

**Some Aspects of Neutron Scattering in India
and Asia-Oceania Region: 1958-2012**

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Some Aspects of Neutron Scattering in India and Asia-Oceania Region: 1958-2012

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Prof. Yasuhiko Fujii, President, Asia-Oceania Neutron Scattering Association, fellow scientists, ladies and gentlemen, first of all allow me to express my deeply felt thanks to AONSA for their 2013 prize.

I understand the prize is awarded 'for impact or contribution to the use or development of neutron scattering science or technology in the Asia-Oceania region'. I shall, therefore, present some of my scientific contributions and try to relate them to the larger context of the growth of neutron scattering in our region. I hope this will become clear as I proceed. I consider this a great honour, and recognition of a lifetime of work in neutron scattering. I thank you very much. I appreciate this immensely.

Neutron scattering experiments are necessarily implemented at facilities which involve a large number of persons to run them and the experiments involve many colleagues. At the very outset, I would like to acknowledge my gratitude to my seniors from whom I learnt the rules of the game, express my thanks to contemporaries and colleagues for continued intellectual and physical cooperation over many decades and my deep appreciation to the younger ones for their inputs and endeavours to the programme at Trombay. I regret that lack of space prevents me from mentioning each one of them by name.

It is significant that this regional prize is being awarded during an international meet. To me, it emphasizes the importance of intra-regional and inter-regional linkages in the growth of science. AONSA stands for this and therefore, this prize is dear to me. While this need not be over emphasized in these days of major international collaborations, I think, this was less obvious in 1958 when I started my life as a research scientist at the Atomic Energy Establishment Trombay. AEET is now called Bhabha Atomic Research Centre (BARC) after the demise of the great scientist and visionary who founded India's Atomic Energy programme in 1952 under the patronage of the enlightened and science oriented Prime Minister of India,

Jawahar Lal Nehru.

India became independent on 15th August 1947, a backward and impoverished nation without a manufacturing base worth its name for such a large country but with a substantial legacy of intellectual pursuit of several millennia. Bhabha, with great confidence and audacity, convinced Prime Minister Nehru of the need for a broad based Atomic Energy programme amidst considerable opposition. Nehru, with his developmental vision for the country, backed him to the hilt. The first reactor, Apsara, was built indigenously with a small group of scientists and engineers. It became critical on 4th August 1956 (Fig.1). United Kingdom supplied the highly enriched uranium core in a great spirit of scientific cooperation. This was essentially a reactor with a flux of $>10^{11}$ n/cm²/sec at 100-250 KW, the power at which it operated most of the time.



Fig.1. Apsara reactor

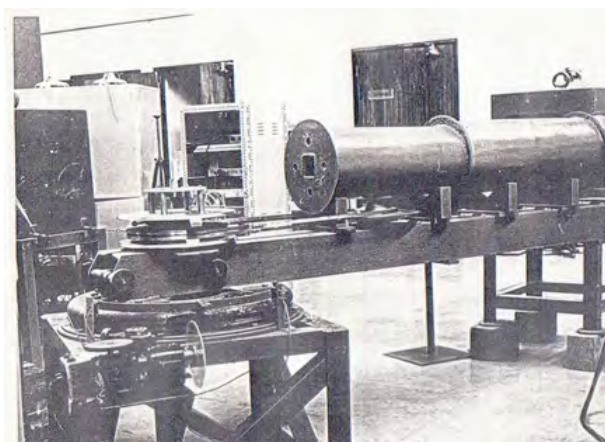


Fig.2. First automatic diffractometer (~1958-59)

Initiation at Trombay- (1958-)

P.K. Iyengar initiated the Indian programme on neutron scattering at Apsara reactor after his return from Canada in March 1958 where he had worked with Brockhouse for some time. Following our founder Bhabha, it was generally accepted at BARC that if we wished to establish a large scale and sustainable research programme, it would be necessary to develop the needed instruments locally. Firstly, this would generate the required expertise to innovate and carry out long term research and secondly, building equipment locally would cost substantially less compared to importing by paying in foreign currency of which there was a severe shortage.

N.S. Satyamurthy and I joined P.K. Iyengar about four months after his return from Canada. Our first task was to build an automatic powder diffractometer. Its basic design was similar to the Canadian machine: all the mechanical parts as well as electronics and automation and the detector were built within the Establishment. Fig. 2 shows the photograph of this instrument. The first set of data on

antiferromagnetic FeSn_2 is shown in Fig.3. It required several days to record this data. It was reported at the International Conference on Magnetism in Japan in 1961 and published in J. Phys. Soc. Japan in 1962 [1].

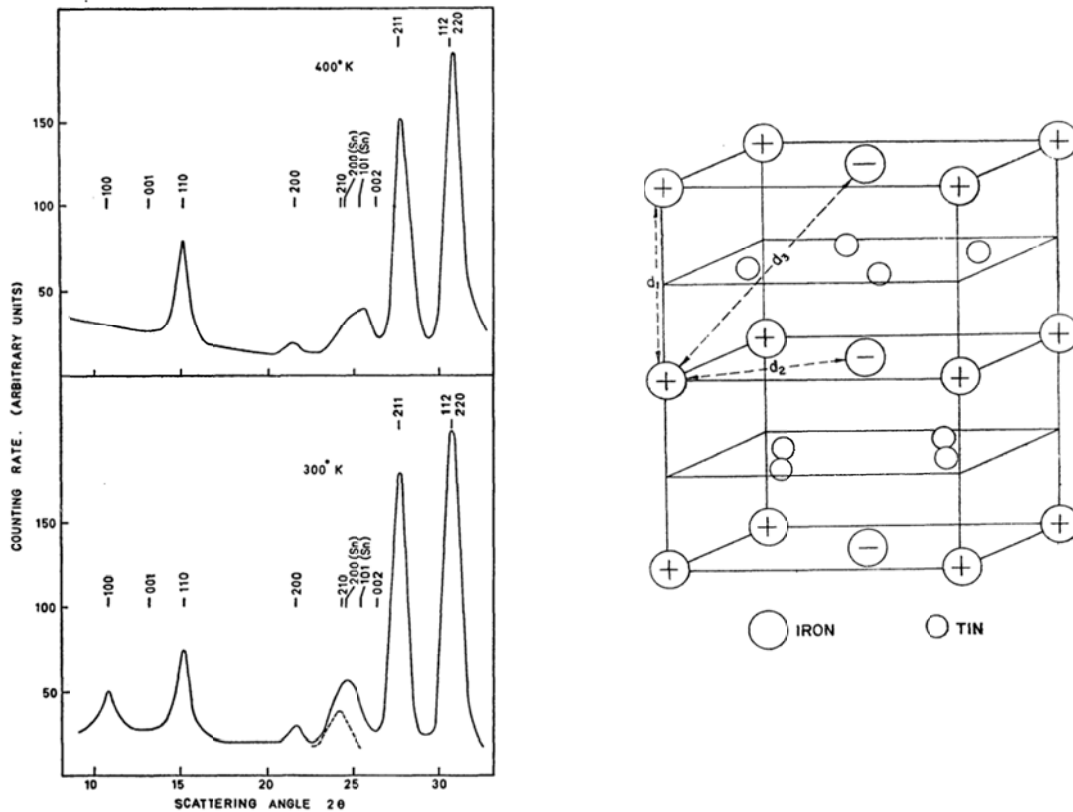


Fig.3. Neutron diffraction pattern and magnetic structure of FeSn_2

In parallel with this, a commercial diffractometer from UK was converted to an inelastic spectrometer (Fig.4) and some phonons in Fe were reported at the 1961 Vienna meeting on Inelastic Scattering of Neutrons in Solids [2].

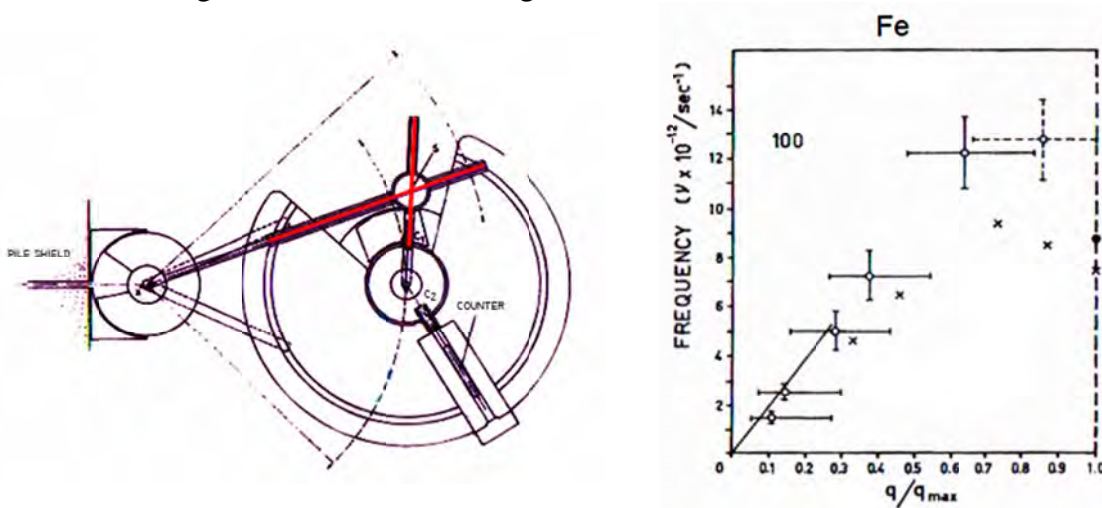


Fig.4. Diffractometer converted for inelastic studies (left) and some phonons in Iron (right)

To Chalk River, Canada (1961-)

After three years in Trombay, I was deputed to Chalk River, Canada to work with Brockhouse under a Colombo Plan fellowship in August 1961. During the next sixteen months, the major experiment that I would be doing was on liquid argon at the high-flux NRU reactor. The constant-Q technique was established by this time and we collected such data on the Triple Axis Spectrometer. For smaller wave-vector transfers, time-of-flight data was collected on the rotating crystal spectrometer at several closely spaced scattering angles. It was converted to constant-Q information; this was probably the first such exercise. As late as 2006, Roger Cowley re-emphasized the importance of constant-Q data for certain sensitive experiments [4]. Incidentally, this was also a period when there was considerable debate about peaks in time-of-flight data at a fixed scattering angle being seen as evidence of phonons in liquids; I think this issue is largely sorted out now. Combining these two data sets, after removing the effects of resolution at the level of intermediate scattering function, we derived the van-Hove time dependent self and pair correlation functions [3] (Figs. 5 and 6). While on the subject of simple liquids, let me add that much later, in 1974, when I was on a sabbatical at KFA, Juelich with Springer, we observed [5] Raleigh and Brillouin peaks in constant-Q experiments in normal ^4He at 4.2°K at small q values between 0.06 and 0.2 \AA^{-1} (Fig 7) and examined the limits of hydrodynamics.

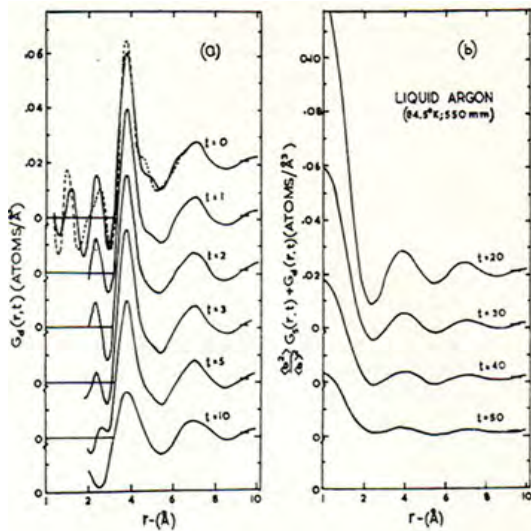


Fig. 5 Pair-correlation function of liquid Ar at 84.5K.

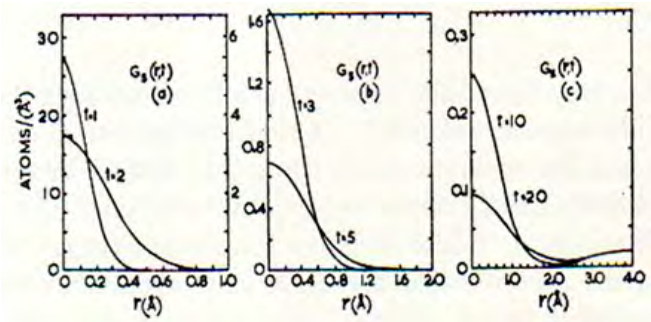


Fig. 6. Self-correlation function of liquid Ar as function of time.

Back to Trombay-Cirus (1963-)

I returned to India in January 1963. Even before I had left for Canada, the second reactor, CIR to be later named Cirus, had become critical. Cirus was a medium flux reactor delivering a flux of about 10^{13} $\text{n/cm}^2/\text{sec}$, much better than Apsara. A major

neutron scattering programme was initiated there under the leadership of P.K. Iyengar. By the end of 1961, three more diffractometers -- a powder machine, a triple axis spectrometer and a filter detector spectrometer were set up and the instruments at Apsara were shifted to Cirus. G. Venkataraman and K. Usha built a rotating crystal spectrometer. Inelastic scattering measurements on phonons in Mg and librational modes in ammonium halides were reported at the 1962 IAEA Conference in Chalk River, Canada. IAEA thereafter decided to hold the next meeting at Trombay in December 1964 on India's invitation. The ideas of window filter spectrometer-- with Be filter and BeO back reflector-- and multi-arm spectrometer were introduced and implemented by Iyengar and his team. Window filter improved the resolution of the analyser vis-à-vis the Be filter both in energy and momentum [6]. This led to measurements of (a) anharmonicity of the rotational potential in NH_4Cl and (b) phonons in Mg. All this happened during my absence from Trombay.

I realised on returning from Canada that with a reactor like Cirus, we are always going to be struggling for intensity and therefore thought of concentrating on hydrogenous materials where intensity would be less of a constraint. After looking at the canonical liquid argon in Chalk River, methane, a spherical top molecule, seemed a natural choice. Rotational states of CH_4 are separated by 1.3 meV. Rotating crystal spectrometer with its good resolution of 0.36 meV (reducible to 0.2 meV) was an ideal instrument for observing rotational lines with such a separation. Initial experiments were reported at the 1964 IAEA Conference at Bombay (now Mumbai) [7]. Our conclusion was that methane molecules do not freely rotate in the liquid state (Fig. 8). This was contrary to some existing neutron results [8] but in agreement with infrared absorption and Raman scattering experiments. We also treated the entire quasi-elastic and inelastic spectrum in a single framework, not common then [7,9a] (Fig. 8). These experiments were followed by those on liquids CD_4 [10] and NH_3 [11]. Sears [12] showed how to quantitatively integrate neutron and optical data into a single framework using our data on liquid methane. He used

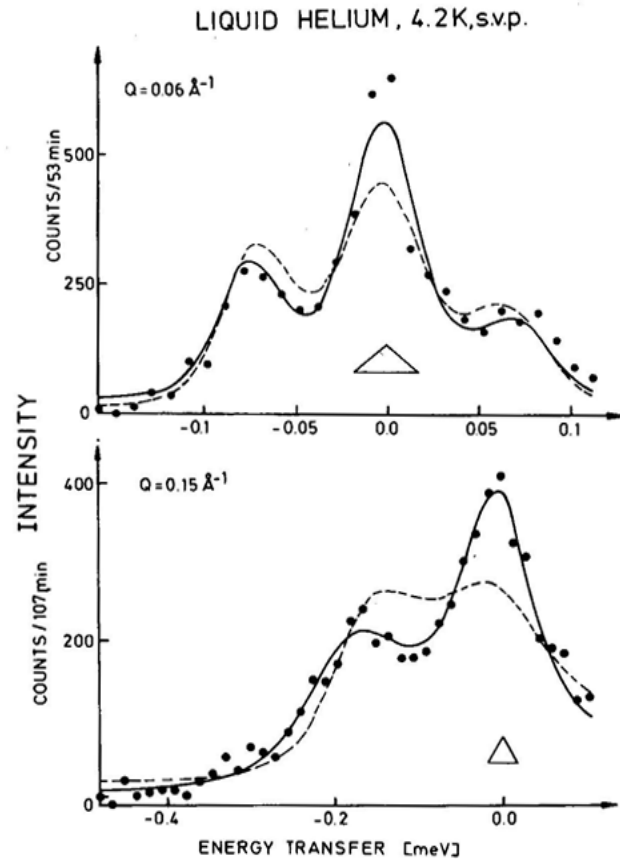


Fig.7. Rayleigh and Brillouin scattering of neutrons from liquid Helium at 4.2K

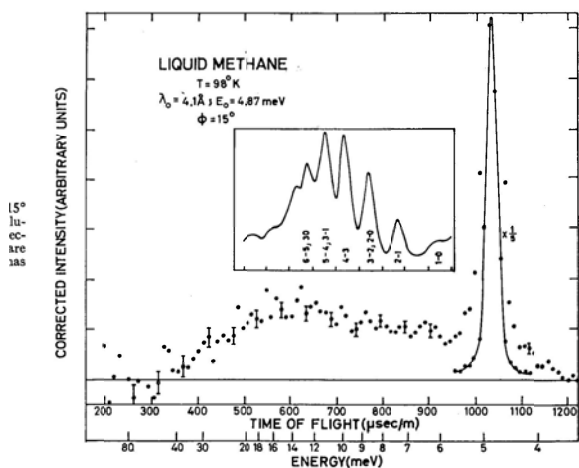


Fig.8. Neutron scattering from liquid methane at 98K at $\phi = 15^\circ$. Inset shows calculated spectrum if CH₄ molecules are rotating freely.

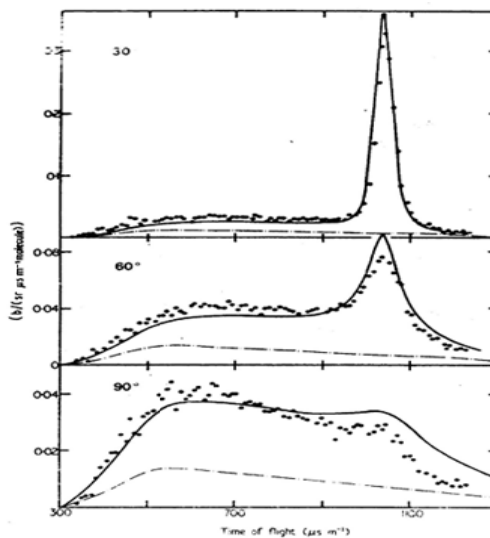


Fig.9. Neutron scattering from liquid CH₄ at 98K compared with the calculated curves using four rotational correlation functions and allowing for multiple scattering (dashed lines). Inset shows contributions from four correlation functions.

first and second order rotational correlation functions measured using infrared absorption and Raman scattering experiments to describe the neutron data. We extended the analysis to include higher order correlations up to fourth [9b]. As our data suffered from multiple scattering, we also examined it in detail [13]; final comparison with our data is given in Fig. 9.

A similar analysis was done for liquid CD₄ [10] though it was not necessary to apply multiple scattering correction there. However, effect of coherent scattering was accounted for using a simple model which would take care of second moment and give proper de Gennes narrowing.

This procedure was not feasible for liquid ammonia as optical data was not available. So the approach of Agrawal and Yip [14], which makes a Gaussian approximation and uses only the first order rotational correlation, was used. Thus, using our data (Fig. 10), a model first order rotational correlation function was extracted after due correction for multiple scattering.

Scattering from solids NH₃ and CH₄ was also observed to get effective $g(\omega)$ [15] in the former and to show almost identical spectra for liquid and plastic solid phases of CH₄ except for the

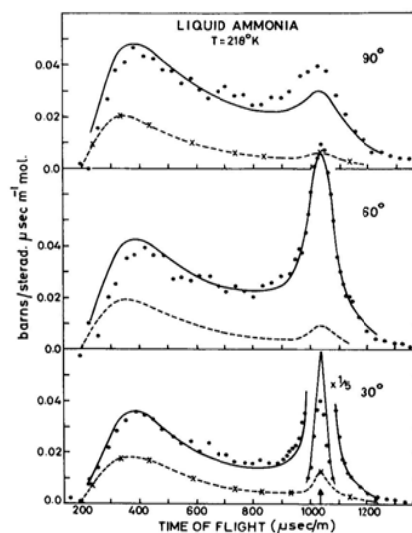


Fig. 10. Neutron scattering from liquid Ammonia at 218K compared with analysis using formulation of Agrawal and Yip [14]. Dashed line shows contribution due to multiple scattering.

presence of pure elastic peak in the solid which is absent in liquid [16]. Thus, at the freezing point, while translational diffusion changes by many orders, expectedly there is no observable change in the rotational motion.

The Philippines (1966/67): Regional Cooperation Agreement (RCA)

Following the Bombay conference of 1964, R. Ramanna and P.K. Iyengar proposed a Cooperative Research Project (CRP) under the regional collaboration agreement (RCA) in South East Asia under the aegis of the International Atomic Energy Agency, Vienna. The goal was to train scientists from countries of the region like the Philippines, Korea, Indonesia, Thailand, Taiwan, etc. in methods of neutron scattering. BARC donated a home built diffractometer and installed it at the Triga reactor at Philippine Atomic Research Centre in 1965. I visited PARC in 1966/67 for a year lecturing, building a beryllium detector spectrometer in-house and doing experiments with the diffractometer. Here again, using a small research reactor, we reported our work on neutron diffraction by liquid zinc (Fig. 11) in Physical Review [17]. We showed (a)

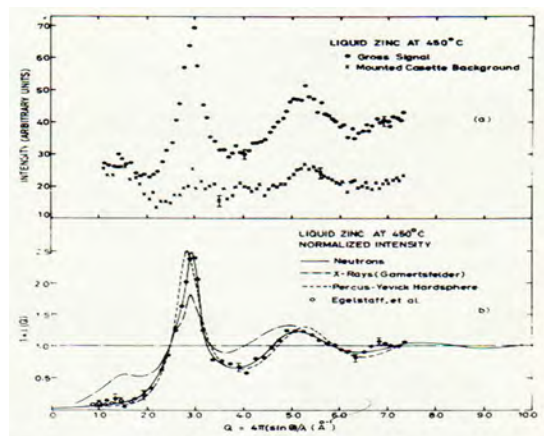


Fig. 11. Diffraction from liquid Zinc at 480°C

(b) that the law of corresponding states suggested by Paskin, using a hard sphere model, was not an adequate description for all monatomic liquids and shadows of the structure of the solid are retained in the liquid near the melting point, thus permitting a quasicrystalline model description and (c) that the use of existing pseudo potential of Animalu & Heine to calculate the resistivity gives a value almost half of the measured value; we conjectured this to be due to some basic reason (later experiments at Trombay on phonons in another hexagonal metal, Be, proved breakdown of simple pseudopotential theory in Be!). Some of the scientists who worked under RCA went on to start neutron scattering programmes in their respective countries. Some scientists who benefited from RCA and whose names come readily to my mind include M. Natera, H. Ibarra, Q. Navarro (the Philippines), Marsongkohadi (Indonesia), Therawoot and S. Chatraphorn (Thailand). G. B. Lee (South Korea) and there were several others.

Cirus again: 'Molecular' Solids: Rotational Diffusion and Librations (1967-)

By the time I returned from the Philippines in September 1967, scientists were beginning to appreciate that rotational diffusion of molecular groups like NH_4^+ , CH_3 , CH_4 etc in solids should show quasi elastic broadening. Skold [18] and

Stockmeyer & Stiller [19] reported the first measurements. G. Vekataraman also decided to undertake such measurements on the rotating crystal spectrometer at Trombay. The first set of measurements on ammonium sulfate [20] was done when Kim Hun Jun from South Korea was at BARC as an IAEA Fellow. He would contribute to neutron scattering programme in Korea on his return as they built their new HANARO reactor. We looked at rotational diffusion and librations in a number of compounds with the ammonium ion in different environments at Trombay: several publications ensued as a consequence [21]. I shall give a couple of examples here.

It is now well understood that in the case of rotational stochastic motion the scattered spectrum consists of an elastic peak and a quasi-elastic one under the elastic one. Depending on the instrument's energy resolution, the two parts may or may not appear as two distinct parts. As the characteristic diffusive jump time changes from a small value at higher temperatures (fast motion) to a larger value on cooling, crossing the $\Delta E/h$ of the resolution, the width of the composite peak first increases and then gradually falls back to its resolution. This is shown in Fig. 12

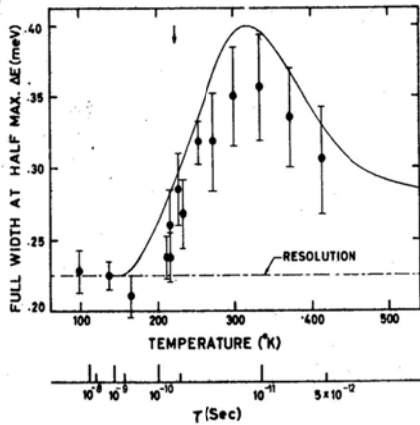


Fig.12. FWHM as function of temperature for $(\text{NH}_4)_2\text{SO}_4$.

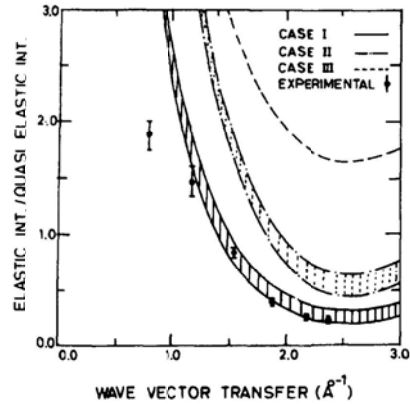


Fig.13. Ratio of elastic to quasielastic scattering intensity for $(\text{NH}_4)_2\text{SO}_4$. Data shows that the reorientation rates for the two NH_4 ions are comparable (case I).

[20] for $(\text{NH}_4)_2\text{SO}_4$. The other well appreciated aspect connected with study of stochastic rotational motion is that the intensity of the elastic part of the scattering (elastic intensity structure factor, EISF, or the ratio of elastic to quasi-elastic intensity) gives information about the geometry of the associated diffusion process. Using further quasi-elastic as well as inelastic scattering experiments on $(\text{NH}_4)_2\text{SO}_4$ and $[(\text{NH}_4)_x\text{K}_{(1-x)}]_2\text{SO}_4$ [21a,b,i], we were able to show the following: (a) it is possible to get information about the two NH_4 ions separately from EISF data on pure salt alone (Fig. 13), (b) the reorientation rates for $\text{NH}_4(\text{I})$ about its four N-H bonds are nearly same whereas for $\text{NH}_4(\text{II})$ there is a distribution of characteristic reorientation times (τ) about its four N-H bonds, (c) τ_1 (10.4psec) and τ_2 (15.8 psec) at room temperature are not very different, and (d) they do not drastically change below ferroelectric transition temperature of 223K and continue to be nearly similar in the ferroelectric phase [21a,b,f]. In another detailed set of experiments we

examined stochastic and librational dynamics of NH_4 ion in pure NH_4I and its mixed salts $(\text{NH}_4)_{0.16} \text{K}_{0.84} \text{I/Br}$ where all the phase transitions of the pure salt are quenched and NH_4 ion continues in its octahedral first neighbour environment down to low temperatures. ‘Localised’ translational mode, a broad librational spectrum and quasi-elastic spectra were observed; an attempt was made to explain diffraction, quasi-elastic and inelastic scattering observations in a symbiotic fashion using a model proposed by us [21c,d,e].

On a slightly different note, we were probably the earliest to examine the polarization dependence of incoherent scattering, through the $\underline{Q} \cdot \underline{\alpha}$ term in the cross section, in single crystals of barium chlorate monohydrate and potassium oxalate monohydrate to identify the character of water librations and measure its angular dependence [22]. Fig. 14 shows how the librational spectrum changes depending on whether wave-vector transfer, \underline{Q} , is parallel or perpendicular to the H--H vector and thus permitting identification of the rocking mode unambiguously. This is further ascertained by observing the cosine angular distribution of the intensity of the mode (Fig. 15). While on the subject of classical stochastic reorientations, let me also mention that during my sabbatical in 1974 at Juelich, I had the opportunity to be a collaborator with Alefeld and Kollmar to make one of the earliest observations of quantum rotational tunneling in 4-methyl pyridine [23] at Juelich; this was a precursor of a great many experiments on quantum tunneling of molecular groups.

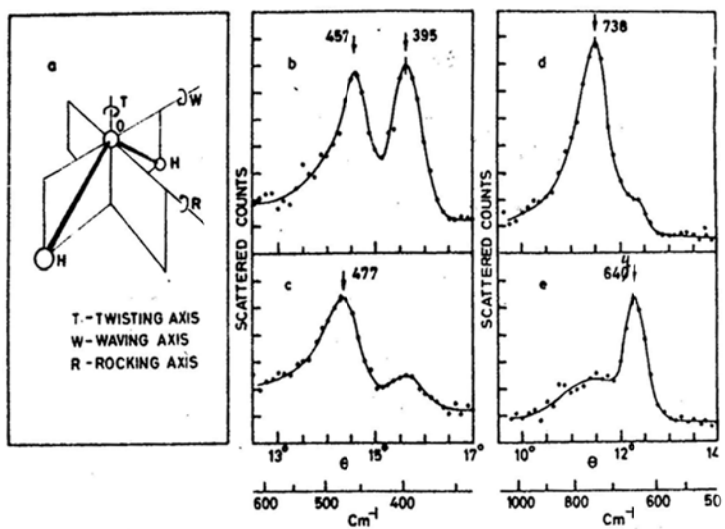


Fig. 14

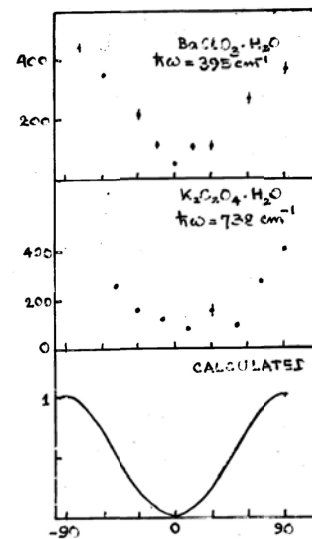


Fig. 15

Fig.14. Polarization dependence of incoherent scattering of neutrons from librational modes of water molecule in single crystals of $\text{K}_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$ and $\text{Ba}(\text{ClO}_3)_2 \cdot \text{H}_2\text{O}$

Fig.15. Angular dependence of librational modes in single crystals of $\text{K}_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$ and $\text{Ba}(\text{ClO}_3)_2 \cdot \text{H}_2\text{O}$: Curves show the calculated behaviour.

Filter Detector for Phonons (1966-)

Filter detector spectrometer is not an instrument of choice for measuring dispersion

curves as the final wave-vector is not well defined. However, the available intensities of incoming neutrons, especially for large energy transfers is substantial. With Cirrus reactor, it was prohibitively difficult to observe phonons higher than about 13THz in Be using a triple axis spectrometer. So we decided to examine the feasibility of FDS for such measurements. We demonstrated quantitatively, through line shape calculations using an asymmetric resolution function, that the filter detector spectrometer can indeed be used to accurately measure even steep dispersion curves [24] in Be: we measured phonons from ~ 7.5 THz to 20 THz using the moderate flux Cirrus reactor. We provided experimental proof of the breakdown of simple pseudo potential theory in Be [25] (Fig. 16). This opened up the possibility of measuring high energy phonons even with a modest reactor.

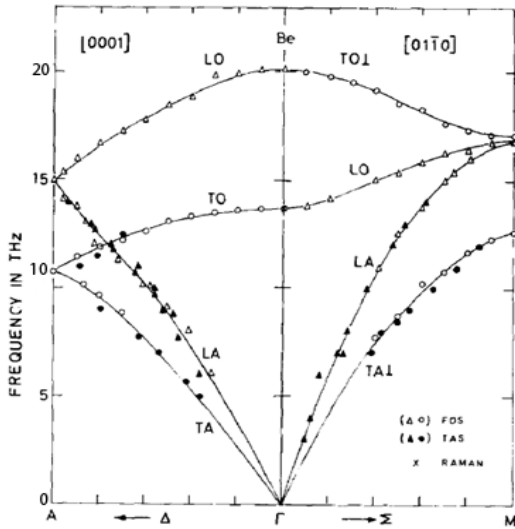


Fig.16(left). Phonon dispersion curves in Be at room temperature. Curves through the data are guide to eye [24].

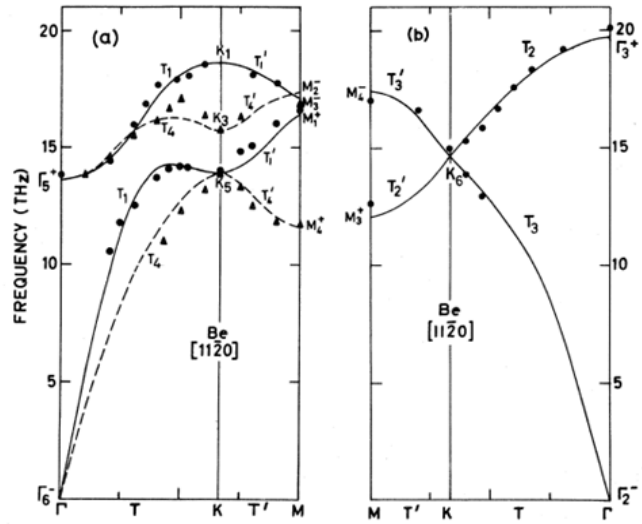


Fig. 16(right). Proof of non-local pseudo potential in Be through measurement of phonon dispersion relations [25].

Dhruva (1972 -)

BARC decided to build a higher flux reactor than Cirrus in 1972. This offered new opportunities to develop better instruments and also design more efficient beam delivery devices. I was given the task of proposing a set of beam tubes required for neutron scattering experiments. The layout of the beam channels is shown in Fig. 17. Besides several conventional radial beam tubes in the pile block, there are four tangential beam tubes, two through tubes and beam tubes to insert cold and hot neutron sources. The design also incorporates built-in recessed cavities and cutaways in the biological shielding to enable closer access to the high flux region. Two guide tubes beginning at the calendria get terminated outside the reactor hall in the guide tube laboratory. The design permits improved accessibility to neutrons and better signal to noise ratio.

It was decided to have a suite of instruments [26] which can be divided into three groups: (a) Classical four-circle diffractometer, triple axis spectrometer (TAS), polarized neutron TAS and filter detector spectrometer, (b) instruments based on position sensitive detectors for quasi elastic scattering, high-Q diffraction and powder diffraction, and (c) instruments (like SANS, USANS, polarized neutron reflectometer and spin-echo spectrometer) installed on the two guide tubes leading outside the reactor hall. N.S. Satya Murthy was the leader of this programme; on his unfortunate passing away in 1984, K. R. Rao and I took charge. I took specific interest in the PSD based instruments and focusing crystals as I was convinced that future lay in their extensive utilization. The reactor became critical only in 1985 and is now functioning normally. Fig. 18 shows a recent photograph of some of the instruments at Dhruva reactor hall.

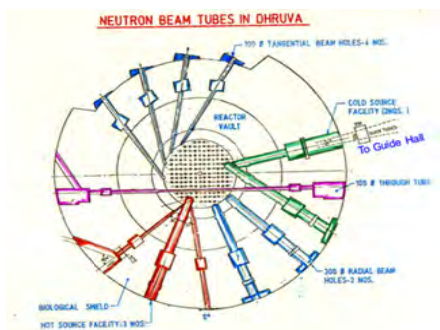


Fig.17. Beam channel layout at Dhruva

Fig. 18. Some neutron instruments at Dhruva (~2003)

Dhruva National Facility (1986-), IUC-DAEF (1989 -)

Completion of this reactor would have major impact on increasing the use of neutrons in India. With the increased intensity as a combined result of (a) higher reactor power, (b) superior beam channel design and (c) better instrument design, it would become possible to do experiments more than an order of magnitude faster than at Cirus and with better quality. Thus, the facilities would be more readily usable by users from universities. So Dhruva was made a National Facility. Special funding was allocated by BARC for university scientists to participate. Schools for neutron scattering started to be held, first one being organized by BARC in 1986 as an IAEA school at Mumbai. At this school, I expressed my dream of creating a community of at least a couple of hundred users of these instruments in India. In 1989, an agreement was signed between University Grants Commission (UGC) and Department of Atomic Energy (DAE) to establish a new Inter University Consortium for Utilization of DAE Facilities (IUC-DAEF) wherein UGC took over the responsibility of funding users from universities and DAE of providing the use of neutron instruments free of cost. Then onwards regular neutron schools were jointly held between BARC and IUC-DAEF. Number of users increased rapidly. I

understand the latest in this series was a school in 2010 at BARC in cooperation with AONSA.

In December 1995, I moved over from BARC and took up the Directorship of IUC-DAEF to help consolidate this joint effort of the Solid State Physics Division, BARC and IUC-DAEF. I was a happy and satisfied person as a large number of participants from about forty institutions spread all over India started using neutrons before I left IUC-DAEF in October 2002. I shall return to another facet of IUC-DAEF (now renamed UGC-DAE-CSR or University Grants commission - Department of Atomic Energy Consortium for Scientific Research) later.

SANS at Cirus (1985--

While Dhruva was under construction, some relevant developments were undertaken at Cirus. We installed a primitive SANS machine at Cirus and started SANS experiments [27] with a view to having a full-fledged PSD based machine at the new Dhruva reactor (100MW; 1.8×10^{14} n/cm²/sec). As Dhruva took a long time to come to operational stage, the SANS experiments were well established at Cirus itself [28] with continuous upgrades. Along with powder diffractometers, it became the most sought after neutron facility; the new SANS machine [29] at Dhruva continues to be so.

Spallation Neutron Source: ISIS-BARC collaboration: ΔT -Analyser (1980/1-

At this point, let me switch over to another parallel development which took place in early eighties. George Manning, Director of Rutherford Appleton Laboratory, UK was passing through BARC when P K Iyengar was the Director. They knew each other from their Chalk River days. Manning mentioned to Iyengar that they were looking for international participation/ collaboration for their Spallation Neutron Source (SNS) project. They had already decided on several instruments and were prepared to look for collaboration if a new idea could be proposed. With my background with different types of inelastic instruments, I felt that there is a place for an instrument with resolution in an energy window of tens of μeV , i.e., between a triple axis and a back scattering spectrometer. That is how the thought of ΔT -window analyzer with an energy resolution of tens of μeV was born [30]. My colleague Goyal suggested [31] that this could ideally match with a long incident flight path of ~ 60 meters with regard to energy resolution at SNS. We worked out various numbers and made the proposal. RAL thought it to be sufficiently different from other proposed instruments to open up a new beam with cold hydrogen moderator. Thus, the original IRIS beam line with ΔT -analyzer came into being.

Let me spend a few minutes on the ΔT -window analyzer. A standard window filter

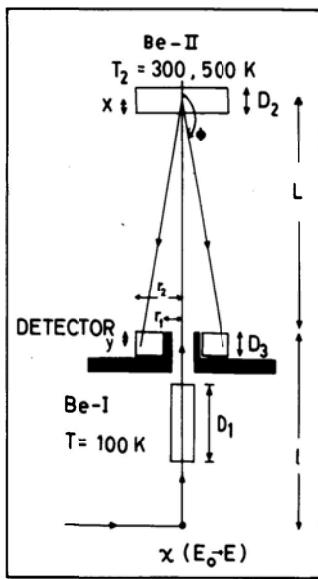


Fig. 19. Schematic of a window filter.

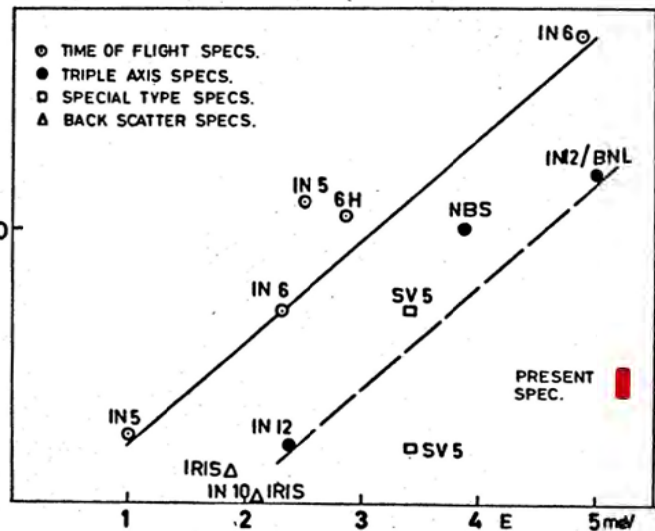


Fig. 20. Typical energy resolutions of various neutron spectrometers.

permits incident neutrons larger than 3.96 \AA to pass through a Be filter and neutrons between 3.96 \AA (Bragg cut-off of Be) and 4.7 \AA (cut-off of BeO) to get nearly back reflected and detected in an annular detector (Fig. 19). This produces an energy window between $\sim 5 \text{ meV}$ and 3.7 meV , i.e., $\sim 1.3 \text{ meV}$ at $\sim 4.35 \text{ meV}$. In a ΔT -window analyzer, the BeO is replaced by a Be block at room temperature and the first Be block is cooled to liquid nitrogen temperature, thus reducing the width to \sim

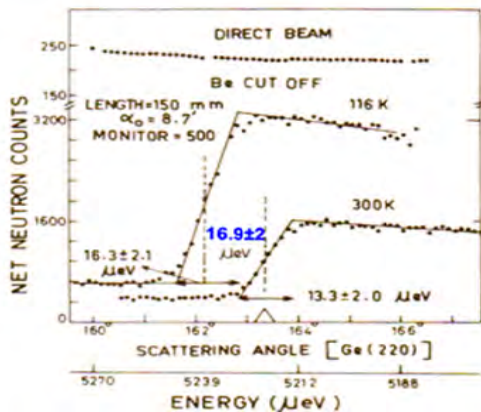


Fig. 21. Measurement of width of Be cut-off and its shift with temperature.

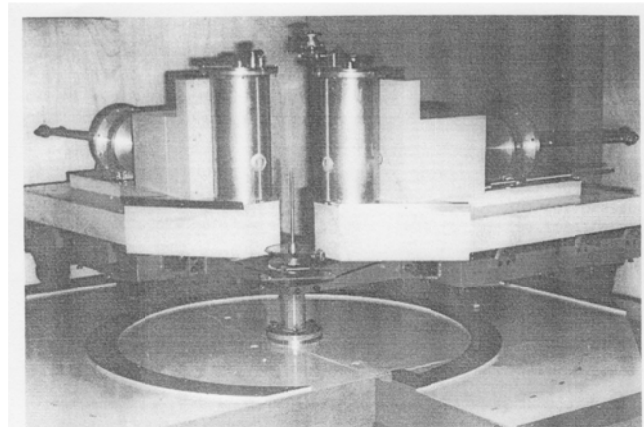


Fig. 22. Photograph of a pair of ΔT -window analysers.

0.02 meV from 1.3 meV . The width can be changed by changing the temperature of the reflector block. Thus, one obtains a resolution of 0.4% at $\sim 5 \text{ meV}$, which was somewhat favorably removed from any other available spectrometer [32] (Fig. 20). To validate this idea, we still had to be sure that the natural width of cut-off of hot pressed Be block is well below the difference in the Be cut-off at room temperature and liquid nitrogen temperature. As the best available measurement [33] was done

with a resolution of 20 μeV , we had to set up a special spectrometer with a resolution of $\sim 5 \mu\text{eV}$ [34] to measure the width of the cut-off and also its shift between the two temperatures (Fig. 21). Having validated the basics, the ΔT -window analyzer was built at BARC (Fig. 22) and installed at the end of a 30 metre long incident flight path at the hydrogen cold source at SNS, later called ISIS, to receive Day-1 neutrons. Thus, a unique beamline with energy resolution of $\sim 30\text{-}50 \mu\text{eV}$ at $\sim 5.0 \text{ meV}$ and Q up to 3.0 \AA^{-1} was opened up at ISIS (Fig.23). Experiments on reorientation in NH_4Br , ferroelectric to paraelectric transition in



Fig.23. The IRIS user group in front of the Indian Analyser

$(\text{NH}_4)_2\text{SO}_4$, tunneling in methyl acetate by Nottingham group of Clough and motion of H_2 in intercalated carbon $[\text{C}_{24}\text{Cs}(\text{H}_2)_{1.8}]$ by the Oxford group of John White were performed in 1985/86 (RAL Annual Reports 1985, 1986). The analyser was later replaced with a more versatile one using many crystals of pyrographite. This improved the throughput, gave improved energy resolution but reduced range in Q . The most important consequence of this collaboration from the Indian point of view was that our scientists got access to ALL the neutron instruments at ISIS which was world's best pulsed neutron source at that time and indeed for a long time to come. Many Indian scientists benefited from this collaboration for nearly two decades.

IUC-DAEF (now UGC-DAE CSR) beamline at Dhruva (1994--

With the BARC-University cooperation maturing, Inter University Consortium for Department of Atomic Energy Facilities (IUC-DAEF) thought it fit to involve itself deeper in the neutron scattering programme by proposing to build instruments on a new beam line. The through-tube TT-1015 was made available to IUC-DAEF for

this.

In an IAEA workshop on Research Reactor Utilisation at Budapest in 1994, I had examined the possibility of using multiple instruments in tandem on a single beam line and it was decided to use this idea. This meant minimum use of Soller collimators and we opted for open geometry (Fig. 24).

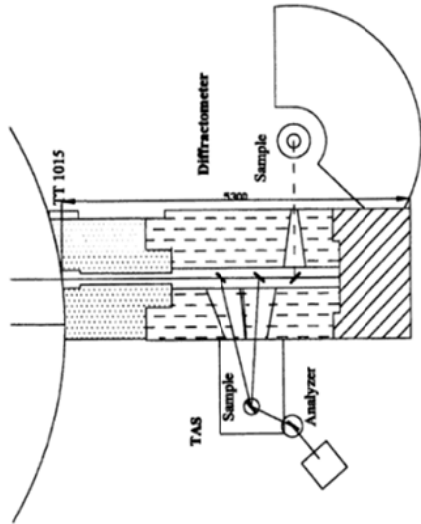


Fig. 24. Conceptual layout of multiple monochromator beamline.



Fig. 25. Diffractometer based on multi-monochromator layout. White monochromator shield and green detector shield are seen in the photograph at Dhruva

The needed resolution in wave-vector transfer was to be attained through the use of focusing perfect crystals [35]. Monte Carlo simulations for a powder diffractometer [36] and a triple axis spectrometer [37] showed that in both cases one would gain in resolution as well as intensity. For the diffractometer one obtains full widths of Bragg peaks of about 0.3 degree over the full angular range from 10 to 125 degrees at 1.48 Å. For the triple axis instrument with PG, the energy resolution is ~0.2 meV at 4.83 meV, whereas with Si(311) at 15.5 meV, resolution can be ~0.1 meV, though with much reduced intensity. While a single integral shield has been designed and built for three monochromators, only the diffractometer has been installed. A number of groups from universities were given the responsibility of developing specific components like boronated rubber (now commercialized), toroidal monochromators etc and the Mumbai Centre of IUC-DAEF was responsible for the overall project. Such a diffractometer has been installed (Fig. 25) and has completely borne out the anticipated promise. It has a $\Delta d/d < 0.3\%$ with flux of 7×10^7 n/cm²/sec at the sample. With addition of low temperature (from 1.5 K) and high magnetic field (7 Tesla) sample environment [38] Indian neutron scattering community has now access to a top-of-the-line diffractometer locally. This has permitted one to address sophisticated problems on multiferroics, quasi 1-D systems, kinetic arrest in magnetic glass etc. Fig. 26 shows some recent resolution data demonstrating the use of low temperature and high magnetic field.

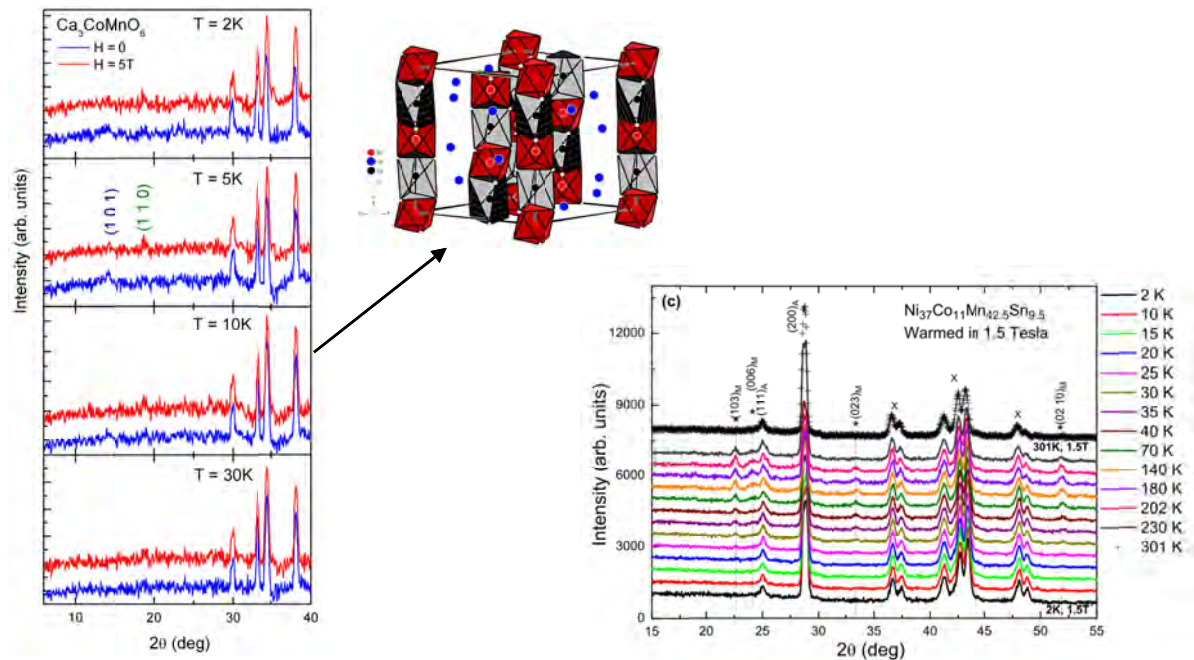


Fig. 26(a): Magnetolectric coupling in $\text{Ca}_3\text{CoMnO}_6$ Fig.26(b). Kinetic arrest of Austenite to Martensite transition in a shape memory alloy.

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