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# WE NEED MORE INTENSE THERMAL-NEUTRON BEAMS

Most experiments have now reached sensitivity limits. If this unique probe is to continue exploration of atomic and nuclear forces, its operators should have bigger fluxes than are now available.

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NEW SCHEMES FOR producing neutrons can dramatically increase thermal fluxes.[1–4] One proposed method would produce short, intense pulses (figure 1)[5] while another would make steady fluxes at a greater average intensity than sources that now exist.

Ever since their discovery, neutrons have been uniquely useful in studying matter. Their peculiar character enables their users to explore properties not accessible with other probes like x rays, infrared and microwaves. Neutron beams have shown their usefulness in studies of nuclear forces, crystal structure, atomic arrangements in liquids and molecules, and even structure of large organic molecules. With more intense beams we can take on experiments now impossible such as observations of atomic motions during shocks and measurements of Fermi surfaces in liquids. Neutron beams are likely also to become valuable analytical tools for everyday production needs.

Now, though, the experimenters have pushed many of their experiments to the available sensitivity limits; an urgent need exists for more intense sources. Although the invention of the nuclear reactor produced a source that kept them busy for several years, their instrumentation has now caught up. In the past 15 years, while techniques for using neutrons have been improving, available neutron sources have not increased appreciably in intensity.

Let us discuss the history of thermal-neutron sources and experiments you can do with them. Let us look at some of the experiments that would become feasible if we had more intense sources to work with. Keep in mind that by "thermal neutrons" I mean those with a Maxwellian velocity distribution centered around 0.025 eV and that I am emphasizing beam experiments rather than neutron irradiation. I will use the usable or "effective" flux at the source of each beam as my standard.

### *Source development*

To put the experiments in their proper perspective, consider first how the intensity of thermal-neutron sources has increased over the years. In 1932 James Chadwick discovered the neutron as the product of the bombardment of beryllium with alpha particles. Shortly thereafter more intense sources were created merely by using more intense alpha emitters. It also was learned that the neutrons could be reduced to thermal energies, and this development introduced new research capabilities. These advances in source strength are depicted in region 1 of figure 2 in which a few of the charged-particle sources are indicated. As the source intensity increased, each order-of-magnitude increase made possible *entirely new groups of experiments.*

In 1942 the first fission reactor went critical, and the thermal-neutron intensity from reactors quickly exceeded that of charged-particle reactions. As shown in region 2 of figure 2, the source flux quickly rose but then leveled off near $10^{14}$ to $10^{15}$ n cm$^{-2}$ sec$^{-1}$. Only minor gains in available neutron fluxes have been made in the last 15 years, and the possibility of

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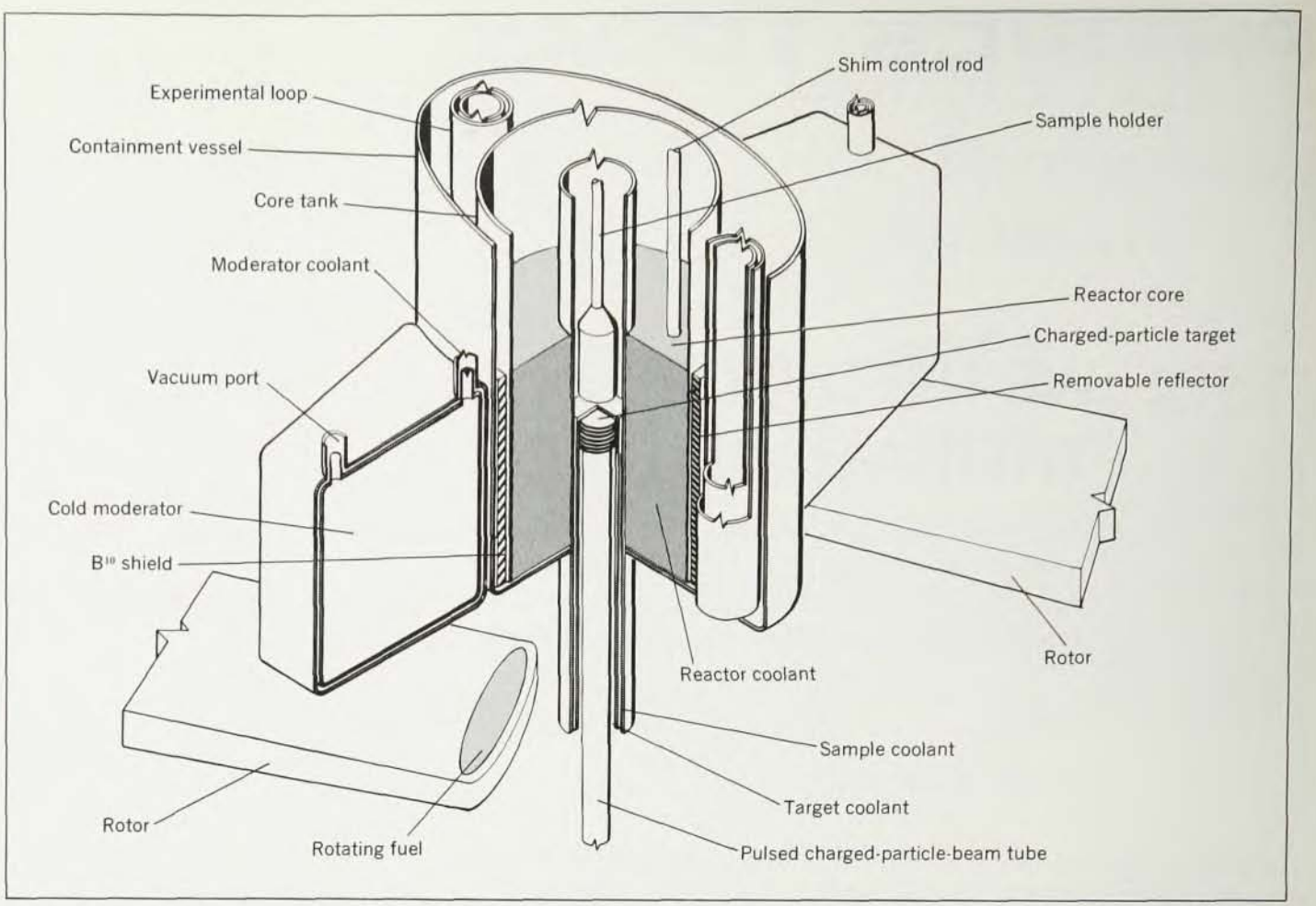



**REPETITIVELY PULSED SOURCE** would make intense neutron bursts when rotors move bits of fuel into place making it supercritical and multiplying accelerator-injected pulse of fast neutrons. —FIG. 1

rising above this plateau with conventional fission sources does not look promising. Since more intense sources are needed, we must use new techniques.

The initial phases of several possible techniques are shown in region 3 of figure 2. One source is the repetitively pulsed reactor[5] of figure 1 that can produce neutrons in very intense short bursts just when they are needed for time-of-flight experiments. By this concentration of neutrons into short time intervals, the effective flux for many beam experiments can be greatly increased over that of steady-state reactors. A good example is the pulsed reactor[6] at Dubna, USSR. Although it has an average power of only 6 kW, for many beam experiments it is comparable to a steady-state reactor of several megawatts with fluxes near $10^{14}$ n $cm^{-2}$ $sec^{-1}$. Improved repetitively pulsed sources having an average power of several megawatts now are feasible and can raise the effective experimental beam flux to $10^{17}$ n $cm^{-2}$ $sec^{-1}$ well above the level of present neutron sources.

The proposed repetitively pulsed source, RPTF, which can produce intense neutron bursts, is one of the next generation of neutron sources for beam research. The reactor is subcritical except when rotors drive additional fuel near the core and the reactor becomes delayed critical. At this instant, when the reactor has a multiplication factor greater than 100, an intense pulse of neutrons is introduced into the reactor from an accelerator. These fast neutrons are multiplied by the reactor and then are thermalized by the cold moderators to produce beams for time-of-flight experiments. It is predicted that such a device will multiply experimental capabilities by 100 times over the best sources that are presently available.

A second new type of source employs the technique by which neutrons were first produced but incorporates the tremendous advances in accelerator design to obtain the charged particles. This source is the proposed Canadian Intense Neutron Generator,[1] (ING) from which effective experimental fluxes of $10^{16}$ and possibly $10^{17}$ will be achieved. A third possibility is the single-pulse sources, nuclear explosions. These have not been included in figure 2 because one has yet to be used for a thermal-beam experiment, and the possibility of making a moderator that would yield neutrons of energies less than 0.1 eV is untested. Yet, nuclear explosions should not be ignored as another possible way to produce thermal neutrons.

While figure 2 shows the advances made over the years in thermal-neutron sources, figures 3 and 4 show some of the progress made in using these sources. Each major gain in intensity, as seen by comparing these figures, is accompanied by new experimental advances. Usually experimental advances keep pace with flux increase, but the rapid increase around

1945 did not allow time for development of optimal instrumentation. The plateau that fission sources have experienced for the last 15 years has allowed this instrumentation to catch up with the source fluxes. Now more intense sources are needed if the field is to realize its future potential.

### *Atomic structure*

In looking at some of the experiments for which more intense neutron sources are needed, let us first consider investigation of forces determining atomic structure.[7] Four characteristics of neutrons give them advantages over other methods for such studies. First, they have no charge; so their dominant interaction is with the nuclei of atoms and not with the cloud of electrons around each nucleus. Thus neutrons usually penetrate deeper into a material than do x rays and electrons to see the positions of the nuclei. Second, thermal neutrons have less energy than is required to displace atoms in the sample. In neutron diffraction, samples are not damaged or destroyed by neutrons. Third, the intensity of interaction between neutrons and nuclei depends on nuclear forces, and it varies with each isotopic species in a random fashion rather than being an increasing function of Z as are x-ray and charged-particle interactions. Thus neutrons have a different sensitivity. Compared with x rays they can better locate hydrogen nuclei in hydrocarbons and elements with similar atomic numbers in alloys. A fourth advantage is that a neutron has a magnetic moment that allows it to detect magnetic ordering in crystals. This detection is impossible with electromagnetic radiation. Thus neutrons have yielded much information about ferromagnetic and antiferromagnetic ordering in crystals. Because of these advantages neutron diffraction has become a practical research method. This progress of neutron diffraction is depicted in figure 3.

Despite the success of neutron diffraction and its routine use as a basic research method, determination of more complicated structures awaits more intense sources. As an indication of past success, consider the following progression: Neutron diffraction was first observed with source fluxes of about $10^{11}$ n cm$^{-2}$ sec$^{-1}$ for crystals with two atoms per unit cell. At present with sources of $10^{14}$–$10^{15}$ n cm$^{-2}$ sec$^{-1}$ samples with 50 atoms per unit cell have been studied. It appears that, to obtain statistical accuracy and resolution, progress goes as the cube root of the flux. Thus with sources of $10^{17}$ n cm$^{-2}$ sec$^{-1}$, samples with unknown structures of about 200 atoms per unit cell should be possible. At these fluxes, crystals with more atoms per unit cell, however, will probably be completely analyzed because the neutrons will be employed only to locate the light atoms after x rays have located the lattice of heavy atoms.

### *Organic molecules, impurities*

One very important goal of neutron diffraction is to contribute to our understanding of complicated organic molecules, such as the simpler biological molecules, by defining the locations of the hydrogens. Positions of heavier atoms (carbon, oxygen, nitrogen, etc.) in the simplest of biological molecules have only recently been determined by x-ray diffraction; even for x rays the experiment is very difficult. The low symmetry that these organic crystals display and the large number of atoms per unit cell mean that locations and intensities of thousands of diffraction peaks must be measured before a lattice and space-group determination can be attempted.

Regardless of the difficulty of the experiment and the limited sources available, neutron diffraction measurements that complement x-ray measurements of biological molecules are attempted because of the great need for the information that they provide. The practicality of these measurements is not assured at present because of the many peaks that must be observed and the length of time that each peak must be scanned to get good statistics. More intense sources would shorten this time considerably and guarantee the success of these experiments. Such structure determination will help to define biological systems better.

Impurity atoms cause many beneficial and detrimental effects in solids such as change in conductance and embrittlement. Some of these effects can be studied by neutrons because impurities cause distortion of scattering from host atoms. At present neutron experiments are capable of observing effects of impurities in concentrations of about 1% or $10^{22}$ dislocations/cm$^3$. These numbers are so great as to be almost past the point of being called impurities or damage. One would like to observe effects of less than one impurity atom per thousand host atoms where it could be assumed that the impurity atoms are not being influenced by other impurity atoms. More intense sources will allow this.

### *Liquid structure*

The structure of liquids can be determined with thermal neutrons. The diffraction pattern one obtains can be Fourier transformed so that one gets the time-independent pair-correlation function $g(r)$. An exact representation of this function is of great interest because of its connection with macroscopic physical properties such as electrical resistivity and thermoelectric power. The measurements are insufficient, however, because of their limited range, which prevents accurate Fourier transformations, because of a confusion caused by multiple scattering and because of a confusion caused by a poor definition of the momentum parameter. More intense beams can overcome these difficulties and yield more accurate measurements.

A better definition of the atomic forces in liquids is one of the prime goals of science to which thermal-neutron experiments contribute. Among the variety of models to describe the liquid state, several postulate that liquids have crystal-like structures for large groups of atoms called "globules." It is postulated that these groups form and disintegrate over periods of time that are long compared with the interaction time of the neutron probe. Therefore the neutron should be ideal for observing existence and structure of these globules if they do exist. Such experiments have not been well formulated but they probably will require very intense sources of cold neutrons.

A part of structure determinations by neutrons that has not yet been demonstrated is use of thermal neutrons to determine the relocation process of atoms when a transient force is applied to the sample. Such forces could be shock waves, magnetic pulses, electric pulses and thermal pulses. One would expect to observe translations, relocations, reordering and migration of the atoms. These phenomena would probably be more interesting near or across a phase transition or at the critical point. The rate of these relocations could be measured with neutrons. As a specific example, we could obtain a better knowledge of phase transitions in fissionable materials as heat and pressure are ap-

plied. This information could be important to our understanding of the safety of reactors. Since these transient forces also provide a means of applying more pressure, more intense magnetic fields and higher temperatures than can be achieved by static methods, they extend the range of the conventional static studies.

### *Motions of atoms*

The most recent field and one of the most popular in which slow neutrons have been used as a probe is that of slow-neutron inelastic scattering.[8] In these experiments, both the energy exchange and momentum exchange experienced when neutrons interact with the sample are measured to reveal the energy and momentum of vibrations in the sample. These measurements give one of the most accurate pictures on a microscopic scale of the atomic forces in crystals, liquids and molecules. Because these experiments are the equivalent of triple-scattering experiments, they are very wasteful of beam and were not possible until source fluxes of $10^{12}$–$10^{13}$ n cm$^{-2}$ sec$^{-1}$ became available. This development is shown in figure 4. With sources of $10^{14}$ n cm$^{-2}$ sec$^{-1}$ certain measurements in the field are performed as practical basic-research experiments whereas some of the more difficult types have only been observed and others await more intense beams.

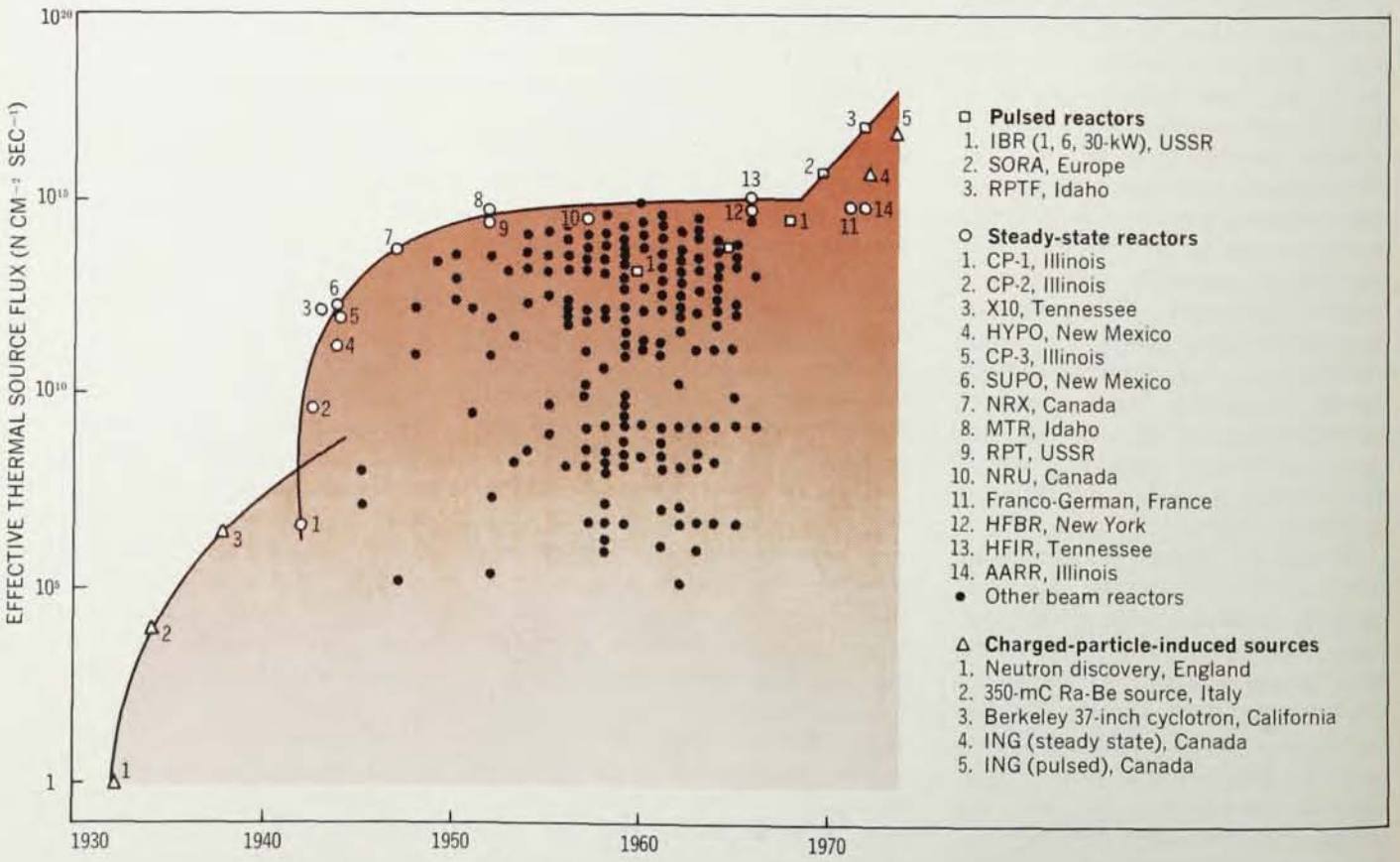
Besides the advantages outlined for neutron diffraction, neutrons have additional advantages as compared to electromagnetic radiation and charged-particle interactions for inelastic-scattering experiments. Because they can most easily observe energy transitions of a magnitude similar to their own and because they are thermal, their effective range is at the extreme low-energy end of infrared radiation and the extreme high end of microwave radiation. This effective range, coupled with the fact that neutrons interact according to a different set of selection rules than does electromagnetic radiation, allows measurements of molecular excitations not observable by infrared methods.

### *Dispersion relations*

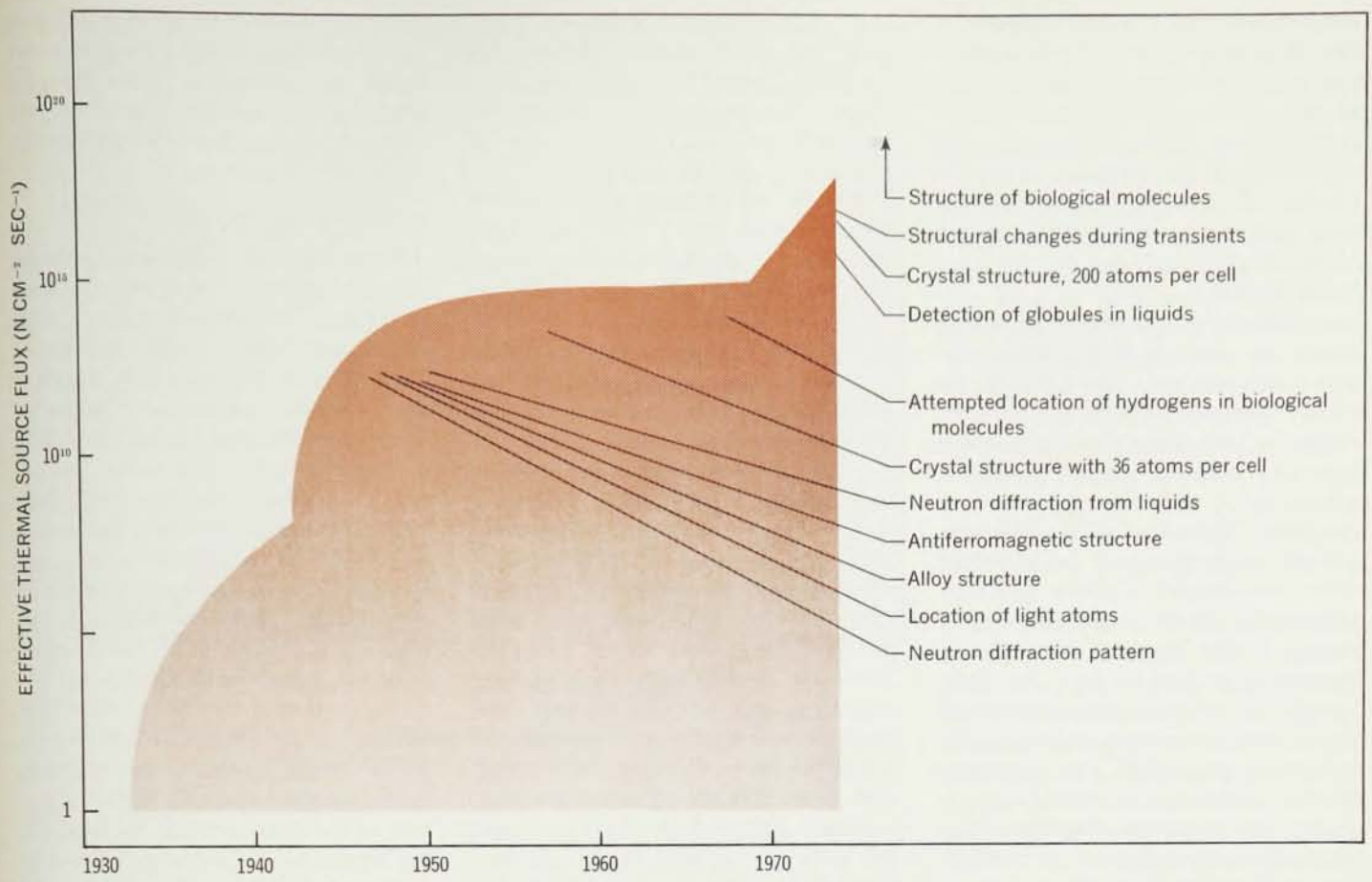
In addition to their sensitivity in observations of thermal vibrations, thermal neutrons have characteristic wavelengths that allow them to observe simultaneously positions of atoms that are vibrating. This simultaneous observation of positions and motions of atoms has been one of the most profitable advantages for the thermal-neutron experiments as demonstrated by success in measuring dispersion relations of waves in crystals by inelastic neutron scattering. In fact neutron experiments are the only way at present to get a complete and accurate measurement of these dispersion relations.

The dispersion relations, which are the relations between the energy and momentum carried by waves moving through crystals, are directly determined by the crystal structure (usually known from x-ray- and neutron-diffraction measurements) and the forces holding each atom to its neighbor. Conversely, the measured dispersion relations are the most sensitive test of any model of forces holding the atoms in crystals.

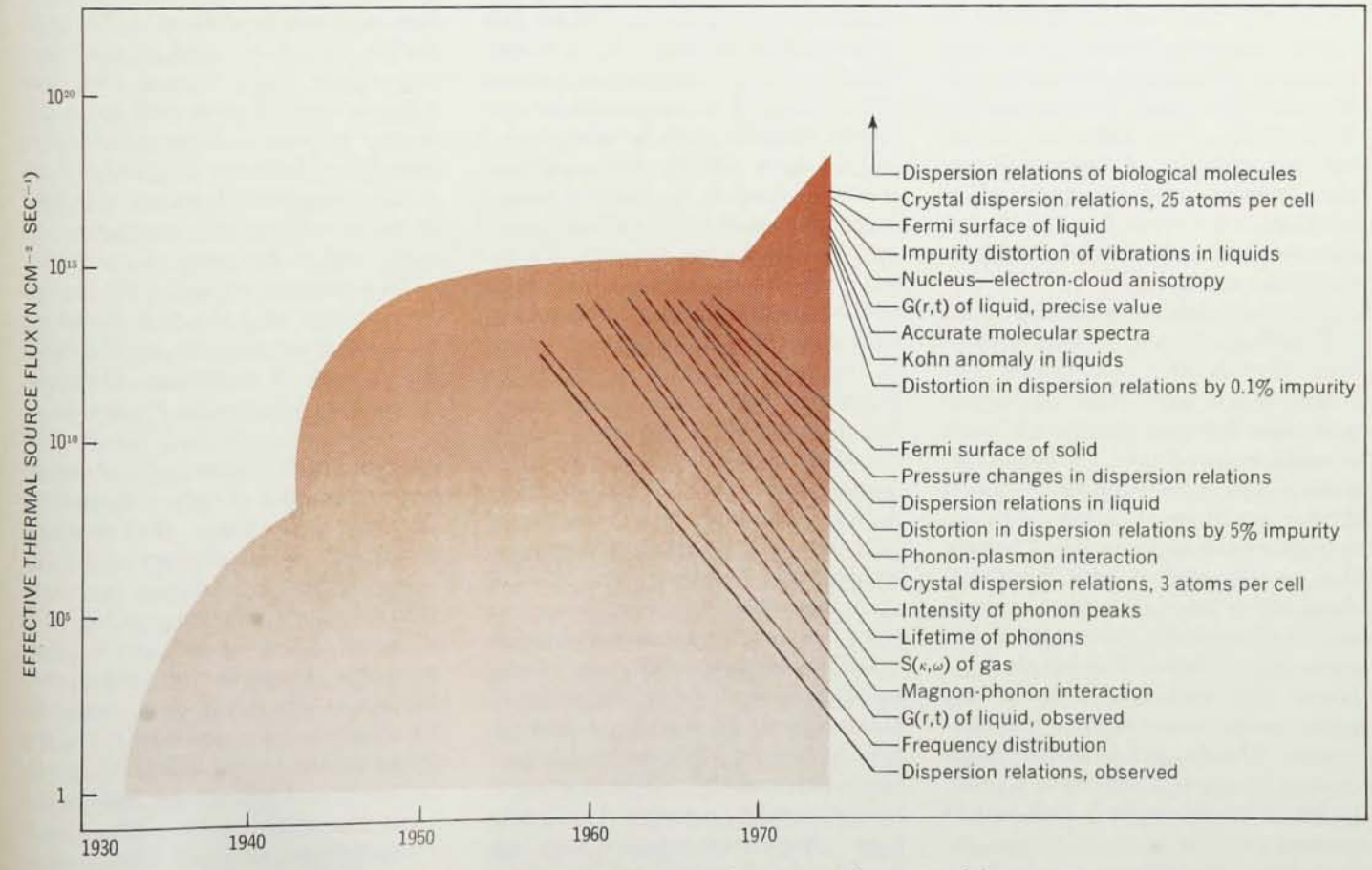
In the decade since the first measurement demonstrated that dispersion relations could be observed, measurements of the acoustical and optical lattice waves have been made for about 100 crystals. Because of limited beam fluxes available, experiments have required crystal samples having much symmetry and only a few atoms per unit cell, and materials that can be obtained as large single crystals. In addition to the dispersion relations for lattice waves, experi-




**AVAILABLE NEUTRON FLUXES** have increased with development of accelerator sources and nuclear reactors. Future methods might increase them further by ten- to a thousandfold. —FIG. 2




**ATOMIC-STRUCTURE STUDIES** using neutrons began with first diffraction observations. Measurements of many-atom crystals, liquid globules and biological molecules need bigger fluxes. —FIG. 3




**ATOMIC-MOTION STUDIES** now look at dispersion relations and Fermi surfaces in solids. Some day they will measure such things more accurately and study more complex materials. —FIG. 4

menters have made measurements of a few dispersion relations for spin waves and magnetic waves moving through crystals. These dispersion relations give the most direct and accurate test of models of the magnetic forces in crystals. These measurements of magnetic waves, too, are for simple crystal structures for which one can get large single crystals.

Additional information about atomic forces can come from dispersion-relation measurements. The effect of the magnon-phonon interaction can be observed in some dispersion relations that can give a direct test of models in which atomic and magnetic forces are coupled. The effect of the electron-phonon interaction can be observed in some dispersion relations, and such observation allows Fermi surfaces of metals to be mapped not only at liquid-helium temperatures for pure samples but at room temperature and above and for less than pure samples. Measuring the width and intensities of the inelastically-scattered-neutron peaks that define the dispersion relations allows measurement of the lifetime of the waves and speculations on anharmonicity of the forces. Perturbation of dispersion relations by impurities allows one to find the change in local forces near the impurity. Other interactions that one can imagine affecting and being elucidated by measurements of dispersion relations are phonon-exciton and phonon-plasmon interactions. To understand atomic forces completely, all types of dispersion relations must be measured as functions of temperature and pressure with particular attention as phase transitions are crossed.

Dispersion-relation measurements will continue for many years because they provide the best insight into forces in crystals. Many of the experiments that were mentioned in the preceding paragraphs, however, require more intense neutron sources if they are to be exploited. For lattice waves, about the smallest sample that can be studied with fluxes less than $10^{15}$ n cm$^{-2}$ sec$^{-1}$ has a volume greater than 1 cm$^3$. But most solids can only be obtained as simple crystals of very small size. Graphite is a prime example and one of great interest. The largest available single crystals of graphite are about 1 mm$^3$. Unless a breakthrough is achieved in growing graphite crystals, you can deduce from the difference in volume that fluxes greater than $10^{16}$ n cm$^{-2}$ sec$^{-1}$ will be needed before the complete set of dispersion relations for the elastic waves in graphite are measured. Measurements of a Fermi surface and the effect of impurities in graphite lie well beyond this.

Besides the complication that only small samples are available, another limit on the dispersion-relation measurements is that only the simpler crystal structures have been attempted so far. As the field progresses to crystals with less symmetry and more and different kinds of atoms per unit cell, the experiments will reach a limit that can only be overcome with increased source fluxes. To illustrate this point consider the following progression: With source fluxes of $10^{12}$ n cm$^{-2}$ sec$^{-1}$, dispersion relations for crystals with one atom per unit cell were just detected. With source fluxes of $10^{14}$–$10^{15}$, crystals with three to four atoms per unit cell are studied. At this rate one might estimate that six atoms per unit cell might be reached with fluxes of $10^{15}$, 12 atoms per unit cell with $10^{16}$ and 25 atoms per unit cell with $10^{17}$ n cm$^{-2}$ sec$^{-1}$. An extreme case of this progression would be to study a sample of a biological molecule that has little symmetry and many atoms per unit cell and is only available in small single crystals. Such a study lies well in the future. But understanding of forces holding biological molecules together is of prime importance and measurements of dispersion relations must be attempted.

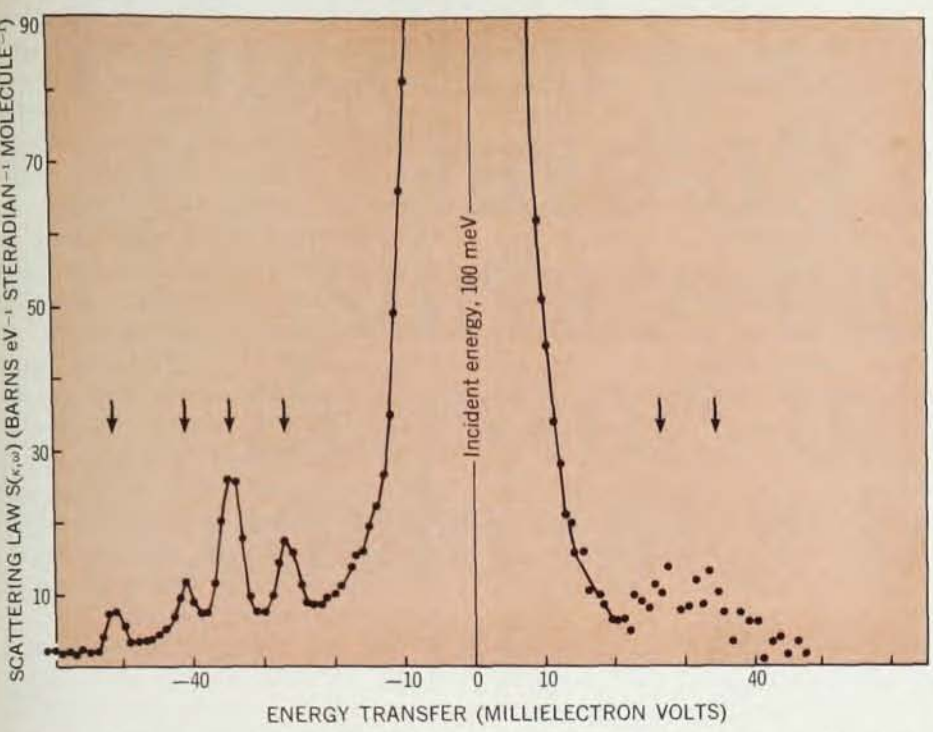
As I have already said, measurements leading to a detailed microscopic picture of forces exerted by impurities are of great interest. To observe the effect in dispersion relations with reasonable counting rates and resolution, we need 2–5% impurity atoms in the sample. In such samples fewer than three host atoms separate each impurity atom from the next one, and the effect of impurity atoms on other impurity atoms surely is not negligible. A more meaningful experiment would have less than one impurity atom in a thousand. To observe the effect of such impurities will require sources more intense than presently available.

Before leaving solids, we should mention several other experiments. Measurements of frequency distributions of normal vibration modes have been obtained by measuring incoherent inelastic scattering of slow neutrons. But nature supplied only one good sample, vanadium. By using polarized neutrons and observing only those neutrons whose spins are flipped in scattering, these measurements could be extended to more samples. This extension has not been attempted but probably can be with source fluxes above $10^{15}$ n cm$^{-2}$ sec$^{-1}$.

### *Scattering from liquids*

Thermal-neutron inelastic-scattering experiments with liquid samples have so far been less rewarding than similar experiments with solids and gases. The difficulty in explaining liquids is that atoms in liquids have stronger interactions with neighboring atoms than do atoms in gases, and these stronger interactions complicate the force field. Atoms in liquids have less order than do atoms in solids, however, and the simplicity of symmetry can not be introduced. Since the liquid is isotropic, it is possible to scatter neutrons from the sample inelastically and obtain a scattering law $S(\kappa,\omega)$ that contains all of the obtainable information about atomic positions and motions in the sample. Here $\hbar\kappa$ is the magnitude of the momentum of the waves in the liquid; $\hbar\omega$ is the energy carried by these waves. It has been shown by Léon Van Hove[9] that this $S(\kappa,\omega)$ can be doubly Fourier transformed to yield $G(r,t)$, the space- and time-dependent pair-correlation function. This function is classically defined as the probability that, if an atom of the liquid was at the origin at time zero, that atom or another atom will be at distance $r$ at time $t$. When $t$ is equal to zero, $G(r,0)$ becomes $g(r)$, which is the space correlation function measured in neutron-diffraction experiments and mentioned in the previous section.

To determine accurately the scattering law one must not only determine an energy precisely but also determine the intensity of scattering. Moreover, to perform an accurate Fourier transformation, the scattering law must be extended over a wide range of energy and momentum change. Because of limited source fluxes, the measured scattering law in all cases so far has been of limited statistical accuracy with too poor resolution over too small a range. It has been shown, however, that we can measure the scattering law in which collective oscillatory behavior can be observed. From this behavior, diffusion coefficients can be obtained, and we can get information about the critical point. These measurements are all insufficient in some way even though fluxes of $10^{14}$ n cm$^{-2}$ sec$^{-1}$ were used. Probably fluxes




**SCATTERING FROM MOLECULES** detects vibrations not accessible with infrared and Raman scattering. Sample here was solid neopentane at 103 K. —FIG. 5

greater than $10^{16}$ n cm$^{-2}$ sec$^{-1}$ are needed before these measurements are firmly established.

Figure 4 lists other future thermal-neutron probings of liquids. We might measure Kohn anomalies, which are discontinuities in the phonon dispersion relations arising from singularities in the dielectric function. They occur whenever the phonon wave vector is equal to an extremal distance across the Fermi surface. But the measurement of the Kohn anomaly, which would define the Fermi surface in a liquid metal, probably requires more intense flux than is now available.

Once having found the Kohn anomaly, we will wish to map Fermi surfaces for liquids and also measure the uncertainty in the Fermi surfaces, that is, the energy width of the upper edge of the Fermi distribution. Then studies of the temperature and pressure modifications of the Fermi surface will be attempted. We can envision experiments in which impurities distorting the local environment of a liquid will be observed. These experiments will be much more difficult than similar experiments for solids because the effect is blurred by the liquid state and is observed in the experimental data, not just as an energy shift as are many of the effects in solids, but as an energy change and an intensity change.

### *Molecular vibrations*

Besides being scattered from solids and liquids, thermal neutrons can be inelastically scattered from molecules to detect intramolecular vibrational states that are unobservable by infrared or Raman methods. To observe transitions between vibrational levels, experiments must be arranged to limit recoil-motion effects. Some experiments have achieved this limitation by having the molecule bound in a solid or liquid, but the disadvantage of this approach is that the molecules are no longer free, and the molecular vibrations may be perturbed by intermolecular forces. A second possible way is to cool the molecules, but this is limited because most samples condense before temperature is reduced sufficiently to reduce recoil motion appreciably. A third way is to measure the scattering law for gases at very small momentum changes. At small enough momentum changes the vibrational transitions emerge as separated peaks in the data. Such small momentum-exchange measurements are now accurately measuring transition energies of normal vibrations that are inaccessible to infrared techniques (figure 5). These measurements are for simple molecules. Similar measurements for biological molecules require much more intense sources.

Turning now to other future experiments, as with liquids, the scattering law can be measured for a molecular gas. This scattering law defines the positions and motions of the nuclei of the atoms in the molecules. An x-ray diffraction pattern of the gas will define the shape of the electron cloud around these nuclei. A careful measurement of both would detect any asymmetry in electron positions with respect to nuclei and provide a valuable test of any wave functions postulated to define such molecules. Such a coupled measurement of x-ray diffraction and neutron inelastic scattering has not yet been tried. Precision in the neutron measurement will probably require source fluxes of $10^{16}$ n cm$^{-2}$ sec$^{-1}$.

In the section on structure measurements, I mentioned that neutrons could be used to study properties of matter when transient forces are applied to the sample. In like manner, slow-neutron inelastic scattering could be used to follow microscopic motions of atoms as transient forces are applied. These transient forces also permit higher limits than do steady-state methods. Such experiments have not yet been attempted and probably lie in the $10^{17}$-n-cm$^{-2}$-sec$^{-1}$ range.

### *Nuclear forces*

Thermal neutrons have been used to study fundamental nuclear properties of neutrons and nuclear forces in other nuclei. Because the neutron is a fundamental particle, exact values and limits of its properties are of great interest. Many have been measured, but because of the fundamental nature of the neutron, they will be remeasured to greater accuracy each time a more intense source permits a significant improvement.

Despite availability of neutrons for the past 35 years, several basic interactions of neutrons have not been detected. One such measurement is direct observation of the strength of interaction of neutrons with neutrons. Results of such a measurement compared with the strength of interaction of neutrons with protons would give direct evidence of the charge dependence or independence of nuclear forces. Although for these experiments a beam of neutrons of sufficient intensity is not hard to obtain, it is very difficult to prepare a dense sample.

Another experiment of great interest that lies in the future is the inverse

of the neutron-electron interaction. This experiment depends also on getting a "neutron target". Diffraction of high energy electrons from free neutrons would measure directly the neutron-charge distribution. So far measurements of this important property have been made with deuterons as targets and corrections of the observations for the proton, whose charge distribution has been measured previously. An independent measurement with neutron targets would provide a valuable confirmation of the assumptions made in determining the neutron-charge distribution.

### *Analytical tools*

For the same reasons that neutrons are such good probes in basic research they also have potential as analytical probes. For many materials the neutrons are a penetrating probe that can observe 2 to 5 cm into materials. Neutrons are a nondestructive probe. Neutrons interact according to their own unique set of selection rules, which allow observation of properties not available to other probes.

Neutron radiography, detection of one element inside a second when the first element preferentially removes neutrons from a beam, is beginning to have wide applications. The neutron's preference for observing hydrogen is of real significance in these experiments. Present sources are adequate in many cases, but more intense sources will permit significant improvement in definition. More versatile, less expensive sources are needed for routine analysis.

Neutron diffraction will probably become an analytical tool when source intensities reach the $10^{16}$-n-cm$^{-2}$-sec$^{-1}$ range. As an analytical tool, neutron diffraction would be a penetrating probe to determine location and crystal structure of one material inside another and the change in crystal structure with depth in a single material. Information about work hardening of drawn materials and the effectiveness of welds with depth are examples of information that could be of great interest. Neutron diffraction could be used on radioactive samples where x-ray techniques are swamped by the radioactivity. Neutron diffraction would observe all these effects in a nondestructive way so that the actual material or weld could be examined. With collimation small volumes several centimeters inside the material could be observed.

Slow-neutron inelastic-scattering methods can complement infrared methods for analytical spectroscopy when source strengths of neutrons reach about $10^{17}$ n cm$^{-2}$ sec$^{-1}$. Here the energy spectra of the scattered neutrons would give characteristic spectra for materials. As an example, because hydrocarbons are composed of the same kinds of atoms, activation analysis can not unravel them. But since hydrocarbons have different structures and different vibration frequencies, neutrons can observe these differences in structure and in vibrational spectra to analyze the material. Neutron spectroscopy could be used on matter in bulk and would sample the material in depth and not just on the surface. With collimation, different layers in the sample could be determined. For example, a cross linking at the surface and center of organic long-chain molecular fibers might be detected by neutron spectroscopy.

Temperatures of ions and electrons in a plasma are quite different, and it is important to measure both. The basic research on inelastic scattering of neutrons from gases has shown that the motion and temperature of the nuclei of these molecules can be measured quite precisely by neutron scattering. In past experiments the samples had densities of about $10^{20}$ nuclei/cm$^3$, and one could observe the scattering with a flux of $10^{14}$ n cm$^{-2}$ sec$^{-1}$. Thus a source of $10^{17}$ n cm$^{-2}$ sec$^{-1}$ would provide a probe to measure the ion temperature of a plasma of $10^{17}$ ions/cm$^3$. If the plasma is pulsed and only exists for a short time, pulsed neutron sources would sample the temperature of the ions.

As basic research methods are developed for using pulsed neutrons with samples subjected to transient forces, these will be adapted to transient phenomena. The neutron radiography of exploding systems might be the first example.

### *New experiments will arise*

Because the experiments I have discussed lie in the future, some uncertainty exists in their fruitfulness and the fluxes needed to perform them. A few of the proposed experiments will probably be accomplished with existing sources or will lose their interest. But for each experiment that is done or abandoned, a score of new experiments unknown at the present time will certainly rise to take its place. A few of the important experiments will be accomplished with presently attainable sources by persistence over a long time. But success with most of the proposed experiments will not be achieved by such persistence or a proliferation of sources in the presently available range of fluxes. Only a more intense source of thermal neutrons will permit success. Although steady-state fission reactors appear to have reached a practical flux limit, proposed techniques offer more intense effective source fluxes. These new technologies appear to require only a modest extrapolation of existing engineering. Either a charged-particle-induced steady-state thermal-neutron source such as the ING proposal or repetitively pulsed reactors such as RPTF[5] can deliver effective thermal fluxes of $10^{16}$–$10^{17}$ n cm$^{-2}$ sec$^{-1}$. These will open up the new vistas for the thermal-neturon beam.

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