

The neutron physics uses of low and medium flux reactors can be arranged very coarsely into two groups. The first group contains those cases, where work at such a reactor primarily served to demonstrate the feasibility of a new experimental method or to test a new principle. The routine application of the new method or its systematic exploitation is then transferred to a high flux source. The second group covers those cases where a full-fledged research program is carried out at the lower flux source and where any application at a high flux source is more or less accidental.

Demonstration of Neutron Spin Echo and Interferometry

A very prominent member of the first group is the preliminary demonstration of the basic principle of the neutron spin echo method as performed by Mezei (1) at the Nuclear Reactor of the Central Research Institute for Physics in Budapest, Hungary. In that pioneering work both the idea of a novel type of spin-turn coil is put forward and its use in novel inelastic neutron scattering experiments is proposed. In order to prove the feasibility of these ideas, two very simple and elegant experiments were done. In the first one Mezei demonstrated the feasibility of his new spin turners by varying the distance between two of them and thus tracing very nicely the Larmor precession in the external magnetic field. He also saw the important effect of a decrease of polarization with increasing distance between the two coils. By varying the wavelength spread he could identify this as being due to nonmonochromaticity of the neutron beam. But, most importantly, he reports an experiment where he recovered the initial polarization by employing a field reversal half way between the two spin-turn coils thus undoing the Larmor precession. This is the principle of the neutron spin echo. The subsequent and systematic development of this technique to a quite successful inelastic scattering method as done at the ILL Grenoble is one of the highlights of recent neutron physics experimentation (2).

Also into the first group falls the development of neutron interferometry. This technique was first developed at the small 250 kW TRIGA reactor in Wien (3). Quite unexpectedly, the neutron interferometer did not work when subsequently moved to the Grenoble high flux reactor, but transferring it back again to Wien brought it back to life (4). It was then realized that the reason for that strange behavior was the extremely high sensitivity of the interferometer operation to ambient vibrational rotation noise (5) which happens to be low enough in Wien, in contrast to that at the busy high flux facility.

Gravity Refractometry and the Equivalence Principle

As an example of the second group of experiments I mention the development of the gravity refractometer at the Garching Atomei reactor by Koester and co-workers (6). There one measures the reflectivity of liquid mirror surfaces as a function of the height of fall of neutrons. If the surface is smooth enough, this method is one of the most precise existing ones for the measurement of neutron refractive indices and hence for the determination of scattering lengths and thus it has led to numerous precision determinations of these quantities. A very interesting fundamental physics aspect comes in, when the results thus obtained by gravity refractometry are compared with those obtained via other methods not involving gravity (7). It turns out that the scattering lengths determined via these different methods agree with each other on the average within about 3×10^{-4}. This result leads strong support to the universality of free fall and hence to the equivalence principle on the level of individual particles. Though such experiments probably never will attain the level of precision reached by experiments on macroscopic bodies, the mere fact, that they are done with masses many orders of magnitude smaller is significant.

Numerous other cases of successfull neutron physics work at various low and medium flux reactors around the world exist. Among those I point out the development of ultra-cold neutron capabilities in Munich and at various reactors in the USSR (8). Another outstanding example is the neutron interferometry work of Werner's group at the Missouri University Reactor (9).

NEUTRON PHYSICS AT MITR-II

The work done covered mainly the fields of neutron interferometry and of dynamical diffraction, i.e. diffraction at perfect crystals. Two other projects concerned with fundamental solid state physics questions (10,11) are again examples of successful cooperation with a high-flux facility.

Development of New Interferometer Types

Working initially with a three-crystal interferometer interference action within one individual beam was observed. This led to the development of a two-crystal Laue-case interferometer (12). In such an interferometer the in-crystal propagation properties of neutrons are explicitely utilized (Fig.1). This interferometer type is easier to

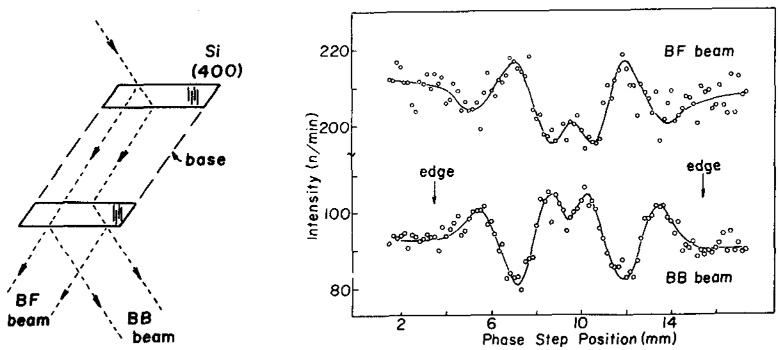

Fig.1: The Laue-case double-crystal interferometer. Principle (left) and interference action due to a 3π step in the beam.

fabricate than the conventional three-crystal interferometer, with the useable neutron intensities somewhat but not significantly lower. During routine application of that interferometer interference contrasts of 90% or better are regularly attainable. This interferometer type is very sensitive to the relative angular orientation of the two crystal plates as signified by the fact, that the empty interferometer interference pattern as shown in Fig.1 is characteristic for a deflection of the beam on its way between the two crystals by 5.6×10^{-3} arc sec. The resulting high angular sensitivity is given by the ratio λ/w between the wavelength λ of the neutrons and the width w of the beam, because a change of the optical path by λ at the edges of the beam produces the phase shift 2π between these extreme rays. An alternative but equivalent interpretation of the same phenomenon has been given in terms of the oscillatory character of Laue-case rocking curves (13).

This same interferometer crystal has recently been employed in an experimental demonstration of a Bragg-case neutron interferometer (14) where one uses explicitly those waves which even in the Bragg case penetrate deeply into the crystal and are partially reflected at its back face. Since on the average the transmission and reflection coefficients are rather small, that interferometer type suffers from lower available intensity. In the experiments a precision determination of the intensity distributions of the interferometer beams was done in order to demonstrate quantitatively the validity of dynamical diffraction theory calculations and excellent agreement was found (Fig.2). Also, the interferometer operation could success-

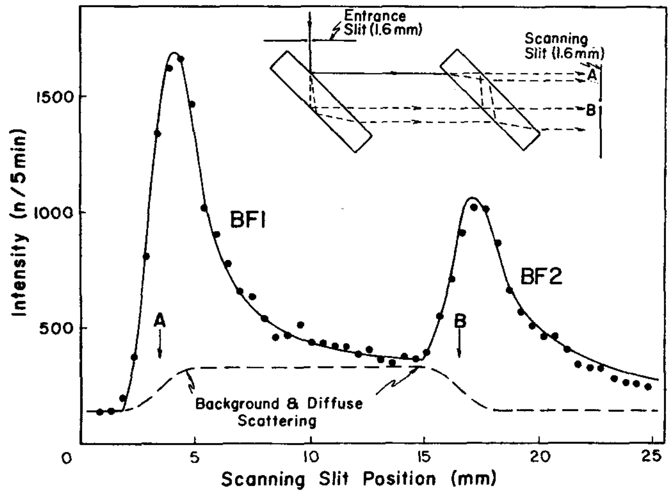

Fig.2: Measured intensity distribution (points) behind a Bragg-case double-crystal interferometer together with theoretical first principles prediction. Note the TDS background shelf.

fully be demonstrated. The advantage of this interferometer type is that one of the interfering beams does not suffer from Borrmann-fan spreading.

Searches for Neutron Aharonov-Bohm Effects

In an early stage a three-crystal interferometer was employed in a search for an isospin Aharonov-Bohm effect (15). The existence of such an effect had been proposed by Wu and Yang (16) based on a possible gauge principle related to isospin conservation. In the experiment the solenoid of the conventional Aharonov-Bohm experiment was substituted by a rapidly spinning uranium rod in order to create an "isospin vector potential". The result found can be interpreted as giving upper limits on the strength and/or range of such an unknown interaction.

Using the Laue double-crystal interferometer a conventional Aharonov-Bohm effect, i.e. a coupling of the neutron to the electromagnetic vector potential, was searched for (17). The magnetic flux was produced by a ferromagnetic frame crystal. The null result obtained had been expected on the basis of the electric neutrality of the neutron. From a broader point of view it places a limit on more complicated coupling mechanisms of the neutron to the electromagnetic field.

The Neutron and the Schrödinger Equation

From the early days on neutron interferometry was used to demonstrate the peculiar behavior of deBroglie waves. This leads to the possibility of explicitely testing the Schrödinger equation in particular its linearity. An experiment appropriate for testing the reality of some nonlinearities (18) had been proposed by Shimony (19) for the Laue-case double-crystal interferometer. The experiment gave a null result (20) on the basis of which a new upper limit on the strength of hypothetical nonlinear terms in the Schrödinger equation could be given. This result was later on improved again in a conceptually different cold neutron experiment. (21).

Another quite recent experiment concerned the verification in the Laue-case double-crystal interferometer of the neutron analog of the Sagnac effect (22). There the effect on the phase of the neutron of active laboratory rotations is observed. The result can be interpreted as a test of the validity of the Schrödinger equation in non-inertial frames. This is related to the question of the proper de-

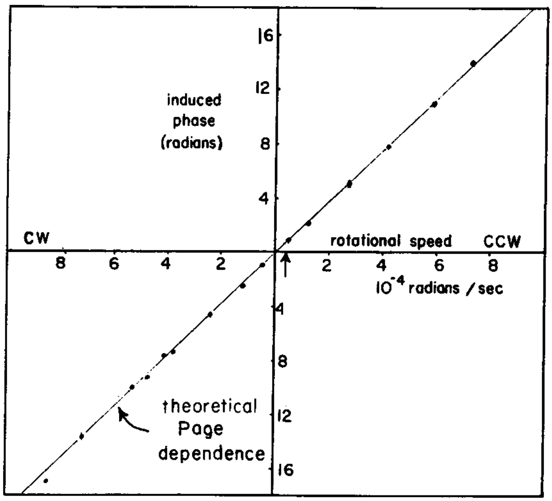

Fig.3: The neutron Sagnac experiment. The measured phase shift agrees excellently with the expectation.

scription of the neutron wave inside a noninertial diffracting crystal. For the double-crystal arrangement it turns out that the conventional approach of the phase shift being proportional to the area enclosed by the beams is still valid for low rotation speeds. The experiment done at rotation speeds many times that of the earth is in excellent agreement with that prediction (Fig.3).

Fundamental Dynamical Diffraction Experiments

Besides the application of dynamical diffraction in neutron interferometry, a number of experiments directly aiming at dynamical diffraction phenomena have been performed. An interesting prediction of dynamical theory is, that the propagation velocity of neutron wave packets inside a crystal should be smaller than the vacuum speed quite analogous to waveguides. All neutrons which propagate within the Borrmann fan have a common drift velocity v_d which is related to the normal group velocity v_g as $v_d = v_g \cos \theta_B$. The longer transit time resulting from the reduced drift velocity was measured (23) using a 20.41 cm long crystal (Fig.4). The agreement of the results with theoretical expectation was excellent. In the experiment we also observed the anomalous transmission effect due to dynamical diffraction.

Other rather fundamental work concerned a dynamical diffraction analysis of simultaneous mirror surface reflection and Bragg diffraction at the same crystal (24). Detailed numerical calculations led to various predictions. One of them is that at incidence below the critical angle the Bragg-diffracted wave is extremely weak despite the existence of the evanescent wave inside the crystal. This was experimentally veryfied by studying the diffraction at internal lattice planes with neutrons incident at grazing angles at a highly

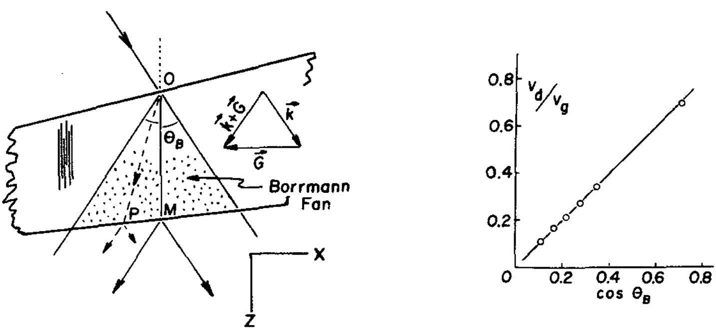

Fig.4: Measurement of the drift velocity of neutrons in crystals. Principle (left) and experimental results (right).

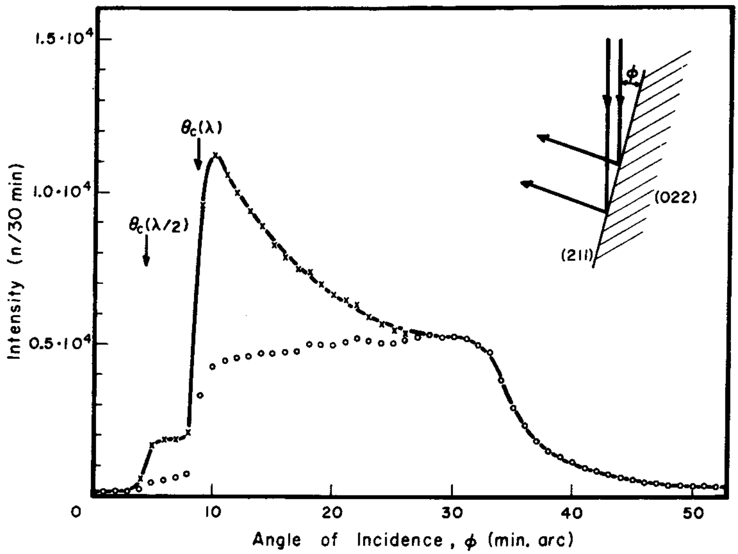

Fig.5: Bragg reflectivity at grazing incidence. The cutoff at the critical angle is clearly visible, the lower-angle cutoff is due to second order radiation.

polished external crystal face (Fig.5).

Experimental work finished recently concerned the influence of the width of a defining entrance slit on the intensity distribution behind the Laue-case double-crystal interferometer (25). If such slits are fine enough, they introduce spherical wave type coherence between rays incident from different directions which leads to characteristic changes in the spatial intensity distribution at the back face of the second crystal plate.

Related to the high angular sensitivity of the double-crystal arrangement very small changes of the neutron wavelength are measurable. This was shown in a determination of the minute change of neutron momentum when entering a magnetic field (26). This is the longitudinal Stern-Gerlach effect since with long enough flight path a separation of the spin states in a direction parallel to their momentum will result.

Another interesting experimental possibility was found when comparing the spatial intensity distributions after crystal diffraction with dynamical theory. As shown in Fig.2 an anomalous background level can be found which results from temperature diffuse scattering (TDS). This leads to a new method of directly observing TDS (27).

A completely new field of work arises when a force is applied on the neutron while propagating in a crystal under diffraction conditions as treated theoretically by Werner (28). Forces of sufficient strength are the neutron's gravitational interaction and the interaction of the neutron magnetic moment with gradient fields. An experiment using the latter is analogous to the Stern-Gerlach effect and has been proposed by Zeilinger (29). Such experiments can be described by introducing the concept of an effective mass in analogy to electrons in solids (30). The effect scales with the ratio between the neutron kinetic energy and the neutron potential of the crystal. The deflections found inside a crystal are therefore characteristically larger by five orders of magnitude than those in the same field configurations in free space. Fig.6 shows the setup used together with the experimental results. The results agree nicely with the theoretical prediction based on the effective mass concept.

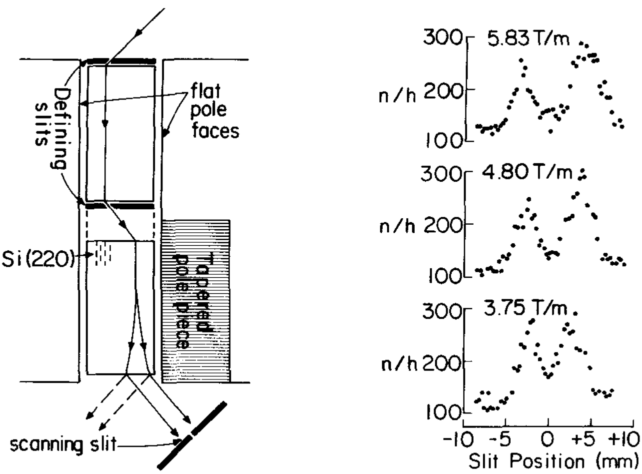

Fig.6: Measurement of the effective mass of neutrons in crystals. Schematic sketch of the setup (left) and experimental results (right). The free-space deflection in the same gradients would be of the order of 10^{-8} m.

Concluding Comments

I hope that I was able to demonstrate convincingly that neutron physics at small and medium flux reactors plays a useful role particularly when basically new questions with as yet no or little support in the scientific community are tackled. It is also a well-known fact, that for innovative work the direct university connection is vital. It should be mentioned in that sense that the yearly operation cost of university based reactors in the United States are only about 15% of the operating costs of all U.S. neutron source reactor facilities with the research program support for low energy neutron scattering at these university facilities being only 9% of that at all reactors (31).

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