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LOW TEMPERATURE AND NEUTRON PHYSICS STUDIES

Progress Report
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"Low Temperature and Neutron Physics Studies"

Abstract

Experimental research work with the neutron diffraction spectrometers at the MIT Research Reactor has concentrated during the past period in two general areas, (a) a study of diamagnetic scattering of neutrons by bismuth and (b) physical effects associated with dynamical diffraction by perfect crystals. The former study has shown that the outermost valence (or lattice) electrons contribute dominantly to the field-induced diamagnetism. Fourier transformation of the scattering data has provided maps showing the distribution of diamagnetization density throughout the unit cell with pronounced spatial variations. In the latter studies, some of the anomalous effects associated with neutron propagation through diffracting perfect crystals have been investigated. These include the very sensitive modification of transport direction within the crystal when the entrance direction is changed slightly or when the neutron energy is changed slightly by application of a modest magnetic field. Additional studies have shown that neutrons propagate through a diffracting crystal with a drift velocity which can be pronouncedly smaller than the usual group velocity.

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Introduction

During the past contract period ranging from December 1, 1977 to the present, we have carried on an active experimental research program in our Neutron Diffraction Laboratory in two general areas, (a) a study of diamagnetic scattering by bismuth and (b) physical effects associated with dynamical diffraction by perfect crystals. These studies have of course been carried out with the neutron diffraction spectrometer facilities set up at the MITR-II Research Reactor which has been operating very regularly since reconstruction during the period 1975-1977. Our facilities have been augmented by those available at the HFIR Reactor at Oak Ridge in the case of the bismuth study since here it was imperative that the highest intensity be used in the final stages of data collection. We have been fortunate in having very strong visiting scientist support during most of this period with the presence of Dr. A. Zeilinger (Research Associate from Atominstitut der Österreichischen Universitäten, Vienna) and Professors G. L. Squires and M. A. Horne on sabbatical leave from University of Cambridge and Stonehill College respectively.

Project Research Activities

(A) Diamagnetic Scattering of Neutrons by Bismuth

Bismuth has long been known to possess anomalous diamagnetic properties in that the diamagnetic susceptibility is nearly an order of magnitude larger than that expected and moreover it exhibits both a directional and a temperature dependence. It became apparent a few years ago that the sensitivity of the polarized neutron scattering technique in studying very small magnetization effects had reached the point where one might hope to study diamagnetization effects in crystals. Accordingly a search for this in bismuth was started which turned out to be successful. Moreover there were indications of directionality and temperature effects and it was decided to make a major research effort in studying this problem. The preliminary study was interrupted by our reactor reconstruction and we have now resumed the study in the form of a doctoral thesis presentation by Mr. S. Collins.

In the present study, a collection of new specimen crystals was prepared and after orienting and cutting these into suitable geometric form, extensive mosaic structure studies were carried out. It is imperative that this mosaic structure be carefully characterized so that the eventual polarized neutron intensities can be properly interpreted with respect to extinction losses and secondary scattering effects in the diffraction process. In attempting to minimize these perturbing effects, it was established that the usual cold-pressing technique introduced a strong mosaic directionality depending upon strain direction in the crystal. This was studied in detail until finally specimen crystals with desired characteristics were obtained. Following these characterization studies at MIT, the specimen crystals were taken to Oak Ridge where a period of polarized beam data collection had been scheduled at the HFIR Reactor with the collaboration of Dr. R. M. Moon.

In the polarized beam study a strong magnetic field of 4.25 Tesla is applied to the specimen along the neutron polarization axis. Polarization ratio (intensity ratio upon neutron polarization inversion) measurements were obtained for 23 Bragg reflections about three zone axes (trigonal, binary and bisectrix). This yields a set of diamagnetic structure factors or diamagnetic scattering amplitudes as a function of the scattering angle variable $\sin \theta / \lambda$. Such amplitudes show a very pronounced angular dependence as well as a directional dependence. This implies that the electrons that contribute dominantly to the diamagnetism are far removed from nuclear sites and that they are distributed in an asymmetric way about atomic sites.

This very interesting, real-space structure of the contributory diamagnetic electrons is seen most clearly when the experimental structure factors are Fourier transformed. Such procedure yields a set of projection (as viewed along the three zone axes) maps which portray the diamagnetization density as a function of position in the unit cell. These maps show regions of excess and deficient (relative to the spatial average) diamagnetization at positions far removed from atom centers. Thus we are able to map out the response of electrons (which are better considered lattice rather than atomic electrons) to the applied field. In a way, this is a portrayal of the effective mass that the electrons exhibit as a function of their instantaneous position in the lattice.

(B) Magnetic Field Effects on Dynamical Diffraction of Neutrons by Perfect Crystals

When neutrons enter a perfect crystal at the exact Bragg angle for diffraction, it is expected (and confirmed by experiment) that they propagate along the diffracting atom planes until reaching the exit surface where they split coherently into two components travelling in the forward and Bragg directions. This action forms the basis of interferometric systems which have been studied and exploited in recent years. If now a magnetic field is applied to such a crystal, the neutron energy (and wavelength) is altered and exact Bragg conditions are no longer satisfied. With a modest field, the wavelength change is very small and the crystal will still accept the neutrons for diffraction. However the direction of propagation within the crystal is affected in a gross way, many orders of magnitude larger in angular change than the angular change of the Bragg angle associated with the energy shift. For example a field of only 1660 gauss with neutrons of incident energy 0.02353 eV ($\lambda = 1.865 \text{ \AA}$) produces a wavelength change of $40 \cdot 10^{-8} \text{ \AA}$ and hence a Bragg angle change of $1.15 \cdot 10^{-5}$ degrees, but the direction of propagation of neutrons within the crystal changes by 5.1 degrees!

These implications, that follow directly from dynamical diffraction theory, have been given direct experimental test in experiments performed during the last period. The necessary incident neutron beam (all of which are incident on the test crystal at exact Bragg angle within 0.01 arc second) were prepared by a crystal collimator first demonstrated by Shull and a modest magnetic field was applied to the test crystal of Si (of thickness 1 cm) in (400) diffraction. The resultant shifts of angular propagation were sensed by scanning the intensity profile on the exit face and these were found to

fully support the theoretical expectation. Thus we have demonstrated a technique that can sense (and quantitatively measure) neutron energy changes of less than 10^{-8} eV. This is an order of magnitude greater in sensitivity than competing techniques, namely the spin-echo and back-reflection techniques, have been able to attain.

Further implications in this study follow that the neutron shifts are also to be associated with neutron spin state separation and a separate study of this aspect has indeed shown that components of the exiting beam are completely polarized. Thus we have shown that neutrons can be polarized by scattering from non-magnetic crystals.

(C) Anomalous Flight Time of Neutrons in Diffracting Crystals

It has been mentioned above that neutrons which approach a crystal at exact Bragg angle (the so-called central ray neutrons) propagate through the crystal along the Bragg planes. Within the crystal one must consider two propagating waves, one travelling in the Bragg direction and one in the forward direction with dynamical interaction between the two, and this results in energy propagation along the Bragg diffracting planes. A consequence of this is that neutrons travel through the crystal with an anomalous drift velocity which is smaller than the normal group velocity by the factor $\cos \theta_B$. Thus the transit time through the crystal is expected to be longer than normal.

We have studied this anomalous effect by use of a small neutron chopper, giving time separated bursts of neutrons, before a long length crystal (20 cm) of silicon placed in Bragg diffraction. With the use of a multi-channel analyzer and a small He^3 detector at the end of the crystal ingot, the flight time through the crystal could be measured. Measurements have shown indeed the existence of this anomalous drift time. At present we have measured drift times as much as 250% longer than normal travel time and this is being extended to cases where the anomaly will be even greater. In principle there is no limit to this and one can think of exploiting this to obtain very large storage times of neutron radiation within crystals. This storage feature differs from that of the usual storage technique (total reflection by cavity walls of ultra-cold neutrons) in that neutrons of normal thermal energy can be utilized. It is tempting to think of interesting experimentation in which this is exploited.

Laboratory Staff

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 Dr. A. Zeilinger, Research Associate (until November 1978)
 Professor M.A. Horne (on sabbatical leave from Stonehill College
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 Mr. A. D'Addario, Engineering Design Assistant

Laboratory Publications

Four papers as follow were presented at the "International Conference on Neutron Interferometry", Institut Laue-Langevin, Grenoble, France in June 1978. These are to be published in the Conference Proceedings, Oxford University Press, 1979.

"Laue-Case Dynamical Neutron Diffraction with Perfect Non-Magnetic Crystals in Magnetic Fields"

A. Zeilinger

"Fizeau Effect for Thermal Neutrons"

M.A. Horne and A. Zeilinger

"Some Magnetic and Spin Effects in Neutron Interferometry"

A. Zeilinger

"Two-Crystal Neutron Interferometry"

A. Zeilinger, C.G. Shull, M.A. Horne and G.L. Squires

 "Magnetic Field Effects on Dynamical Diffraction of Neutrons by Perfect Crystals"

A. Zeilinger and C.G. Shull, Phys. Rev. B, April 1979.

"Exact Spin Precession during Neutron Interferometry"

H.J. Bernstein and A. Zeilinger, Phys. Letters 1979.