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Slow Neutron Studies of Molecular Motions
in Condensed Matter*

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With the advent of research reactors after World War II, work was started in various national reactor laboratories, notably at Harwell, Saclay, Chalk River, and Brookhaven to explore the interaction of neutrons and condensed matter. As the work progressed it became clear that the neutron technique offered a new and powerful tool for probing the nature of matter. Today this technique is probably the most important research application of reactor neutrons.

Let us first discuss what is observed in the simplest kind of neutron interaction with matter, the transmission of neutrons as a function of their energy, through a polycrystalline sample. Here we know that the transmission T is related exponentially to the cross section σ by $T \sim e^{-n\sigma x}$, where n is the number of scattering atoms per unit volume and x is the thickness of the sample. Figure 1 shows an idealized cross section curve (for the case where the nuclear absorption is zero). At energies of about 1 eV and above the cross section is observed to be independent of the state of matter; it is the same whether we observe the transmission of neutrons through a solid, liquid, or gaseous sample. The effect of interatomic forces is

vanishingly small. This measured cross section is called the free-atom cross section. As the neutron energy decreases, sharp discontinuities are seen, and these are from Bragg scattering and arise from the regular spacial distributions of the atoms in the microcrystal. The positions of the discontinuities is given by the usual Bragg condition,

$$n_{\lambda} = 2d \sin \theta \quad (1)$$

with $\sin \theta = 1$, and where λ is the de Broglie wavelength of the neutron, $\lambda = h/p = h/\sqrt{2mE}$; d is the spacing between planes of scattering atoms; and E is the energy of the neutron. Finally, when the energy is so low that $\lambda > 2d_{\max}$, where $d_{\max}$ is the largest spacing between atoms, the cross section drops nearly to zero. At this point the coherent scattering is non-zero only in the forward direction and the material becomes transparent to neutrons. However, you will note that the cross section does not quite drop to zero for wavelengths $\lambda > 2d_{\max}$. In this wavelength region it is experimentally found that the cross section is a sensitive function of the temperature of the material and the wavelength of the neutron. Figure 2 shows the measured cross section of polycrystalline Be as a function of wavelength,

exhibiting all the features discussed above. Note that at an energy slightly lower than 5×10^{-3} eV ($\lambda > 4 \text{ \AA}$) the cross section drops from ~ 10 b to 5 mb for a sample temperature of $\sim 100^\circ\text{K}$. The mean free path for a neutron of energy just above 5×10^{-3} eV is 1 cm, whereas for an energy slightly below 5×10^{-3} eV, the mean free path becomes greater than 2 meters. The Be literally becomes transparent to neutrons. Note that the cross section does not go to zero. The small remaining cross section arises from nuclear absorption and from the interaction of the neutron and the correlated motions of the atoms in a solid. This latter effect gave rise to the field of neutron studies of microscopic motions of condensed matter.

Now in order to better appreciate the power of the neutron technique, let us first discuss a physical phenomenon that is well understood, the scattering of x-rays from matter. Here it is known that when the wavelength of the photon becomes comparable to the spacing of the scattering centers in the sample, the photon undergoes large momentum transfers on scattering. The position of these peaks we understand in terms of the elastic scattering of a wave from a fixed lattice of scatterers

from which we get Bragg's law. Now the question we ask is how does one interpret the natural width or shape of the peaks arising from thermal agitation? It turns out that one can still use wave optics in the following way: one considers not the scattering from a perfect lattice, but a disordered one - to be more precise, from an ensemble of disordered lattices representing all the possible configurations the atoms assume due to thermal agitation. By this approach the calculated line shape agrees with the measured shape. Now in one sense it is rather surprising that a purely elastic scattering model gives the correct answer because we are obviously dealing with inelastic processes. However, the reason the elastic calculation is valid is seen if one asks about the time of interaction of the photon with the scattering centers. For a typical material having atomic spacing of $3 \text{ \AA}$,

$$t_Y = \frac{3 \times 10^{-8}}{3 \times 10^{10}} = 10^{-18} \text{ sec.} \quad (2)$$

This time is much shorter than the periods of thermal motion in condensed matter and so in effect an x-ray photon during its interaction time sees a static picture of some particular state of motion of the

assembly of atoms. Now if we ask the same question concerning time of interaction of the neutron (let us choose as typical a $4 \text{ \AA}$ neutron which has a velocity of 1000 meters/sec) we have,

$$t_n = \frac{3 \times 10^{-8}}{10^5} = 3 \times 10^{-13} \text{ sec, } (3)$$

which is a time typical of the period of interatomic motions. Therefore, when a slow neutron scatters from an assembly of atoms it no longer sees a static lattice but one in which the atoms are moving during the interaction. The correlated motions between scatterers produce an energy change in the scattered neutron comparable to the incident neutron energy and provide the basis for measurement. In general, the kinematics of the inelastic scattering of neutrons are given by energy and momentum conservation equations,

$$\frac{\hbar^2}{2m} (k_f^2 - k_i^2) = E(\vec{q}) \quad (5)$$

$$\hbar(\vec{k}_f - \vec{k}_i) = \hbar(2\pi\vec{T} + \vec{q}) \quad (6)$$

where $\vec{k}_i$ is the incident neutron wave vector; $\vec{k}_f$ is the scattered neutron wave vector; and $E(\vec{q})$ is the energy of a collective excitation (phonon) with wave vector $\vec{q}$.

In the foregoing discussion we have assumed that the neutron interacts in some way with the atoms and thereby is scattered, but we have not discussed the nature of the interaction. The interaction with the atom is via the neutron-nuclear interaction. The neutron-electron interaction is negligible compared to the nuclear interaction. However, the neutron can strongly interact via its magnetic moment with unpaired atomic electrons. The neutron-nuclear interaction, in general, is very complicated; however, because slow neutrons possess wavelengths in the order of 10^{-8} cm compared to nuclear dimensions in the order of 10^{-12} cm, a rather simple description obtains. Only s-wave scattering is important, and the scattering amplitude is independent of angle (scattering is isotropic). The cross section is just $\sigma = 4\pi a^2$, where a is the scattering amplitude. There is no way of predicting a priori from theory what the magnitude or sign of the amplitude, a , will be for a particular nuclide, but the amplitudes must be determined by measurement. At the present time, this poses no problem because most of the interesting amplitudes have been determined with some accuracy. For all practical purposes the magnitude of the scattering amplitude over the range of incoming

neutron energies used in experiment is constant.

The scattering amplitude is spin dependent. That means if the target nucleus has a spin I the scattering intensity will be different from the case where the neutron spin is parallel $J = I + \frac{1}{2}$ to the nucleus spin, as compared to the opposite case, $J = I - \frac{1}{2}$ (J is the total spin quantum number). The scattering amplitude, being a nuclear effect, in general varies from isotope to isotope of the same nucleus, and finally the sign of the scattering amplitude while most often positive can sometimes be negative. A negative amplitude implies a nuclear resonance level near the thermal neutron energy region.

When the sample under investigation consists of nuclides possessing different scattering amplitudes, this results in incoherence in the scattering process. In the general case the coherent cross section for an ensemble of atoms is given by,

$$\sigma_{\text{coh}} = 4\pi \left(\sum_i p_i a_i \right)^2, \quad (7)$$

whereas the total cross section is,

$$\sigma_{\text{total}} = 4\pi \sum_i p_i a_i^2 \quad (8)$$

and the incoherent cross section is given by the difference of σ_{total} and σ_{coh} and is,

$$\sigma_{\text{incoh}} = 4\pi \sum_i \sum_j p_i p_j (a_i - a_j)^2 \quad (9)$$

where p_i is the weight factor for a given isotope or a given spin state. For the spin state it is just the quantum mechanical fractional multiplicity,

$$p_{I+\frac{1}{2}} = \frac{I+1}{2I+1} \quad p_{I-\frac{1}{2}} = \frac{I}{2I+1}$$

Because the experimental effects depend essentially on the momentum transfer, a variety of experimental approaches are available. The experimental problem of obtaining a balance between maximum counting rate and resolution has led to two parallel developments. In one case very low momentum neutrons ($k \sim 1 \text{ \AA}^{-1}$; $p = \hbar k$) issuing from a reactor are scattered from a sample. These undergo momentum and energy changes large or comparable to their incident momentum or energy and, therefore, the changes are relatively easy to measure with good accuracy. In the second case, higher incident momentum neutrons are used ($k \sim 10 \text{ \AA}^{-1}$) making the necessary requirements on momentum and energy resolution more stringent. However, the nature of reactor neutron spectra is such

that the intensity of the $1 \text{ \AA}^{0-1}$ is much smaller than that of the $10 \text{ \AA}^{0-1}$ neutrons and thereby offsets the measurement advantage of the first case. At the present time, both techniques are available in the larger reactor laboratories.

At Brookhaven we have adopted the first approach, that is using incident neutrons that are cold ($\bar{T} \sim 40^\circ\text{K}$, $\lambda \sim 4 \text{ \AA}$). I will describe the Brookhaven cold-neutron facility which is typical of installations now existing in various U.S., European, and Russian laboratories. Figure 3 shows a diagram of that apparatus installed on top of the Brookhaven Graphite reactor. The neutron radiating surface is ~ 3 meters from the sample. The Be filter is cooled to liquid-nitrogen temperatures to minimize the attenuation of cold neutrons by scattering from phonons. The flux of cold neutrons incident on the sample is $\sim 1.5 \times 10^7$ neutrons/sec. The scattered neutrons pass through a chopper and are timed over a flight path of 5 meters. The detector is a bank of BF_3 counters which is nearly black for cold neutrons. The intensity at the detector as observed by elastically scattering the incident beam of cold neutrons is $\sim 10^2$ neutrons/sec. A factor of $1/300$ is lost because of the duty cycle of the chopper and a factor of $1/500$ comes from the solid

angle of the sample subtended by the BF_3 detectors. Figure 4 shows a photograph of the apparatus at the reactor. The incident beam passes up through the floor into the drum where the sample is located. The arm connected to the drum carries the chopper on one end and the BF_3 bank on the other. The drum and arm arrangement rotate so that the scattering angle may be varied from 90° to 30° . Figure 5 shows a diagram of the chopper. It consists of a stack of cadmium plated steel sheets stacked in a 4" diameter shell. The rotor spins at 15,000 rpm and transmits a burst of neutrons of 30 μsec duration. Figure 6 is the spectrum of the Be filtered neutrons as observed by elastic scattering from a vanadium sample. The dashed curve is the pile spectra as filtered through 8" of polycrystalline Be. The shoulder at low energy (flight time 4.2 millisec) arises from the incomplete filtering of Be. The other sharp breaks are Bragg peaks from the aluminum present in the construction materials of the reactor. The black points represent the measured spectrum and the solid line is derived from a folding of the known instrument resolution into the dashed curve. It is seen that there is good agreement between the measured points and the solid line. Note that the

sharp rise in intensity corresponding to the Bragg "cut-off" in Be is monotonic and free from structure. The rate of rise of the intensity is determined by the overall instrument resolution. For this apparatus the resolution function is approximately Gaussian in shape with a full width at half maximum of 2.5°K .

When a beam of cold neutrons is incident on a polycrystalline sample possessing a totally coherent scattering amplitude, the scattered neutron intensity at some angle $\theta \neq 0$ with respect to the incident beam direction arises solely from the inelastic process. Elastic scattering can only take place in the forward direction. In such cases sharp peaks in intensity at definite energies are observed and these correspond to the normal mode of excitation or phonons. The difference between incoming and outgoing neutron energies determine the phonon energy E as per Eq. (5). A vector construction in reciprocal lattice space can be used to determine the wave vector of the phonon, as per Eq. (6). Figure 7 shows the results of such an investigation of the dispersion relations for phonons in germanium¹ carried out at Brookhaven several years ago. Note that, in principle, all of reciprocal lattice space is amenable to measurement.

This is in contrast to infrared or Raman studies of the optical mode which we restricted to a small region around $q = 0$. In fact the region of large q which, heretofore has been most difficult to investigate, is most easily measured with neutrons.

Several years ago at Chalk River, Cochran, Woods, and Brockhouse postulated that ferroelectricity may arise from the inability of the lattice to support a transverse optical mode of zero wave number. The idea stemmed from the Lyddane-Sachs-Teller relation,

$$\frac{\epsilon_s}{\epsilon_e} = \frac{\omega_l^2}{\omega_t^2} \quad (10)$$

where ω_l and ω_t are the frequencies at $q = 0$ of the longitudinal and transverse modes of the optical branch; ϵ_s the static dielectric constant; and ϵ_e the high frequency dielectric constant. Since for a ferroelectric the static dielectric constant follows a Curie law,

$$\epsilon_s = c/T - T_c, \quad (11)$$

it would follow from the proposed mechanism that,

$$\omega_t^2 = b(T - T_c). \quad (12)$$

A neutron investigation was carried out by Cowley² at

Chalk River in 1963 on strontium titanate. He found that the lowest transverse optic mode was temperature dependent. At $q = 0$ the effect was the greatest, ω_t^2 decreasing linearly with T , whereas at the edge of the zone, ω_t changed only slightly with temperature. Measurements were carried out over a temperature range of 90° to 400°K . When the ω_t^2 ($q = 0$) data are plotted as a function of temperature, they fall on a straight line passing through $\omega = 0$ at $T = 32^\circ\text{K}$, in agreement with the Curie temperature derived from dielectric constant measurements.

For the case where the scattering sample possesses a completely incoherent amplitude, the scattered waves no longer cohere in the sense of Eq. (6). In this case Placzek and Van Hove³ showed that the scattered neutron intensity is simply related to the frequency spectrum $g(\omega)$ of oscillator states in the solid. The relation for a cubic lattice is,

$$\frac{d\sigma}{d\Omega dk} = \frac{k_f}{k_i} e^{-2W} \frac{\kappa^2}{k_f^2 - k_i^2} \frac{1}{e^{h\omega/kT} - 1} g(\omega)$$

where e^{-2W} is the Debye-Waller factor; $1/e^{h\omega/kT} - 1$ is the population of normal modes at temperature T ; and the

other symbols are the same as defined before. There are only two naturally occurring elements which possess nearly totally incoherent scattering amplitudes, hydrogen and vanadium. The spectrum for vanadium obtained a number of years ago at Brookhaven is shown in Fig. 8. The dashed line is the result of unfolding the instrumental resolution. At low frequencies $g(\omega)$ varies as ω^2 . The sharp fall-off in neutron intensity at high frequencies is consistent with a Debye temperature of 350°K obtained from specific heat measurements. The small discontinuity in the slope at $\sim 3 \times 10^{12}$ cycles/sec has been observed in a number of laboratories and it is postulated to arise from electron-phonon effects in vanadium.

Water was one of the first liquids to be studied by the neutron technique.⁴ The scattering of neutrons from H_2O is nearly wholly from the hydrogen atoms and is, therefore, incoherent. Figure 9 shows the results of Brookhaven measurements. The distribution $\sim 5 \times 10^{-3}$ eV is a reflection of the incident Be filtered spectrum. In addition one observes neutron groups corresponding to the various motions of the water molecule in the potential of their neighbors. These are the same ones observed in optical spectroscopy studies and discussed

many years ago by Professor Magat.⁵ The hindered rotational peak is seen very strongly in the neutron data. It should be clear from the preceeding discussion that when neutrons scatter from an incoherent substance, the intensity as a function of scattered neutron energy depends on the density of states. If there are motions of well defined energies these will be reflected as peaks in the scattering data. In a liquid, however, we know that there may be a great variety of particle motions with broad and overlapping energies. These motions are only amenable to some sort of statistical analysis. It was in this spirit that Van Hove⁶ developed a general theory of neutron scattering in terms of correlation functions. The expression for the Van Hove cross section is,

$$\frac{d^2\sigma}{d\Omega d\omega} \sim a^2 \frac{k_f}{k_i} \int e^{i(\vec{k}\vec{r} - \omega t)} G(\vec{r}, t) d\vec{r} dt \quad (13)$$

where a is the neutron-nuclear scattering amplitude; $h\vec{k}$ the momentum transfer, and $h\omega$ the energy transfer on scattering. Classically, $G(\vec{r}, t)$ has a simple meaning. It is the average density distribution at a time $t + t'$ as seen from a point where the neutron passed at time t' . In all cases, both quantum and classical, $G(\vec{r}, t)$ is the correlation

between the presence of a particle at position $\vec{r} + \vec{r}'$ at a time $t + t'$ and the presence of a particle at $\vec{r}'$ and t' averaged over all of $\vec{r}'$. This clearly can come about in two ways, either the same atom that was at r' and t' origin can be at position r at time t , or another atom distinct from the one at r' and t' can be at position r at time t . This leads to a logical separation of $G(\vec{r}, t)$ into two parts $G(\vec{r}, t) = G_s(\vec{r}, t) + G_d(\vec{r}, t)$, where $G_s(\vec{r}, t)$ is called the self-part of the generalized pair distribution function and is related to the self-diffusion of molecules in a liquid, and G_d is called the distinct part. G_s corresponds to the first of the two alternatives above and G_d the latter. For the case where the scattering amplitude is purely coherent, the inelastic scattering experiments are a measure of $G = G_s + G_d$, whereas for the case where the scattering amplitude is incoherent one measures $G_s(\vec{r}, t)$ alone. At time $t = 0$ it essentially reduces to $g(\vec{r})$, the familiar static pair distribution function of Zernike and Prins.

Vineyard⁷ used the Van Hove formalism to discuss the scattering of neutrons from liquids. He pointed out that the diffusive motions of molecules in the liquid should be observed as a broadening of the incident spectrum. For an incoherent scattering sample the broadening is

given by,

$$\Delta E = 2\hbar D k^2,$$

where D is the diffusion constant and $\hbar k$ is the momentum transfer. Figure 10 shows the Brookhaven data in the energy region of interest. The energy region is centered around the incident Be-filtered spectrum. The experimental points are the black circles. The solid line is sketched through these experimental points to focus attention on them. The dashed line is calculated from our known incoming spectrum (Fig. 6) and the generally accepted value for the diffusion constant for water $D = 1.85 \times 10^{-5} \text{ cm}^2/\text{sec}$.

It is seen from Fig. 10 that the expected diffusive broadening of cold neutrons is not observed in H_2O . One way to interpret these results is to say that the water molecules tend to dwell in the vicinity of their neighbors for periods in the order of 10^{-12} sec and then make diffusive jumps. The theory of the expected quasi-elastic neutron scattering from various diffusion models has been considered by Sjölander and Singwi.⁸ A detailed experimental study of H_2O by Larsson⁹ has confirmed the Brookhaven conclusion that the short time behavior of water is solid-like.

The first systematic neutron investigation of the rotational properties of molecules in molecular crystals

was carried out with the ammonium halides.¹⁰ As was the case with water the neutron scattering occurs principally from hydrogen and is, therefore, incoherent. Figure 11 shows the scattered neutron spectra obtained from NH_4Cl at 20°C . The major part of the incident spectrum is at energies less than 5×10^{-3} and is not shown. The two peaks at 48 and 25 millielectron volts correspond to the torsional oscillation and the vibrational oscillation, respectively of the NH_4 ion with respect to the cubic Cl lattice. The energies expressed as wave numbers for these motions are 358 and 166 cm^{-1} , respectively. Notice that these states are observed as single quantum transitions not in combination with other modes as is usually the case with optical measurements. The width torsional oscillation peak is slightly larger than the instrument resolution indicating some anharmonicity in the motion. The width of the optical line is considerably broader than our resolution. With an incoherent scatterer the neutrons sample some average of the optical modes over the entire Brillouin zone. The observed width probably arises from dispersion in the optical branch.

Figure 12 shows the spectrum of NH_4Br at 80°K (phase III) and at 296°K (phase II). The relative measured intensity of the peaks at the two temperatures varies as the Boltzmann population factor, however, for purposes of comparison they are plotted on a comparable scale. Here we have the most direct experimental evidence for the Frenkel hypothesis, that the phase change is the result of an order-disorder transition. The width of the torsional oscillation peak in phase III is accounted entirely by instrument resolution; in phase II this peak has shifted slightly (16 cm^{-1}) towards lower energies and has broadened slightly. A combination appears in the 296°K data, at an energy corresponding to the sum of the torsional and optical lines. The optical line within experimental error does not shift in position or change in width in the two phases. The width of this peak is some $10\text{ meV} = 80\text{ cm}^{-1}$, and as with the NH_4Cl , is much wider than the instrument resolution. The data resulting from the Brookhaven measurements on NH_4Cl and NH_4Br in phases II and III and NH_4I in phase III are given in Table I. Figure 13 is a plot of the NH_4I data at 248°K (phase III).

Figure 14 shows the spectrum from NH_4I in phase I. In making the transition from phase II to phase I the crystal structure changes from a body center to face center cube.

Although the peak in the neutron spectrum does not shift very much from phase II to I the entire character of the spectrum has changed. The rotational "band" has become so broad and intense that it completely obscures the optical line. For purposes of comparison the shape of the neutron spectrum obtained from NH_3 gas is sketched as a dotted line. Before discussing the interpretation of this spectrum it is worthwhile to compare this experimental data with the kind obtained from infrared measurements of the same phenomenon. In the latter measurements the evidence for the onset of some freedom of rotation is based on the disappearance of a combination line. The details of the rotational motion are inferred from very careful observation on how the intensity of the line approached zero. It is clear that the appearance of data rather than the disappearance is much more amenable to measurement and analysis.

A comparison of the data of NH_4I and NH_3 gas would, at first, lead to the conclusion that the motion of the NH_4 ion in NH_4I in phase I was similar to the motion of NH_3 gas molecules. While the above statement contains some element of truth, it is not a correct statement. One important point of difference is that gas molecules are free to translate, whereas the NH_4^+ ions are, by comparison, fixed. Another point is that the NH_3 molecule has 3 degrees of rotational freedom, whereas the neutron diffraction measurements on

NH_4I in phase I indicate that the rotational motion cannot be completely free in this sense.

Whereas it is possible to calculate in a simple, approximate manner the spectrum of neutrons scattered by a rotating gas molecule, there is no method available at present for performing such a calculation when intermolecular effects are important, that is in a liquid or solid. For this reason for the last few years at Brookhaven we have been accumulating neutron data on various systems of "freely" rotating molecules. The first published results are those of Janik et al.¹² A study of methane in gaseous, liquid, and solid forms, by K. Otnes, is in press.¹³ I can only briefly summarize the salient features of the results so far. The shape of the spectra measured in liquid NH_4 , CH_3I , and $\text{CH}_3\text{C} \equiv \text{CCH}_3$ is similar in shape to that calculated for the appropriate free gas molecule. However, the peaks of the measured spectra are always found to be displaced toward higher energies. By empirical rules one can make good estimates whether free rotation is taking place in a solid or liquid. Although effects of hindrance are clearly seen in the neutron data, it is still not possible to describe the hindrance in a quantitative manner because the theoretical framework is lacking.

On the basis of these experimental studies we can now conclude that the spectrum obtained for NH_4I in phase I indicates that the NH_4 ion is rotating freely around a single axis of rotation.

An interesting feature of the measurements of Janik et al. was an attempt to measure the rotational properties of the methyl groups in di-methoxyazoxybenzene. This was done by preparing a "background" molecule of azoxybenzene, and subtracting the spectrum of the latter from the former. The structure of these molecules is shown in Fig. 15. Figure 16 shows the data properly normalized and subtracted at a temperature of -75°C and a scattering angle of 90° . At this temperature the sample is crystalline. Two sharp peaks are observed indicating torsional oscillations. At $+125^\circ\text{C}$ the material becomes nematic and the observed spectrum is shown in Fig. 17. The two peaks seen in the crystalline state are still observed but they have become quite broad and are overlapping. These data would indicate that the rotational motion is not quite free at this temperature.

In this paper I have tried to present a survey of how neutrons are used to probe the microscopic motions of condensed matter. Examples of experimental data are mostly from Brookhaven because I have a firsthand acquaintance with

these data. This field has grown so rapidly that in the allotted space I have only been able to touch on a few of the results. I have not even touched on magnetic inelastic scattering of neutrons, a field where great insight into the nature of magnetism is being gained. For those interested in more details I refer to them the Proceedings of the IAEA meetings in Vienna and Chalk River.¹⁴

Table I. Energy Levels of Torsional Oscillations and Optical Vibrations Observed in Neutron Scattering Data.

<u>Substance</u>	<u>T</u>	<u>Phase</u>	<u>Torsional Wave No.</u>	<u>Vibrational Wave No.</u>
NH ₄ Cl	20°C	II	358 ± 5 cm ⁻¹	166 ± 4 cm ⁻¹
	-195°C	III	388 ± 6	171 ± 5
NH ₄ Br	20°C	II	319 ± 5	156 ± 4
	-195°C	III	336 ± 6	155 ± 5
NH ₄ I	-25°C	III	277 ± 6	136 ± 5

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Figure Captions

- Figure 1: Idealized total neutron cross section of a polycrystalline sample for slow neutrons.
- Figure 2: Measured total cross section of polycrystalline Be.
- Figure 3: Cold neutron measuring facility at the Brookhaven Graphite reactor.
- Figure 4: Photograph of Brookhaven cold neutron facility.
- Figure 5: Diagram of slow chopper.
- Figure 6: Be-filtered incident cold neutron spectrum.
- Figure 7: Dispersion relations in germanium obtained from cold neutron measurements.
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- Figure 10: Spectrum of neutrons scattered from H_2O in quasi-elastic energy region.
- Figure 11: The neutron spectrum from NH_4Cl .
- Figure 12: Spectra of NH_4Br observed from phase III ($T = 80^\circ\text{K}$) and phase II ($T = 296^\circ\text{K}$).
- Figure 13: Spectrum of NH_4I in phase II ($T = -25^\circ\text{C}$).

Figure 14: Spectrum of NH_4I in phase I ($T = 20^\circ\text{C}$). The dashed line represents the experimentally observed spectrum from NH_3 gas at the same temperature.

Figure 15: Structure of di-methoxyazoxybenzene and azoxybenzene.

Figure 16: Spectrum of CH_3 groups of di-methoxyazoxybenzene (p-azoxyanisole) in the crystalline phase.

Figure 17: Spectra of di-methoxyazoxybenzene in the nematic phase.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

FIG. 14

DI-METHOXYAZOXYBENZENE

FIG. 15

AZOXYBENZENE

FIG. 16

FIG. 17