Neutron scattering—Down memory lane

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After a lapse of over a quarter of a century, India played host once again to an international conference on neutron scattering. The first one, in 1964, was held in TIFR, the mother institution that gave birth to our atomic energy programme, including neutron-scattering studies. The venue of the more recent conference, NS-91 (21–25 January 1991), was the Bhabha Atomic Research Centre (BARC) in Bombay, the focal point of neutron-scattering research in the country.

As is well known, experimental research in condensed matter physics largely revolves around a few well-established techniques like X-ray diffraction. Some of these, like Raman scattering and nuclear magnetic resonance (NMR) spectroscopy for example, are associated with major fundamental discoveries that later provided a basis for routine investigations. By contrast, the emergence of the neutron-scattering technique has been an evolutionary process, being in this respect more like infrared spectroscopy.

The neutron was discovered by James Chadwick in 1932. Understandably it was an event of great interest to nuclear physicists, but, as early as 1936, the wave nature of the neutron was demonstrated in simple experiments[1,2] involving the diffraction of neutrons by crystalline matter. To produce neutrons with wavelengths of the order of an Angström, the early experimenters exploited Fermi's discovery that fast neutrons are easily slowed down by collision with the molecules of paraffin. Shortly thereafter, Felix Bloch pointed out that interaction is possible between the magnetic moment of the neutron and those of magnetic atoms[3], and the stage was set for all that was to follow. It is remarkable that, despite the total absence of neutron sources of worthwhile intensity, seminal papers appeared, dealing respectively with magnetic scattering by crystals[4], scattering by *ortho*- and *para*-hydrogen[5], and even the inelastic scattering of neutrons by crystals[6]. Of course, the turning point really was the construction by Fermi in 1942 of the first reactor, or the *pile* as it was then called. Naturally reactors were then top secret, but after the War, not only was reactor technology declassified, but so also was a lot of other information obtained with reactors during the War effort.

In the midst of his numerous preoccupations with weapons research, Fermi found time to perform some classic experiments on the measurement of scattering amplitudes, on diffraction, and on neutron optics[7]. It was said that he could have dominated the newly emerging subject of slow-neutron scattering, but, in a characteristic fashion, he chose instead to move to a new domain—high energy physics. Since those early post-War days, neutron scattering has come a long way.

Three factors make the neutron a very useful probe for exploring condensed matter. These are: (i) the scattering amplitude is roughly of the same order of magnitude across the periodic table, (ii) neutrons can be (magnetically) scattered by atoms possessing magnetic moments, and (iii) the change in the energy of slow neutrons (i.e. neutrons of energy ~ 0.025 eV or, equivalently, neutrons of wavelength ~ 1 Å, *thermal* neutrons as they are often called) upon scattering by the excitations in the medium is easily measured. All three favourable features have been eagerly seized upon, leading in turn (at least in the early days) to three distinct fields of activity, namely neutron crystallography, magnetic diffraction and inelastic scattering. While the fundamental principles of neutron scattering by condensed matter had been spelt out even before reactors came into existence, it was a crucial paper by van Hove[8] in 1954 which really made clear how the experimental data should be analysed for extracting meaningful information about elementary excitations (in condensed matter). In other words, the foundations had finally been laid for a new form of spectroscopy, and it merely needed a translation of the ideas into actual practice.

Time of flight versus the triple axis

The two front-running centres interested in neutron scattering at that time were the Brookhaven National Laboratory near New York and the Atomic Energy of

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Canada Ltd (AECL) at Chalk River in Ontario. Both boasted of high-flux research reactors, which in those days meant reactors with a neutron flux of around 10^{13} n cm^2 sec. Both were interested in measuring the energy change of the neutron following scattering by condensed matter, but they used quite different methods. Whereas Brookhaven adopted the time-of-flight method (earlier employed by Fermi) to measure the *velocities* of scattered neutrons, Brockhouse at Chalk River used the crystal-diffraction technique to measure the *wavelength* change of the neutron following the scattering (of course, the velocity and the wavelength are related by the de Broglie relation). This led Brockhouse to develop the triple-axis spectrometer, which soon dominated all inelastic-scattering research, especially because it greatly facilitated the tracking of phonons, magnons and other excitations with wave-vectors along symmetry directions. The early battle between the time-of-flight and the crystal-diffraction techniques is of interest because of the reemergence of the former in recent times.

Neutron scattering at Trombay

Neutron scattering came to India much earlier than it did to many other countries, including in Europe, and credit for this must go to Homi Bhabha. In 1955 India entered into an agreement with Canada for the construction in Trombay of a high-flux research reactor which was to be a copy of the famous NRX reactor at Chalk River. While the Canada–India Reactor (CIR as it was then called, and now renamed CIRUS) was intended primarily to expose our engineers to the intricacies of nuclear technology (a goal that was successfully accomplished and for isotope production, Bhabha was keen that the reactor at Trombay should be used for basic research also. With this in mind, he persuaded Jawaharlal Nehru to agree to the deputation of a few young scientists from Trombay to work at Chalk River and gain first-hand experience in using neutron beams. The first person to be so deputed was P. K. Iyengar, followed shortly thereafter by me, and later by Usha Deniz.

The race between Brookhaven and Chalk River

Getting back to the race between Brookhaven and Chalk River, both were on to the first-ever study of phonons by neutron scattering. Brookhaven took an early lead but in the end it was Brockhouse of Chalk River who won the race with an epoch-making paper on the phonon dispersion relations in germanium, which he co-authored with Iyengar[9]. The choice of germanium was a master stroke. Brookhaven went after aluminium, and its experiment ended up as a mere feasibility study, whereas, physics-wise, germanium was a far more interesting substance, especially because it was the prime transistor material in those days (silicon was just making its entry). Clearly Brockhouse had a better appreciation of solid state physics than his competitors D. J. Hughes and H. Palevsky of Brookhaven, both of whom were nuclear physicists with a background of weapons research during the War.

Back to Trombay

The paper on germanium was a true landmark, and it spurred many groups in Europe and America to enter the field. By the early sixties, the CIRUS reactor at Trombay was fully operational, and under the leadership of Ramanna and Iyengar, many neutron spectrometers came to be built. Thanks to some useful advice by Canadian scientists, the beam hole disposition around the CIRUS was made more conducive to experiments than it was at the NRX reactor in AECL, where there was a tremendous crowding of experiments, often leading to feuds between neighbouring groups!

Among the many spectrometers then set up at Trombay was a rotating-crystal spectrometer built by me. In this a burst of monochromatic neutrons is produced by a spinning crystal and the velocity of the scattered neutrons is measured by a time-of-flight technique. The spinning-crystal system was fabricated by the late H. L. N. Murthy of the Tata Institute of Fundamental Research (TIFR). Murthy was a superb craftsman who had been picked up by Bhabha when he moved from Bangalore to Bombay to set up the TIFR. His speciality was glass blowing but he loved technical challenge. In this case he had to machine a sphere of aluminium of about 6-cm diameter out of a cylindrical ingot of a single crystal, *this without drilling any through hole*. After the sphere was machined, I aligned it in a neutron beam and located the reflecting plane I wished to use. Murthy then drilled the through hole for inserting the shaft and completed the mechanical assembly. It was truly a fine piece of work, and I was most surprised to learn during my recent visit to Trombay that this spectrometer not only continues to be operational (along with many side gadgets that I had built over a quarter of a century ago), but also still produces publishable results[10].

In the early sixties the International Atomic Energy Agency (IAEA) began to sponsor conferences on neutron scattering. The first of these was held in Vienna in 1960 and the second in Chalk River in 1962. Recognizing the contributions being made by the Trombay group, the IAEA held the third meeting in Bombay in 1964. Of interest perhaps to the readers of this journal is the paper presented then by the Los Alamos (USA) group on phonon dispersion relations in diamond[11], which later enabled a reconciliation of sorts to be effected in the long-standing controversy between C. V. Raman and Max Born concerning the interpretation of the second-order Raman spectrum of diamond[12-14]. Parenthetically one might add that, of late, the IAEA has ceased to sponsor symposia in neutron scattering, being more interested in reactor safety and applied topics; the scattering community itself has now taken over this responsibility.

Enter the high-flux reactors

The early successes of neutron scattering whetted the appetite of condensed matter physicists everywhere, resulting in the construction of several high-flux research reactors (neutron flux $\gtrsim 10^{14}\,\mathrm{n\,cm^{-2}\,sec^{-1}}$). Prominent among these were the reactors at Oak Ridge and Brookhaven in the US and at Grenoble in France.

Oak Ridge produced some fine results, particularly in neutron crystallography and in the study of non-collinear magnetic structures, but in a sense it all ended there. Possibly because of classified work going on elsewhere in the centre, there was not as much of a traffic of visitors as was desirable, and collaborative research did not prosper as it otherwise might have. Both at Oak Ridge and at Brookhaven, the instruments employed were really of an earlier vintage. There was a marked impatience to get on and produce results, instead of spending time on developing new instruments. No doubt this paid off, but only in the short term, as American scientists are now painfully beginning to realize.

The Grenoble reactor offers a marked contrast. It is located in the Institut Laue Langevin (ILL), and while it started off as a Franco-German collaboration, at the present time it is more like a 'low-energy' version of CERN (the European Organization for Nuclear Research in Geneva). A key figure in the planning of the reactor and the experimental programme there was Maier Leibnitz, perhaps better known as the thesis supervisor of Rudolf Mössbauer. I still vividly recall the visit of Maier Leibnitz to Trombay in 1962. At that time he was in Munich, and from a talk he gave it was clear that he was experimenting with bold ideas in instrumentation, with the result the experiments around the Munich reactor were quite different from the canonical type one usually came across while taking a tour around a typical research reactor. Maier Leibnitz inculcated this tradition during the formative years of ILL, later enabling the centre to take the lead. Today it is no exaggeration to say that ILL is the centre of gravity of the neutron scattering world.

The story of Harwell

Brief reference must be made at this juncture to the Atomic Energy Research Establishment (AERE) at Harwell in England. This was founded immediately after the War, with Sir John Cockcroft as the director. Here it was that George Bacon did some pioneering work in neutron diffraction, which later made him one of the leading figures in this field. Neutron inelastic scattering was largely in the hands of Peter Egelstaff, who built a sophisticated phased-chopper system for collecting data. While an engineering feat, this machine was no match for the triple-axis spectrometer, especially where studies of elementary excitations were involved. But Egelstaff also did something else for which he is hardly remembered. He piloted a liquid hydrogen 'cold source', setting the trend for others elsewhere, especially in Grenoble.

Briefly, the idea of a cold source is the following: In thermal reactors, the neutron spectrum is a maxwellian with a temperature of about 300 K or so. This is very convenient for obtaining a copious supply of neutrons with a wavelength of ~ 1 Å, which is what is needed for most experiments. However, there are other experiments that require long-wavelength neutrons, i.e. neutrons with wavelength of 4 Å or even much more. A simple trick to enhance the flux of neutrons of long wavelength is to place a cold moderator right next to the reactor core. Neutrons from the reactor equilibrate with this cold moderator and acquire a lower (maxwellian) temperature.

Among the many candidates for a cold moderator liquid hydrogen is the best, particularly because of the large neutron-proton interaction. By itself liquid hydrogen is supposed to be a hazardous substance, but to have a liquid-hydrogen reservoir right next to the reactor core was initially considered unthinkable. However, Egelstaff at Harwell and also Jacrot at Saclay (France) have, by their pioneering efforts, managed to dispel all such fears. Not only have cold sources now become fairly common (not all sources use liquid hydrogen, other choices also being possible for the cold moderator), but in fact their availability has spurred a new trend in neutron scattering.

Research with cold neutrons

Many studies are possible with cold neutrons, of which perhaps the most common is small-angle scattering (SANS). According to an elementary thumb rule in diffraction, to conveniently explore structure on a length scale l, say, one must use radiation of the same wavelength. If structure on the scale of say 5–10 Å is explored with 1-Å neutrons, the scattering occurs very much in the forward direction and it is not easy to separate the scattered beam from the incident beam. However, with long-wavelength neutrons the scattering is spread out over a much larger range of angles and is therefore conveniently observed. To put it differently, cold neutrons permit a ready exploration of the low-Q region.

As already mentioned, the flux of long-wavelength neutrons is enhanced by the use of a cold source. Many years ago Fermi showed that long-wavelength neutrons can be totally reflected by mirrors. Taking advantage of this, cold-neutron beams are 'piped' away to long distances using *neutron guides*, involving, essentially, multiple reflection. This naturally makes it important to have mirrors of very high reflectivity. Thanks to the initial push given by Maier Leibnitz, considerable effort has been mounted in this direction by the Europeans, and today neutron guides are a familiar sight in many reactors. In fact, to avoid cluttering with existing instruments, the guide beams are usually led away to a building adjacent to the reactor, where one also has the advantage of low backgrounds.

Accelerators in a new *avatar* as pulsed sources

After three and a half decades, neutron scattering has now come of age and has matured. The early excitement has no doubt petered out (not an unusual phenomenon) but thanks to the emergence of research using cold neutrons, a new dimension has also been added. ILL is currently the leading centre for neutron-beam research; by contrast, the US appears to be somewhat on the decline. The Brookhaven reactor has been shut down after the Chernobyl incident since safety experts wanted to review it, and the Oak Ridge reactor has only recently been allowed to restart after many changes, jacking up the operational costs to about $38 million per year and leaving little money for revamping ageing instruments.

Harwell too has suffered a bad decline (as far as neutron-scattering research is concerned), for a different reason altogether. Starting in the mid-sixties, Walter Marshall (now Lord Marshall), who was then the director of AERE, decided to deemphasize neutron-scattering research by Harwell scientists, and to invite university scientists to take their place. This had the beneficial effect of exposing university researchers to neutron scattering, a move that has paid off in the long run. However, the relegation of Harwell scientists to a secondary role had a serious effect, causing many of them to leave—one of them was Egelstaff, who migrated to Canada. Harwell's instruments were not upgraded (there was no one left to do it) and slowly they fell into disuse; they are now being advertised for sale on an as-is-where-is basis.

The enthusiasm of the university researchers in Britain for neutron scattering having been aroused, they now began to look elsewhere for neutron sources. While some went to ILL, an effort was successfully mounted to revive NIMROD, an old high-energy proton accelerator that had been built earlier close to Harwell. When high-energy protons bombard a heavy element (e.g. tantalum), a large number of neutrons are emitted owing to spallation. These neutrons can then be slowed down using a suitable moderator, and neutron-scattering experiments subsequently performed as usual. Actually the use of accelerators for producing neutrons goes back to the early years, and in 1950 Cassels[15] at Cambridge performed some simple (but necessarily crude) experiments to check Weinstock's theory[6]. But with the advent of reactors, accelerators as neutron sources became eclipsed; only lately are they staging a comeback.

Proton synchrotrons are pulsed machines. Neutrons are therefore produced in bursts in spallation machines and time-of-flight techniques must necessarily be used for energy and wavelength analysis. It is in this sense that I mentioned earlier that time of flight is experiencing a revival. The new pulsed-neutron facility based on NIMROD has been named ISIS[16], and is located at the Rutherford Appleton Laboratory near Oxford. Likewise, the now retired proton synchrotron at the Argonne National Laboratory (Argonne, USA) has also been converted into a pulsed-neutron source, called the intense pulsed-neutron source (IPNS). There is also a similar pulsed facility at Los Alamos. The Germans were campaigning for a very powerful state-of-the-art spallation source because that seemed to have a greater chance of acceptability with the German public, which is not quite fond of reactors. That plan has now been given up. It is perhaps worth mentioning that post-Chernobyl fears have resulted in the closing down of the research reactor at the Kurchatov Institute in Moscow—the Muscovites did not want a reactor in the heart of the city. One should not, however, run away with the impression that all reactors are inherently unsafe; just that in some cases, public feeling has been strong enough to compel a shut-down.

Pulsed reactors

Accelerators are not the only source of pulsed neutrons. Many years ago, a novel type of reactor called the pulsed reactor was built at Dubna (USSR). Here one has a neutron-multiplying assembly that is subcritical but is periodically made supercritical for a brief interval by a rotating wheel in the neighbourhood which augments neutron multiplication. Taking cue from the Soviet experience, the EURATOM research centre at Ispra in Italy planned a big pulsed-reactor project called SORA but it was later abandoned. Dubna however pressed on and now has the IBR-2 pulsed reactor whose peak power in pulse is 1500 MW. The pulse repetition rate is variable between 5 and 25 Hz, and the pulse width is about 200 seconds[17].

Pulsed-neutron sources have provided a useful compliment to steady-state reactors. While work at very long wavelengths is ruled out at the pulsed-neutron facilities, there are many other instances in which pulsed-neutron sources have proved to be of great advantage, particularly in the study of diffraction. The higher incident energies of neutrons permits an easy exploration of large-Q phenomena. In the case of liquids, this is expected to lead to much more reliable results for the pair correlation function $g(r)$, and thereby to better interatomic potentials.

While the revamping of obsolete high-energy accelerators as pulsed-neutron sources has been resorted to by some, the yearning for more powerful reactors has by no means died down. In fact, in the US, there is a proposal[18] for a super research reactor with a peak thermal flux of a few times $10^{15}\ \mathrm{n\,cm^{-2}\,sec^{-1}}$, several times higher than that currently available at ILL.

A glimpse of the current status, NS-91

The last international conference on neutron scattering having been held over three years ago, there was keen anticipation about the meeting (NS-91) at Trombay. The response to the call for papers was overwhelming and more than 50 oral presentations including invited lectures, were planned, besides four poster sessions featuring over a hundred papers. Unfortunately, the outbreak of the Gulf War just a week or so prior to the conference caused severe disruption, with over 50 overseas delegates (mainly from the US) dropping out at the very last minute. Despite this setback, there were about 30–40 foreign delegates present, mostly from western Europe and the USSR. There was one representative from Japan and one from China. Heavy and unexpected absences caused, naturally, considerable strain to the organizers, who, however, managed admirably and effected the necessary rescheduling. A feature of the first day's proceedings was the felicitations offered to P. K. Iyengar in a brief but impressive function.

As currently used, the term neutron scattering generally embraces magnetic neutron diffraction, small-angle scattering (which is essentially diffraction at very low Q), and neutron inelastic scattering. Depending on the need of the moment, condensed matter physicists use all these techniques. As yet, a sharp differentiation between the practitioners of these various arts has not occurred, and, thanks to the tradition set by de Gennes, who moved from superconductors to liquid crystals to polymers, many physicists and chemists freely gravitate from one subject to another, using the technique most appropriate for the problem. By contrast, neutron crystallographers have become amalgamated with the rest of the crystallographic community, which is in fact much older. Indeed, some neutron crystallographers with interest in biological molecules keep the company of life scientists.

One area where much was once expected from neutron-scattering studies is liquid state physics. Early studies[19,20] did hold some promise but over the years it came to be realized that dramatic results as in other areas of condensed matter physics would not be forthcoming. Scattering studies on liquids became restricted to a tiny minority (which includes Egelstaff), which bravely sought to illuminate questions raised in early papers by Born and Green on the statistical mechanics of liquids.

Even the study of phonons, which heralded the beginnings of this subject, has sort of petered out as far as condensed matter physics is concerned, since not only have all the simple materials been thoroughly studied, but various aspects related to structural phase transitions also have been exhaustively explored. However, such studies have surfaced in a new area, namely geophysics, as the papers on the mineral fayalite (Fe_2SiO_4) presented at NS-91 show[21,22]. An exception to this general lack of interest in phonons on the part of physicists relates of course to the high-T_c materials. So far, only the phonon density of states was measured

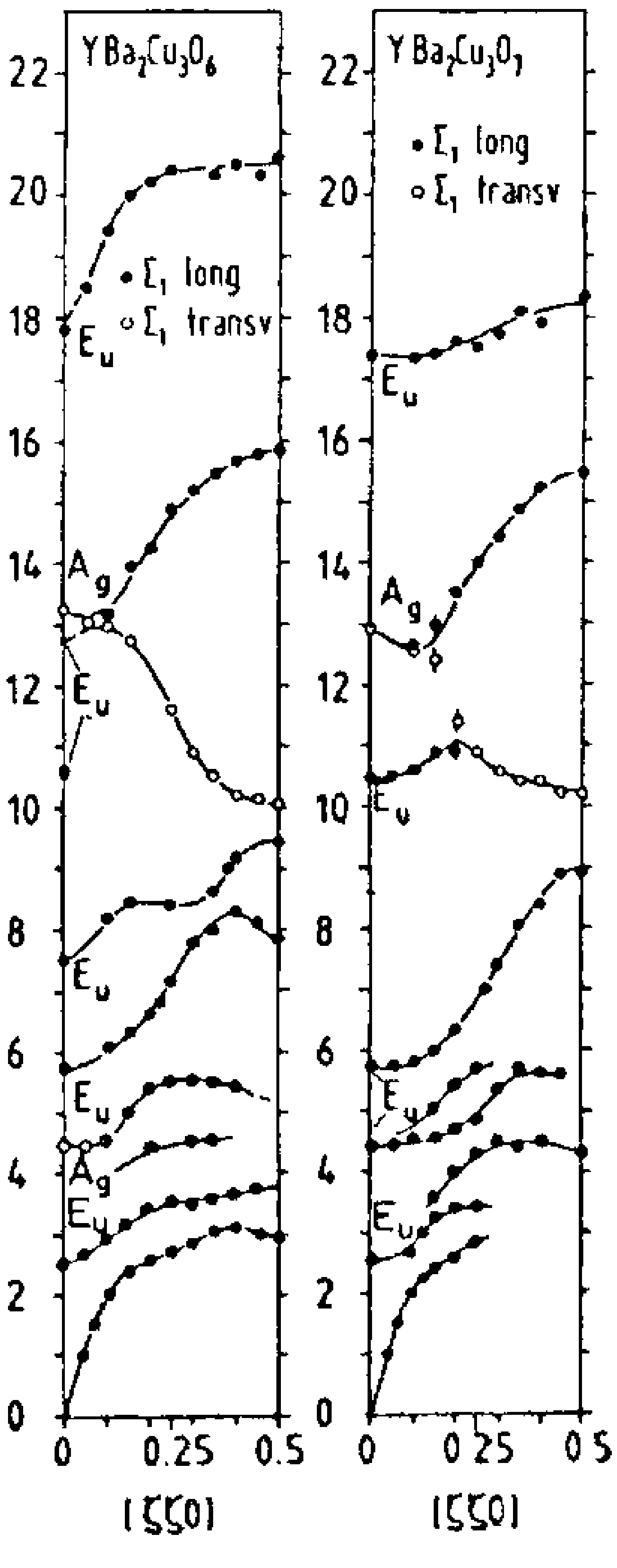

Figure 1. Selected phonon dispersion curves for $YBa_2Cu_3O_6$ and $YBa_2Cu_3O_7$. The lines are mere guides to the eye.

(e.g. papers[23–25] presented at NS-91), but very recently, a beginning has been made in the measurement of the dispersion curves themselves[26]. This is the result of an international collaboration and is a *tour de force* in that the experiment was performed with very tiny single crystals. Figure 1 shows selected dispersion curves for the 1-2-3 compounds. Naturally, suitable model analysis of the data has been made and used for interpreting earlier results on phonon density of states (see Figure 2).

Turning to cold neutrons, SANS is no longer a mere technique. It is producing valuable information, especially in the realm of colloids, liquid crystals and biomolecules, and there were several interesting papers relating to this area at NS-91[27–38]. Of particular interest was the 'motion' picture of the shearing of aligned micelles, following the application of a time-dependent shear force[28]. In this experiment, a solution of TTMA-sal (tetradecyltrimethylammonium salicylate) in D_2O was first prepared. Above a certain critical concentration, TTMA-sal is known to form rod-like micelles. The application of a shear force causes orientational alignments, and the high cold-neutron flux combined with the superb sophistication of the SANS apparatus at ILL permitted a 'motion' picture study. One frame of this movie is displayed in Figure 3. At NS-91, the audience was treated to a full movie, shown using a projector coupled to a computer.

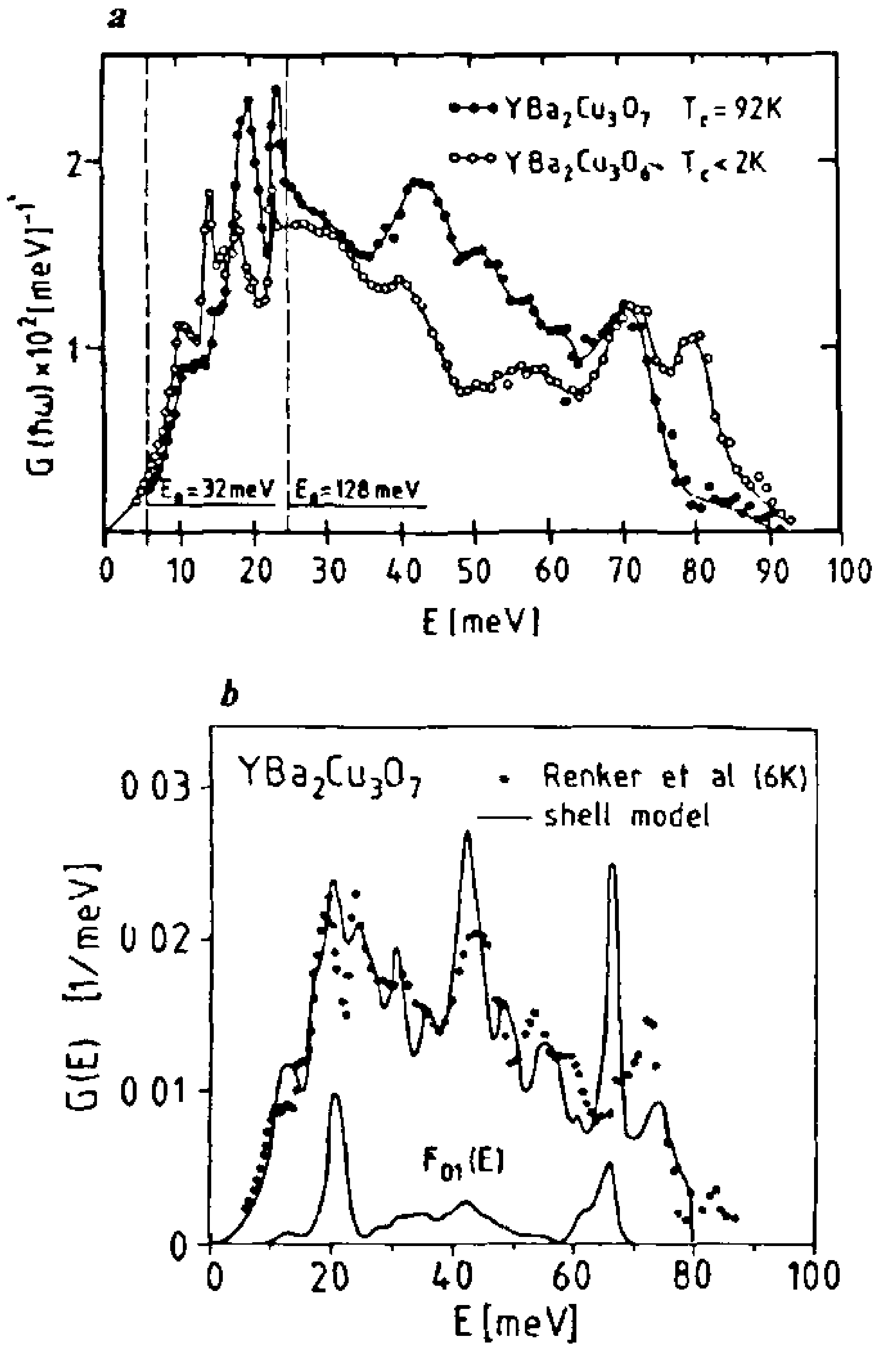

Figure 2. *a*, Experimental results for generalized phonon density of states for the 1-2-3 compounds as obtained by Renker *et al* (*Z. Phys.*, 1988, **B71**, 437). *b*, Comparison of some of the results of Renker *et al.* with a shell-model calculation, model parameters being derived from an analysis of experimental dispersion curves

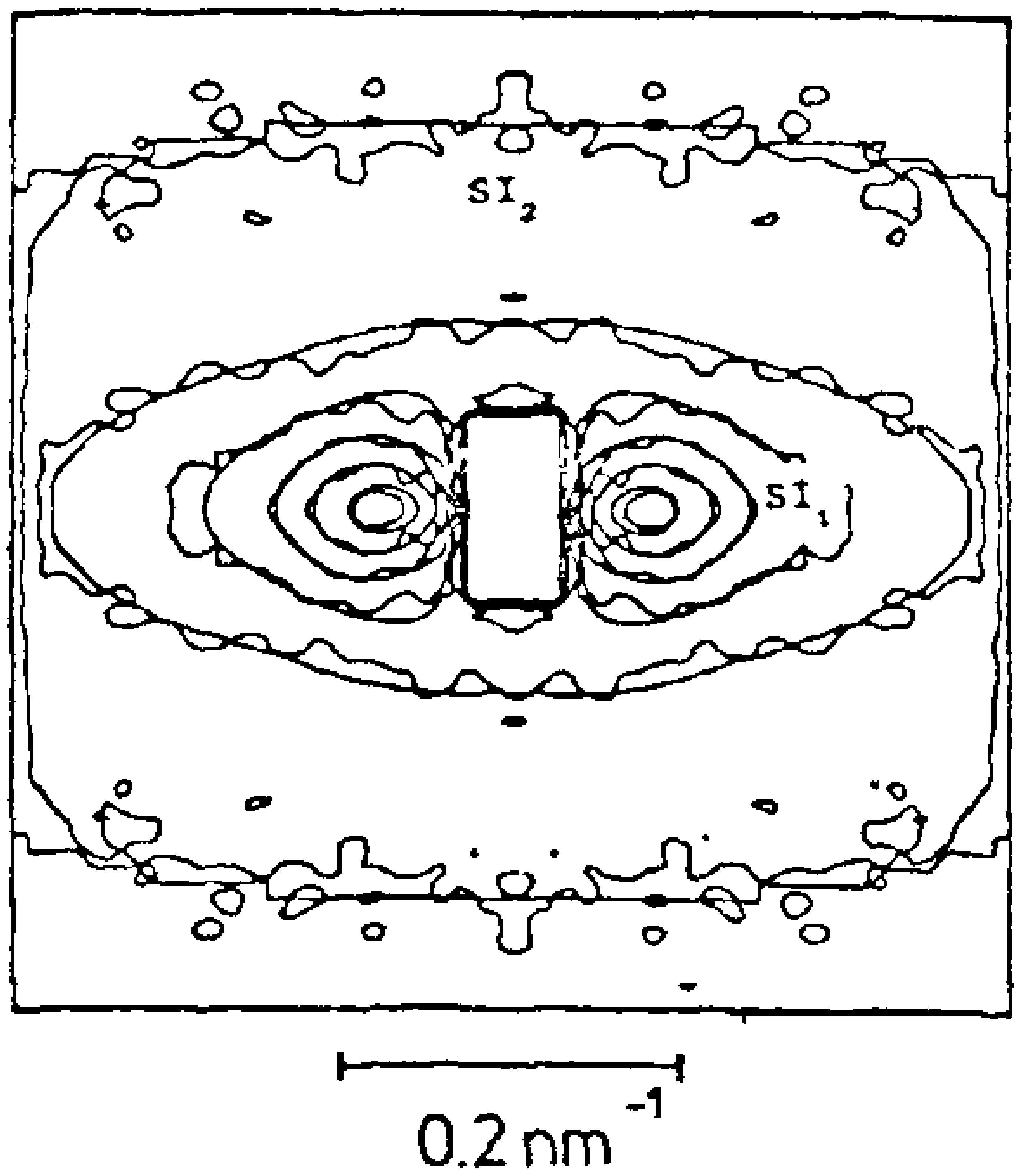

Figure 3. Contour plot of the measured scattering intensity measured about 2.5 sec after the application of a step-function shear force. The contours refer to constant scattered-neutron intensities. The smooth curves represent a fit to the observation, based on a suitable model for shear relaxation of the micelles

Even more spectacular was the experiment (an international collaboration again) reported by Knop[31], wherein biomolecules are studied by carefully introducing protons in some regions and deuterons in others, and achieving a 'spin contrast' by the dynamic nuclear polarization technique first proposed by Abragam in connection with nuclear physics experiments. The idea is roughly as follows: Polarized neutron scattering depends strongly on nuclear spin polarization, particularly on proton spin polarization. A single proton in a deuterated environment then becomes as effective as 10 electrons in X-ray diffraction.

An important problem in biology is the structure of the ribosome. Ribosomes are the site of protein biosynthesis in the living cell. The experiment reported was performed on the ribosomes of *Escherichia coli*. The predominant constituent is ribosomal RNA (rRNA), the residual part largely consisting of various proteins (TP). In normal structural investigations (X-ray diffraction, neutron diffraction, etc.) the RNAs are difficult to resolve because of their low contrast. A protonated rRNA together with deuterated TP in a deuterated solvent is, however, easier to pick out. Through the use of dynamic polarization and cold neutrons, a further enhancement by a factor of nearly a thousand was achieved. True, the use of cold neutrons results in a resolution not better than ~ 6 Å, but then even conventional X-ray diffraction studies of ribosomes do not yield a resolution better than this order. Indeed, since X-ray work is not able to clearly map the boundaries of single ribosomal proteins, structural information obtained via the techniques used by Knop *et al.* is expected to provide useful inputs for further refinement of X-ray data.

The wave nature of the neutron has been extensively exploited for diffracting neutrons from condensed matter, but until a few years ago, there was no serious interest in performing the neutronic analogues of the experiments on interferometry familiar in optics. The first such neutron-interferometry experiments were done using thermal neutrons but more recently cold neutrons are being increasingly used for this purpose. Some of the experiments in progress or being planned are quite basic. For example, Zeilinger[39] is interested in demonstrating the Bohm–Aharanov effect, while Summhammer[40] described at NS-91 how some of Christiansen's old ideas could be reactivated with neutrons. Again at NS-91, Ioffe[41] cautioned that the interaction of neutrons with the gravitational field of the earth is sufficiently important as to cause *gravitational aberrations* that must be suitably corrected. Partha Ghose and Dipankar Home (readers might recall their recent article in this journal[42]) proposed an interesting experiment to test wavefunction collapse and the complementarity principle[43]. Ioffe *et al.*[44] suggested a demonstration of Berry's phase by a neutron-interferometry experiment. In the same vein, some of the experiments planned in Europe are: improvement of the present limit of a possible nonlinearity of the Schrödinger equation, precision test of the unitarity of quantum mechanics, neutron electric charge limit, and the neutron Cavendish experiment[45]. But ultra-cold-neutron spectrometry has practical applications as well, and there are plans to exploit the nanovolt resolution to study very slow dynamical processes in macromolecules, phase transitions of gels, etc.

There is a feeling in certain quarters that, with the advent of synchrotron radiation sources, neutron scattering is finished. Perhaps this gloomy outlook is in part due to the difficulty of keeping active many of the research reactors in the West. S. K. Sinha, who has rich experience in using both neutron as well as synchrotron sources, made a comparative study at the conference of the utility of the two techniques[46]. As he pointed out, the two techniques are complementary, each having its own place. It was his experience that some problems are best solved by a diligent use of *both* techniques. It is worthy of note that, at Brookhaven, where they have a high-flux reactor and a synchrotron source in the same location, the complementary features of the two methods have often been skilfully exploited. Perhaps the decision to locate the powerful European Photon Source at Grenoble, next to the ILL, is also influenced to some extent by this same consideration.

The Indian scene

Where does India stand now in all this? As far as neutron scattering is concerned, the recently commissioned DHRUVA reactor at Trombay does provide us with a fairly powerful neutron source (flux $\sim 10^{14}$ n cm^{-2} sec^{-1}), permitting Indian scientists to continue to be reasonably competitive. In fact, in neutron scattering we are ahead of China, but it is the other way about with respect to synchrotron radiation. However, a good reactor alone is not sufficient, and one must have the right kind of instruments to go with it. In the case of DHRUVA, thanks to the leadership provided by Iyengar, a variety of spectrometers have been built[47]. Indeed, Trombay has cashed in on its expertise in building neutron spectrometers by selling nearly half a million dollars worth of equipment to Bangladesh, Indonesia, the Philippines and South Korea. Even more significant, an instrument based on the window-filter idea of Iyengar[48] and built at Trombay was installed at the ISIS installation at the Rutherford Appleton Laboratory as part of an international collaboration[49]. In passing, it is worth mentioning that when Trombay scientists wanted to coat their neutron mirrors, they went to Kavalur (the site of the 2.34-metre Vainu Bappu optical telescope) to use the coating facility there. The interesting point here is that it was Trombay which had, much earlier, helped the late Vainu Bappu to set up the coating plant. And now they were getting help from one they had helped earlier; altogether, a good example of synergy and symbiotic growth.

While India is comfortably off with respect to both the reactor and even the instruments, there are other aspects that need urgent attention. These include: sample preparation and characterization, providing the right environmental conditions for the sample (i.e. high- and low-temperature attachments etc.), and finally, the most important of all, trained manpower to make efficient and effective use of the expensive facilities that have been built up.

We have a long tradition in neglecting sample preparation and characterization. It calls for hard and time-consuming work; alas, in this country, such work is seldom given either credit or recognition. I still vividly recall a conversation with Cheynoweth, famed for his numerous contributions on semiconductors. He later became a vice-president of Bell Labs, and visited Trombay in the early sixties. Feeling he would have been sufficiently softened up after a friendly tour and a nice lunch, I approached him with a request for some samples. He replied that, while he could very easily oblige, he would be doing me more good by *denying* my request. He added, significantly, 'You cannot have a worthwhile experimental programme in solid state physics if there is no matching activity in sample preparation and characterization.' Sound advice no doubt but difficult to implement when rapid publications seem to count more.

As far as human resources are concerned, Trombay no longer has an abundant supply of eager young scientists. Fortunately, the supply in the country as a whole has not dried up, there being quite a sprinkling of talent in the universities. So the trick is to make use of university students, something that should perhaps have been done ages ago. But better late than never, and it is comforting to see the formation of the inter-university consortium for DAE facilities (IUCDAEF). The first chairman of this consortium was V. G. Bhide, who has laid a solid foundation. The present chairman is R. Srinivasan, who comes to the post with an excellent record of building up first-rate facilities under trying circumstances. Having worked lifelong with students, one presumes he would know what is best for them and would be able to secure the same. Also he is no stranger to neutron scattering (though he has personally not worked in the field). One hopes therefore that the Indian reputation in neutron scattering would continue to remain high, this time through the joint effort of the national laboratories and our universities.

The papers presented at the conference are referred to by their abstract numbers, e g NS-91, HI-3 The proceedings are being published as an issue of *Physica* B.

1 von Halban, H. and Preiswerk, P., *C. R Acad Sci. (Paris)*, 1936, **203**, 73
2. Mitchell, D. P and Powers, P. N., *Phys. Rev*, 1936, **50**, 486
3. Bloch, F., *Phys Rev.*, 1936, **50**, 259, 1937, **51**, 994
4. Halpern, O and Johnson, M H, *Phys. Rev*, 1939, **55**, 898
5. Schwinger, J. and Teller, E., *Phys. Rev.*, 1937, **52**, 286.
6. Weinstock, R., *Phys Rev*, 1944, **65**, 1
7. Hughes, D. J., *Pile Neutron Research*, Addison-Wesley, Cambridge, Mass, USA, 1953
8. van Hove, L., *Phys. Rev.*, 1954, **95**, 249, 1374
9 Brockhouse, B N. and Iyengar, P. K., *Phys. Rev*, 1957, **108**, 894
10 Mukhopadhyay, R, Goyal P. S. and Rao, K. R., *Phys. Status Solidi*, 1991 (in press).
11 Warren, J L, Wenzel, R G. and Yarnell, J L., in *Inelastic Scattering of Neutrons*, IAEA, Vienna, 1965, vol I, p 361
12. Loudon, R, *Adv Phys*, 1964, **13**, 423.
13 Venkataraman, G, *Curr Sci*, 1972, **41**, 349
14. Venkataraman, G, *Journey into Light*, Indian Academy of Sciences, Bangalore, 1988
15 Cassels, T M, *Proc. R Soc London*, 1951, **A208**, 527.
16 Wilson, C C., *Neutron News*, 1990, **1**, 14
17 Aksenov, V L., NS-91, HI-3
18 West Colin, D., NS-91, HI-2.
19 Brockhouse B N and Pope, N K, *Phys Rev*, 1965, **3**, 259
20 Dasannacharya, B A and Rao, K. R., *Phys. Rev*, 1965, **A137**, 417
21 Ghose, S, Hastings, J M, Choudhury, N, Chaplot, S. L. and Rao, K R, NS-91, P1–18
22 Price, D L, Ghose, S, Choudhury, N, Chaplot, S. L. and Rao, K. R, NS-91, P1–19
23 Renker, B., Gompf, F., Adelmann, P., Ewert, D and Mutka, H, NS-91, P4–5.
24 Gompf, F, Renker, B and Mutka, H, NS-91, P4–6
25. Chaplot, S. L. *et al.*, NS-91, P4–11
26 Pintschovius, L, Reichardt, W., Pyka, N, Collin, G and Rumiantsev, A Yu, NS-91, NI–2.
27 Farnoux, B, Lee, L. T., Guiselin, O and Lapp A, NS-91, DI-1.
28 Kalus, J, NS-91, CO-2.
29 Satija, S. K, NS-91, DI–2.
30 Richter, D., Fetters, L. J, Huang, J. S, Farago, B and Ewen, B, NS-91, DI–3
31. Knop, W. *et al*, NS-91. LI–1.
32 Thiyagarajan, P, Hjelm, Jr., R P. and Alkan, H., NS-91, P2-22.
33. Schwahn, D, Jansen, S, Springer, T and Hadicke, E, NS-91, CO-1.
34 Usha Deniz, K, Pepy, G, Parette, G. and Keller, P, NS-91, P2–6
35 Eastoe, J, Robinson, B. H, Steytler, D C. and Dore, J. C., NS-91, P2–16
36. Goyal, P. S, Srinivasa Rao, K, Dasannacharya, B A. and Kelkar, V K, NS-91, P2–20
37 Goyal, P S, Dasannacharya, B A., Kelkar, V. K., Manohar, C., Srinivasa Rao, K and Valaulikar, B. S, NS-91, P2 21.
38. Teixeira, J., Alba-Siminesco, C. and Angell, C. A., NS-91, P2–23
39 Zeilinger, A., *J Phys.*, 1984, **C3**, 213.
40 Summhammer, J, NS-91, BO–1
41 Ioffe, A I, NS-91, BI-1.
42 Ghose, P and Home, D, *Curr Sci*, 1990, **59**, 897.
43 Ghose, P. and Home, D, NS-91, P3–4.
44 Ioffe, A I, Kuzmin, V M, Sbitnev, V I and Zabijakin, V S., NS-91, P3–7.
45 Drexel, W, *Neutron News*, 1990, **1**, 23.
46 Sinha, S. K, NS-91, OI-3
47. Many of these instruments are described in the July–August issue of vol. 27 (1989) of the *Indian Journal of Pure and Applied Physics*, dedicated exclusively to instrumentation activities in India. (This issue was reviewed in *Curr. Sci.*, 1990, **59**, 771. See also a letter in *Curr. Sci*, 1991, 60, 137)
48. Iyengar, P. K., *Nucl Instrum. Methods*, 1964, **25**, 367.
49 Dasannacharya, B A *et al*, Proc. IAEA Conference on Neutron Scattering to the Nineties, IAEA, Vienna, 1985, p. 443.

ACKNOWLEDGEMENT I am grateful to Dr B A Dasannacharya for making available to me the figures reproduced in this article