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Statistical Beam Modulation Techniques in Neutron Physics

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STATISTICAL BEAM MODULATION TECHNIQUES IN NEUTRON PHYSICS +)

by

K. H. Beckurts

+) This is a slightly modified version of an invited talk given at the Annual Meeting of the American Physical Society, New York, February 3, 1969

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1. Introduction

In recent years, the applications of neutron spectroscopy to many fields of science and engineering have expanded considerably. Although its most important use is probably still in nuclear technology, neutron spectroscopy has yielded many extremely valuable results in pure physics. These range from the verification of Landau's theory of excitations in superfluid Helium /1/ to Barschall's experiments /2/ which gave rise to the optical model of nuclear reactions, and to the most recent discovery of well defined doorway states in subthreshold fission reactions /3/.

Among the methods of neutron spectroscopy, the most widely used is the time-of-flight technique which basically consists in a measurement of the velocity of a neutron burst by its flight time along a predetermined path length. This technique has undergone many improvements over the last few years; with respect to resolution, it can now compete with, or even outdo, almost any other method of nuclear spectroscopy (Fig. 1 a). There is, however, one serious obstacle which at present limits the application of the time-of-flight method in many cases. This is the duty cycle problem. Since we normally have to analyze a spectrum containing neutrons of many velocities, we have to limit the burst rate of the source in order to avoid overlap of neutron groups from subsequent cycles at the detector. This means that for high resolution studies, the duty cycle and thus the counting rate may become prohibitively small (Fig. 1 b). This is not a problem when the source is "naturally" pulsed like in electron accelerator photoneutron systems or in nuclear explosions. However, most of our neutron sources are continuous and have to be artificially modulated. This holds in particular for the most expensive, by far, of all neutron sources, the research reactor. Mechanical chopper systems have to be used in order to modulate the beam and in most cases, more than 99 % of the pile neutrons are lost. Statistical beam modulation techniques, which have recently been developed at various laboratories,offer a promising way out of this problem and may thus lead to considerable expansion of the applicability of TOF techniques, especially in solid state physics.

2. Principles of Statistical Beam Modulation

Since the basic ideas to be discussed were largely adopted from communications engineering, let us discuss for a moment a time-of-flight experiment in the language of communication engineers (Fig. 2). Then, the time-of-flight distribution is called the impulse response function of a communication system, and there are three basic ways to measure it. The first way is to excite the system by short bursts and to observe directly the system response function. The second possibility is to excite the system by a sine wave; then the output yields the Fourier transform of the response function. Finally, it is possible to excite the system by white noise and to form a cross-correlation between input and output. Now, since the autocorrelation function of a white noise signal is a delta function in time, the output of the cross-correlation process will be the impulse response function. Obviously, the first method is the one which is employed in classical TOF experiments. The main point of this paper is that both the second and third method can also be used with neutrons. We shall concentrate, however, on the correlation method. We should mention that the Fourier transform method, sometimes also called neutron wave technique, is presently under development at Gulf General Atomic [13].

Actually, it is difficult to achieve a truly statistical modulation of a beam; also, for white noise an infinitely long correlation time would be required. It is therefore preferred to use modulation patterns which are almost random but actually periodic in time. A popular family of patterns are the so-called pseudonoise sequences (Fig. 3). Each PN sequence [4] is periodic with a certain multiple of a basic time step and consists of varying length intervals where the function is either "1" or "0". Fig. 3 shows a very short and simple PN sequence; in practice much larger cycle lengths are used. The autocorrelation function of a PN sequence is close to a periodic delta-function, actually it has a shape which is very close to the resolution function of a normal pulsed neutron source system. Note that the average value of this modulation pattern is 1/2. It is thus obvious that if we can modulate a neutron beam into a PN sequence, we can perform TOF experiments with good resolution but nevertheless get 50 % of the original beam into the actual experiment.

A word of caution should be added, however. The true gain in information rate does not always correspond to this enormous gain in intensity. In comparing the statistical and the classical method applied to the same problem and at the same resolution, one can draw up a simple diagram involving the actual signal, the average signal and the time-uncorrelated background. This is shown in Fig. 4 where straight lines of constant gain are drawn vs. the signal / average signal and background / average background ratios. The gain factor is defined as the ratio of measuring time in a "classical" and a "PN" chopper experiment with the same resolution and the same statistical accuracy. In the shaded area of small signals and small background, the statistical method is actually inferior to the classical method; it becomes the more superior the further we go away from the separating line. Fortunately, in most cases in physics we are far up since we either have high backgrounds or we are looking at resonance type phenomena which lead to a high value of the signal-to-average signal value. Gain factors as high as 70 have actually been reported.

3. PN Modulated Neutron Sources and Their Applications

Correlation analysis methods have been in use for a number of years in various fields of science, for instance in geophysics and in the space sciences. They were first introduced into neutron physics by reactor physicists who used pseudorandom modulated accelerator neutron sources in order to study the kinetic behaviour of subcritical reactors /5/. In 1968, statistical modulation systems for TOF studies werhe implemented independently by groups in Hungary /6/, at Argonne /7/ and at Karlsruhe /8/. All three are thermal-neutron systems at research reactors; they are thus primarily intended for solid state physics applications. Fig. 5 shows a so-called statistical chopping wheel at Karlsruhe. The thermal neutron beam which enters perpendicular to the very rapidly spinning disc is chopped into a PN sequence by a system of absorbing gadolinium masks properly dimensioned and spaced on the nonabsorbing aluminium. Fig. 6 shows the actual modulation pattern which was observed by placing a neutron detector directly behind the modulator. The autocorrelation function which is also shown shows very sharp maxima at the time zeroes, its width depends on the slit width and chopping speed and can be accurately calculated. This autocorrelation function, as all the cross-correlation functions to be shown later, can be obtained in real time using a small on-line computer.

Which are the new results which can be obtained using this technique? Since it is a very recent development, there are not yet many results; however, these few do look very encouraging. Fig. 7 shows some time-of-flight diffraction data on polycrystalline samples taken by Sköld at Argonne /7/. In neutron time-of-flight diffraction studies, the detector is kept at a fixed angle and a Debye-Scherrer reflection is seen whenever the wave length fulfills the Laue condition at the given detector angle. Time-of-flight techniques have a number of advantages over conventional two-axis continuous beam spectrometers, especially in studies of samples under extreme conditions. A detailed discussion of TOF diffraction methods was given recently by Brugger /9/. While for an aluminium sample, no great improvement is seen when a statistical correlation chopper was used instead of a normal one, a decided improvement occurs for the cadmium sample. This is so because cadmium is a very strong neutron absorber and the scattered intensity is extremely small, causing a very unfavourable signal-to-background ratio. The statistical method can thus be of great help in the further development of TOF diffraction methods, expanding their applicability to very highly absorbing materials, to very small samples of rare substances or to samples under extreme conditions. Also, one can now reach much higher resolutions. This is borne out in Fig. 8 where a diffraction picture of antiferromagnetic $BiFeO_3$, taken with a statistical chopper by Gläser and Gompf at Karlsruhe /10/, is shown. The data were obtained at a counter angle of 31^o. $BiFeO_3$ has a small rhombohedric distortion which should lead to a splitting of the 111, 220, 311 and some additional reflections. Apparently, the resolution is not sufficient to show this. The resolution can easily be improved by using a larger detector angle. Fig. 9 shows the situation at a detector angle of 150^o, we now can resolve the splitting of the peaks very well. The prize to be paid for the good resolution in back angle scattering is intensity and it is here where the correlation method is extremely useful. As an additional measure, a cooled Beryllium Filter was used in order to suppress the short wavelength part of the spectrum. This decreases the value of the average signal and thus enhances the gain factor for the statistical method.

Even more promising results have been obtained in inelastic scattering studies of phonons in metals. For these experiments, a neutron beam from the reactor is first made monochromatic by Bragg reflection. It is then modulated (Fig. 10 a) and the time-of-flight technique is used to measure the energy change of the neutrons caused by the creation or anihilation of a phonon in the scattering event. Drexel, Gläser and Gompf /11/ have recently started to use this method on such metals which have a high neutron absorption cross section and which are therefore difficult to attack by classical techniques. With the neutron flux available at their reactor, it is impossible to distinguish any real phonon effect in neutron scattering from silver (ratio of thermal neutron absorption to scattering cross section ≈ 13) when the classical modulation technique is used. With the statistical modulation technique, very clear phonon peaks can be seen (Fig. 10 b) after a reasonably short measuring time. The dispersion relation of phonons in silver as derived from the measurements is shown in Fig. 11. The curves represent a third neighbour Born- von Karman fit. Work on other metals is now in progress as part of a programme to study phonon-electron interactions in metals.

4. Further Applications of PN Modulated Sources

All these first results are quite encouraging, and lead us to believe that the potential of existing research reactors for solid-state investigations can be increased by a considerable factor if proper use is made of the statistical modulation technique. The potential of the technique, however, is still far from beeing truly exploited. For instance, it appears feasible to design multiple statistical modulation systems which could be used to simultaneously record the primary and secondary energy in a scattering event ("Statistical Double Chopper"). Another exciting possibility which largely rests on work done by the group in Hungary is explained in Fig.12 /6/ /12/. Let us assume that we want to study some small effects in the interaction of polarized neutrons with polarized nuclei. This can be done in such a way that a resonance-type spin flipping coil is driven by a pseudonoise sequence generator. We than can use this to modulate the polarization status of an incoming polarized neutron beam. By the spin-dependent interaction mechanism, this polarization modulation would be transformed into an intensity modulation and the energy of the neutrons after the interaction could be measured via time-of-flight. All spin-independent interaction would give rise to a time-uncorrelated background which could easily be rejected. This scheme could be helpful in many fields like diffraction from organic molecules, hyperfine interaction studies, spin-dependent cross-section measurements or the study of collective magnetic excitations in solids.

While almost all of the present work has been restricted to the modulation of thermal neutron beams from reactors, there is no doubt that similar concepts could be used in connection with non-thermal neutrons from accelerators. Quite different modulation techniques, based on charged-particle deflection or bunching, had to be developed. A very important application of statistical modulation techniques in the non-thermal range might be the measurement of nuclear cross sections of highly radioactive materials like the transplutonium elements or fission products. Here one could take advantage of the excellent background rejection capabilities of the statistical method.

Acknowledgement

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Fig. 1a HIGHEST RESOLUTIONS ACHIEVED IN NEUTRON TIME OF FLIGHT SPECTROSCOPY

AT 10^{-4} eV, $\frac{\Delta t}{L} \simeq 10^{-6}$ sec $m^{-1} \rightarrow \Delta E = 10^{-6}$ eV

ΔT 10^{6} eV, $\frac{\Delta t}{L} \simeq 5 \cdot 10^{-12}$ sec $m^{-1} \rightarrow \Delta E = 150$ eV

Fig. 1b THE DUTY CYCLE PROBLEM

T = BURST REPETITION TIME DUTY CYCLE $\frac{\Delta t}{T} \ll 1$

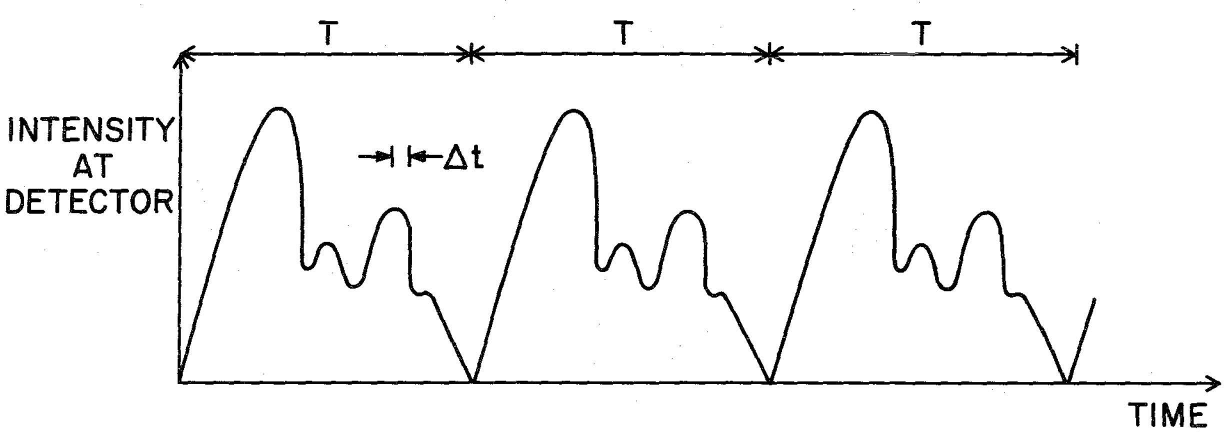


Fig. 2 METHODS TO DETERMINE THE IMPULSE RESPONSE FUNCTION

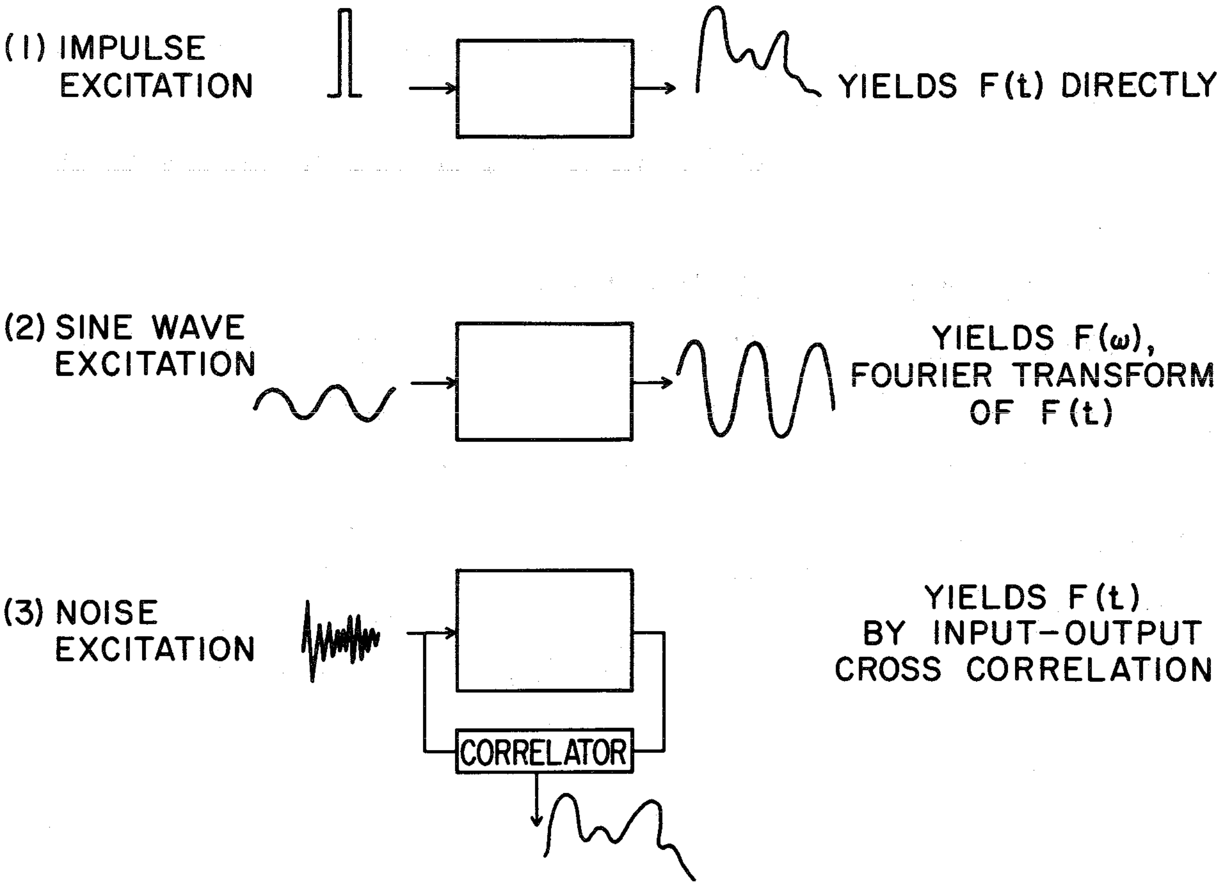


Fig.3 A TYPICAL PSEUDONOISE SEQUENCE AND ITS AUTOCORRELATION FUNCTION

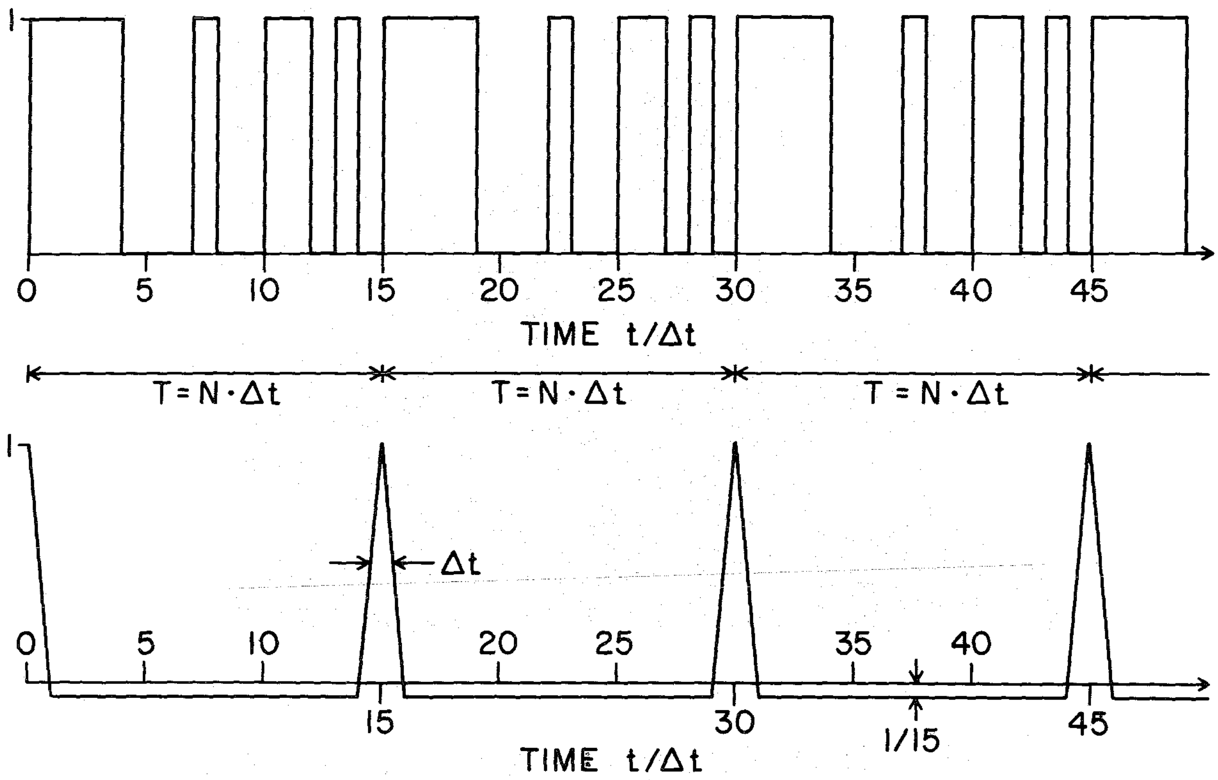
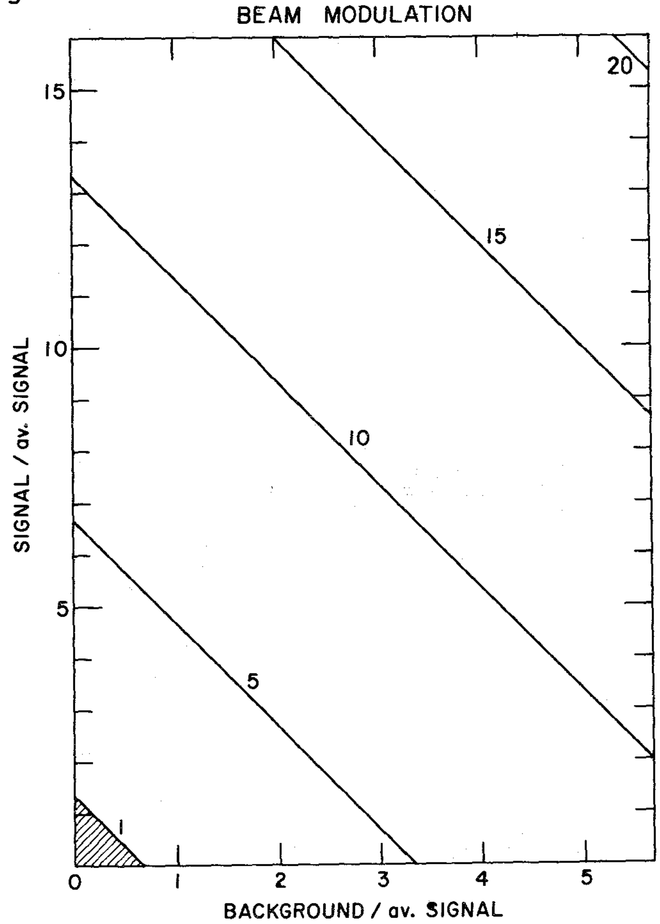


Fig. 4 GAIN FACTORS FOR STATISTICAL vs NORMAL BEAM MODULATION



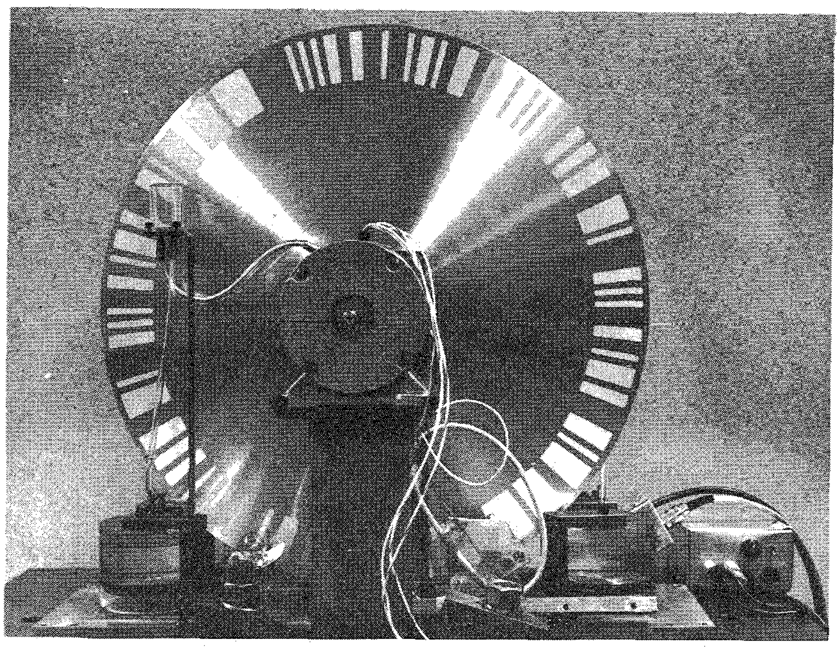


Fig. 5 Statistical Chopping Wheel of Gompf et. al. [8]

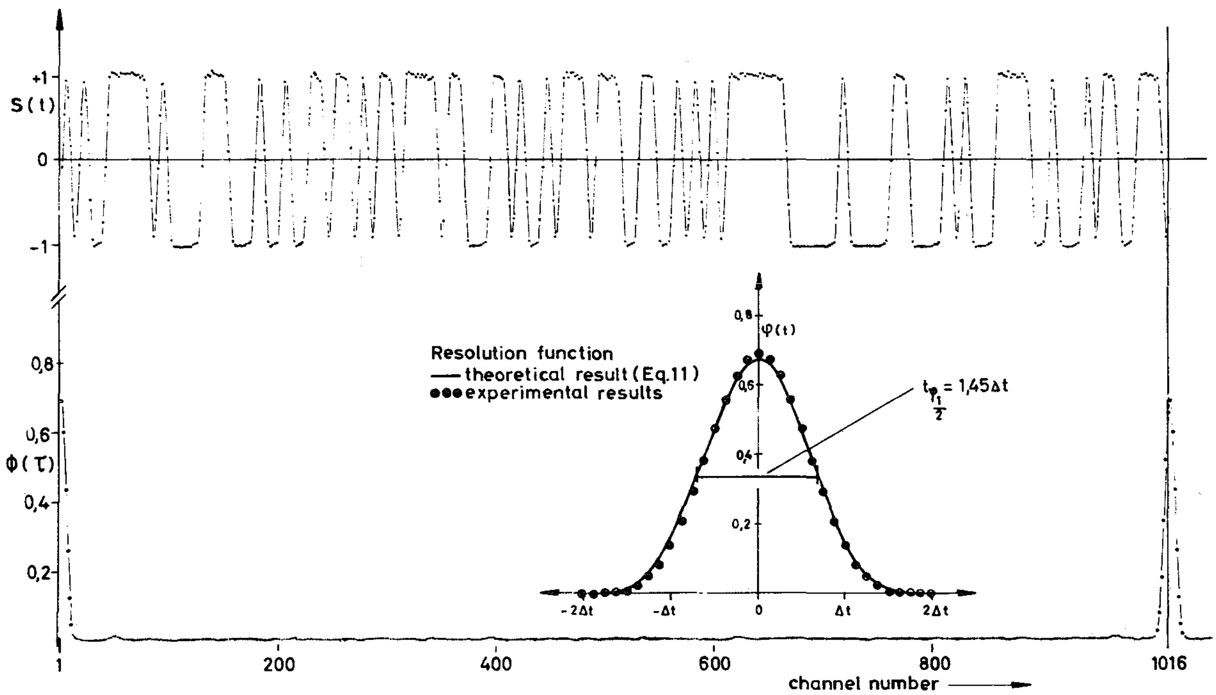


Fig. 6 a) Signal function S(t) b) Autocorrelation function $\Phi(\tau)$

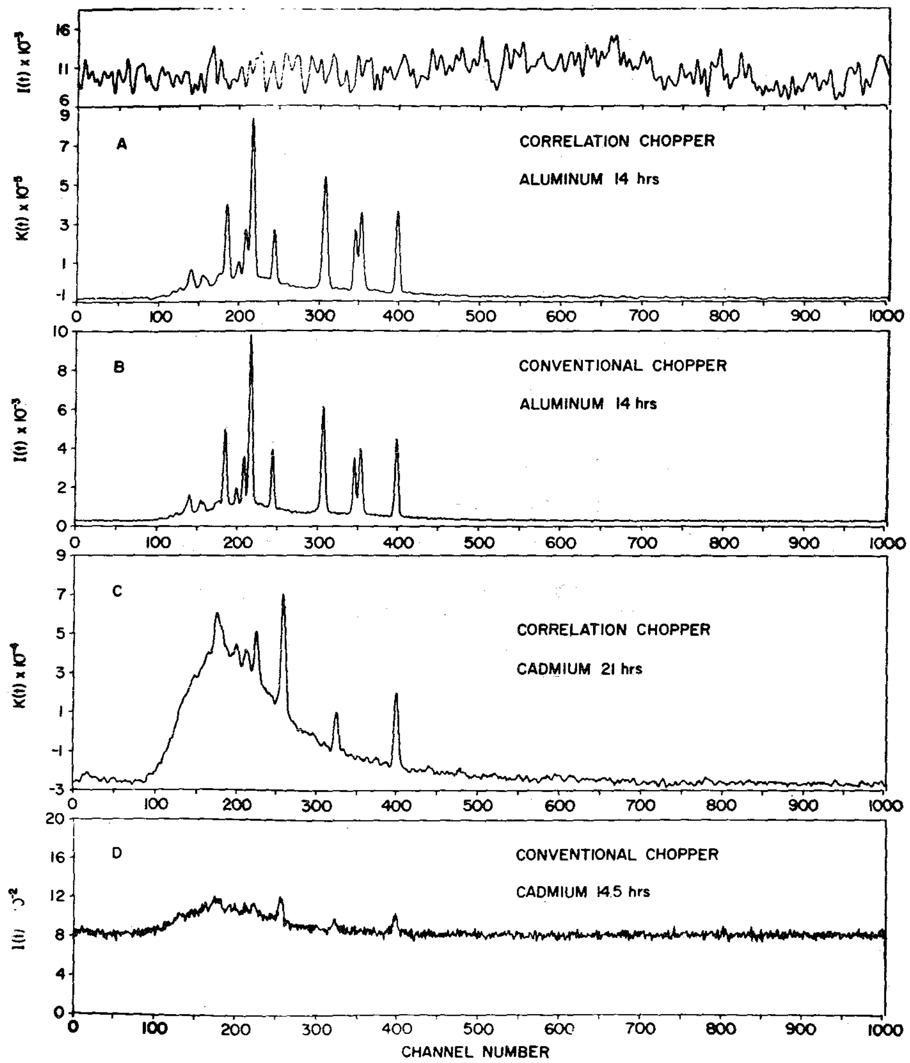


Fig.7 TOF Diffraction Data on Polycristalline Samples observed by Sköld [7]

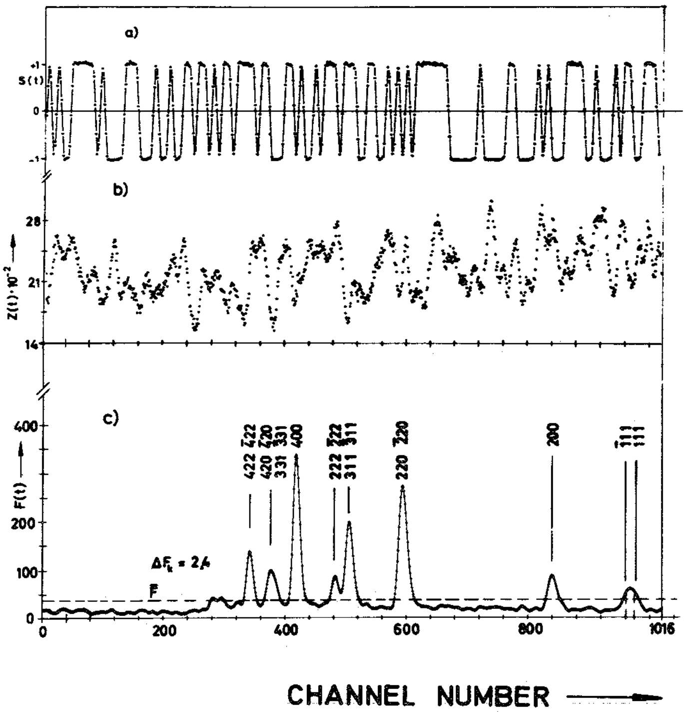


Fig. 8 a) Normalized signal function
b) Counting rate
c) Diffraction diagram for $BiFeO_3$, counter angle 31.4°, flight path 6.2 m measuring time 6.5 h

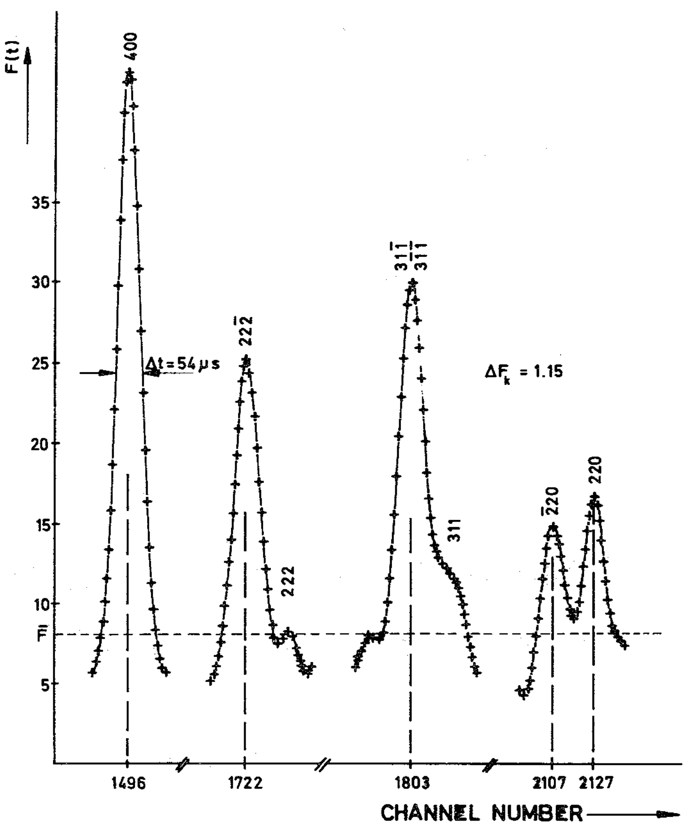
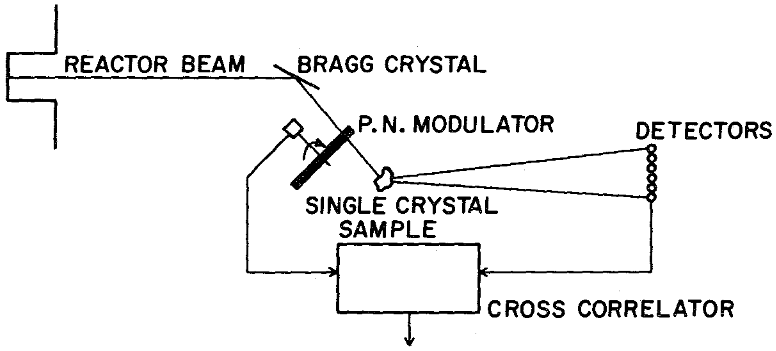


Fig.9 Diffraction diagram for $BiFeO_3$, flight path 6.2 m counter angle 150°, measured with a Be filter

Fig. 10a PHONON MEASUREMENT BY NEUTRON T.O.F. SPECTROSCOPY



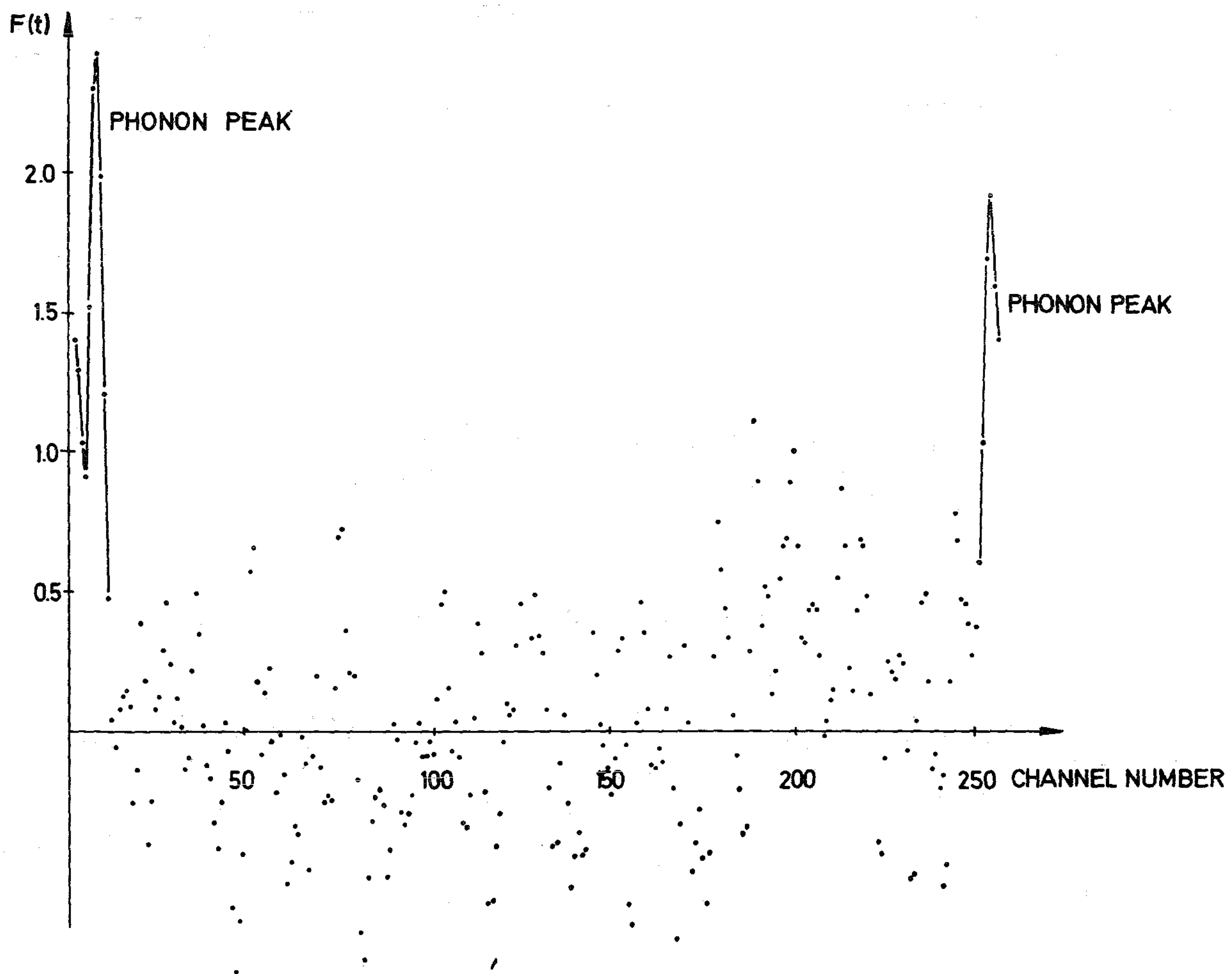


Fig. 10b NEUTRON TIME-OF-FLIGHT DISTRIBUTION FROM SILVER SINGLE CRYSTAL, CORRELATION CHOPPER, 24hrs.

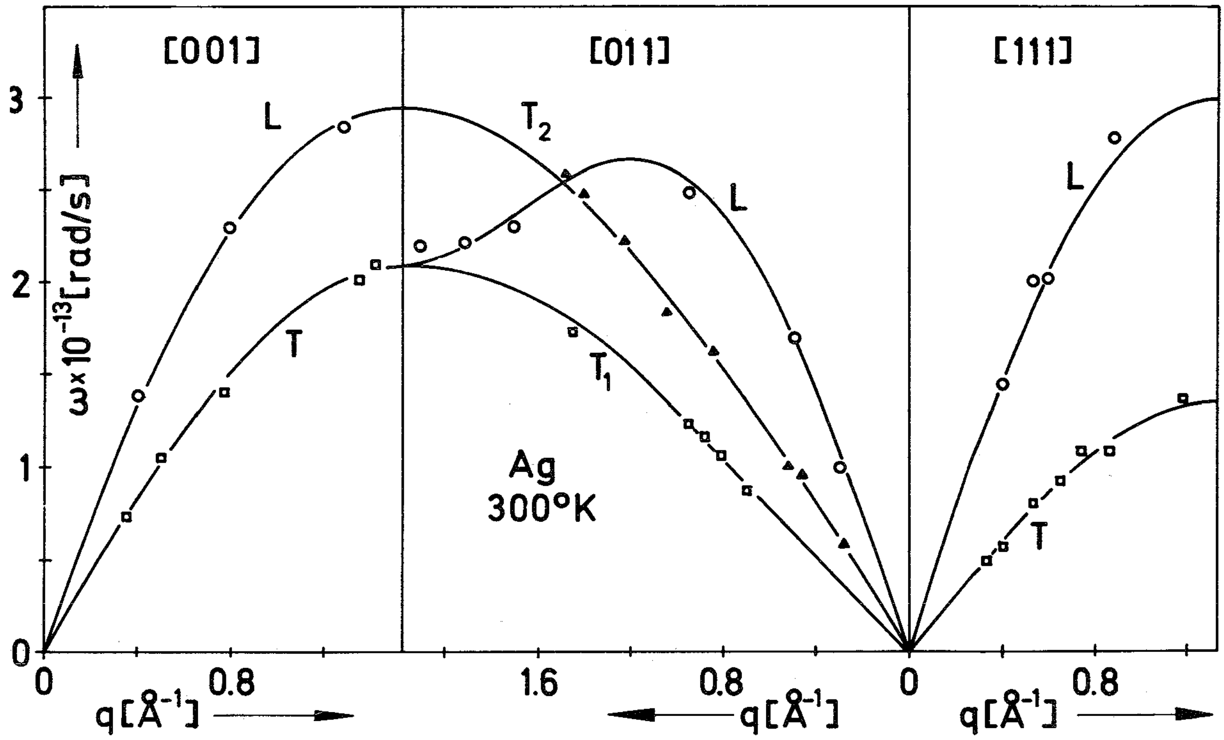


Fig.11 Dispersion curves for F.C.C. silver

Fig.12 POLARIZATION – MODULATED TIME OF FLIGHT EXPERIMENT