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A Phased Rotating-Crystal and Chopper
 for Time-of-Flight Neutron Spectroscopy*

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Described is a slow-neutron spectrometer that uses a rotating single crystal to chop and monochromate the reactor neutron beam. A high-transmission mechanical chopper is operated in phase with the rotating crystal to eliminate undesired crystal reflections, higher order contamination, and to suppress the background of time-uncorrelated neutrons. Pulsed neutron beams of high quality can be obtained from the thermal energy range to greater than 0.5 eV. Energy widths as low as 1% with burst widths around 7 μ sec can be attained at 0.3 eV. Intensities are adequate for inelastic scattering

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studies. The spectrometer is designed primarily for downscattering measurements. Scattering measurements are conducted in a completely shielded scattering chamber with eleven scattered neutron detectors arranged at scattering angles of 15° to 165° . Time-of-flight techniques are used to determine the scattered neutron spectra. The design, construction, and performance characteristics are given. Some representative measurements made on zirconium hydride are presented.

I. INTRODUCTION

The use of slow-neutron scattering techniques is recognized as a powerful tool in the study of atomic and molecular dynamics in solids, liquid, and gases. With pulsed sources of monoenergetic neutrons, time-of-flight (TOF) techniques can be used to measure the entire spectrum of neutrons scattered from a sample. This can be done simultaneously at a number of different scattering angles. Pulsed slow-neutron beams of adequate quality for inelastic scattering experiments have been obtained from reactor sources with the aid of rotating mechanical choppers, rotating single crystals, or combinations involving crystals and mechanical choppers. In this paper, we will describe a slow-neutron TOF spectrometer of the latter type. It is a hybrid system that employs a rotating single crystal to produce short bursts of monoenergetic neutrons and a phased mechanical chopper that eliminates

order contamination, unwanted crystal reflections and that suppresses background.

The rotating crystal neutron spectrometer was first suggested by Brockhouse^{1,2}, who also worked out the theory of the instrument. O'Connor³ has built and analyzed a rotating crystal monochromator. Glaser^{4,5}, Ripfel and Ehret⁶ have reported on the construction of a rotating crystal spectrometer and its use in inelastic neutron scattering experiments. The Brockhouse spectrometer has operated for several years at the Chalk River NRU reactor and has been applied primarily to high-resolution upscattering studies with a source of low energy neutrons obtained using a beryllium filter. A phased rotating shutter^{7,8} has been used for some time with this instrument to eliminate order contamination. Unphased mechanical velocity selectors have been used to eliminate order contamination with rotating crystal spectrometers. Velocity selectors of the latter type have been used by Quittner and Schittenhelm^{9,10} and Ripfel and Ehret⁶. Transmission losses are considerable and often remove 65%-70% of the first order neutrons.

The design of the Hanford Rotating Crystal Spectrometer (RXS), that has been outlined previously^{11,12}, was based upon the need for a slow-neutron spectrometer with the following characteristics:

1. Inelastic and elastic scattering capability. Ability to measure the doubly differential scattering cross section simultaneously at 10 or more scattering angles

2. Conveniently variable initial neutron energy and resolution. Energies from thermal to 0.5 eV or greater
3. Resolutions on energy change of 10% or less for energy changes of at least 0.5 eV. Intensities sufficient to measure inelastic scattering distributions in several days running time with 1%-3% statistics
4. Simplicity and high reliability to permit maintenance with a minimum of support staff.

II. MONOCHROMATING SECTION

A. Neutron Beam Control

The RXS uses one of the Hanford production reactors as a source of thermal neutrons. A shielded step-plug containing a radiation shutter is used to transmit a neutron beam through the reactor biological shield to the experimental area. A section of this step-plug is shown in Fig. 1. The radiation shutter consists of two 30-in.-long pieces of 50-50 Ni-Fe that are moved transversely to the neutron beam by a simple camming mechanism. A maximum opening of 2 x 4 in. is obtained with this mechanism that is placed in a hole through the biological shield that is only 7 in. in diameter near the shutter. The shutter drive system can reproducibly provide any degree of horizontal opening from 0 to 2 in. This is useful in optimizing the background levels for various experimental arrangements, and in tests where it is desired to observe the direct reactor beam with reduced intensity. The shutter

jaws are provided with interlocking teeth to prevent leakage in the fully closed position. At full reactor power this shutter provides sufficient attenuation so that personnel can perform necessary operations (e.g., installing the phased chopper) while receiving much less than the recommended maximum dosages. Neutron shielding and collimation before the shutter doors is obtained by use of several inches of boron carbide followed by 20 in. of Ni-Fe. Beyond the doors the beam is controlled by 12 in. of lead-filled epoxy within the step-plug, and several inches of lead and borated epoxy in the beam pipes leading to the rotors.

All parts of the beam handling system from the entrance end of the step-plug to the exit point of the crystal rotor are made vacuum tight. The use of vacuum or He gas filling in the step-plug decreases the corrosion caused by radiation breakdown-products of air and gives a substantial increase in slow-neutron transmission, approximately 4.5% per meter of air path.

The high degree of collimation required to produce a small energy width beam with the rotating crystal is obtained from two Soller slit collimators. Both are approximately 5 ft. long and have a rectangular inside opening of 2 x 4 in. Spring-tempered nickel shims, 1/32 in. thick, can be inserted to provide effective collimator angles of 1.75 to 0.08 degrees. Collimation in the second collimator can be changed in a matter of minutes while the change in the first collimator requires removal of some shielding and the crystal rotor housing that takes approximately one hour.

B. Shielding

Shielding of the reactor beam in the monochromating section is accomplished with lead and borated paraffin in large metal cans. The dimensions of the shielding are shown to scale in Fig. 1. A mixture of 15%-30% by weight of boric acid in paraffin was used for the bulk of the shielding. Approximately two inches of lead are placed around the chopper and along the sides of the first collimator. Four inches of lead are placed in the main beam beyond the crystal rotor. This shielding reduces the fast-neutron background to less than the allowable exposure rate in all locations around the spectrometer.

Access to the rotors is obtained by using a hoist to remove appropriate shielding blocks. Either rotor can be made completely accessible in a matter of 10 to 15 minutes.

A turning pie-shaped section of shielding surrounds the rotating crystal. This is integrally attached to the scattering chamber in which the second collimator is imbedded. The pie section permits the variation of the Bragg angle from -10 to $+30$ degrees. Using $\text{Al}[111]$ reflections, this gives a lowest attainable neutron energy of 0.015 eV. The high energy limit is determined by count-rate and resolution considerations and not by available Bragg angles. The negative Bragg angle given above refers to operating the RXS with the diffracted neutron beam coming off to the left of the un-deviated beam as viewed from the neutron source. It is useful to have this capability as there are crystal and target configurations for which the spectrometer resolution would be better for negative

arm angles than for positive ones.

C. Chopper Rotor Construction

The coarse chopper presently being used is constructed so that it will produce four neutron bursts per revolution. This design permits the maximum duty cycle for crystals with cubic symmetry. Figure 2 shows the chopper and a crystal rotor. The chopper is constructed of three main parts: two end-bells that are bolted around a center section having two slots machined at right angles through the center. The effective chopping radius is 4.5 in. High-strength magnesium alloy was used to fabricate the center section; this section is hollowed out in the quadrants between the neutron-transmitting slots. Boron-loaded epoxy is used in the hollow quadrants to provide fast-neutron shielding when the chopper slots are not lined up with the collimators. The end-bells are of high-strength, mar-aging steel forgings with a yield strength of about 260,000 psi, and are hardened to about 535 on the Brinell scale. A finish of 16 and 32 microinches, respectively, was used on the end-bells and magnesium center section to decrease the probability of stress concentrations near the surfaces. The end-bells are recessed for the center section and are designed to carry most of the centrifugal stresses. Design speed of the chopper is 18,000 rpm. Bearings to support the rotor are mounted on short shafts that are an integral part of the end-bells. A 12 mm semithrust-type precision ball bearing is used to support the 28-lb chopper and a 10-mm precision ball bearing is used to align the top rotor shaft. Bearings are

greased with high temperature greases and require only infrequent servicing. The use of oil lubrication would be desirable but increases the complexity of the rotor housings. At speeds up to about 12,000 rpm we have found no real need for oil lubrication. The rotor of the synchronous driving motor is pressed directly on the shaft of the top end-bell. This construction provides a rigid drive train and eliminates the necessity of separate motor bearings and a flexible coupling between motor and chopper. Power requirements are significantly reduced by using two bearings instead of four.

Inserts consisting of a sandwich of 1/32 in., borated fiber glass epoxy¹³ sheets or B¹⁰ loaded polyethylene stiffened with steel sheets and aluminum spacers are inserted into the 2-in.-wide chopper slots to provide the required beam chopping action. The aluminum spacers are designed to give minimum neutron attenuation. Slit systems are locked into position by an overlapping edge on the end-bells. Four separate inserts are used since the central region of the chopper must remain open to permit transmission every 90° of rotation. The number and spacing of the borated shims are determined, for a fixed distance between the chopper and crystal-rotor, by the neutron energy range and the available rotor speeds. Figure 2 shows a slit system that consists of only two diagonally opposed fiber glass shims with one-half inch aluminum spacers. With rotor speeds of 12,000 rpm, this simple high-transmission slit system chops against second order neutrons and unwanted reflections for neutron energies up to 0.5 eV. The slit system shown mounted in the

rotor of Fig. 3 accomplishes the same function at a speed of only 6,000 rpm. Transmission of this latter system, which requires 5 borated fiber glass shims and a full 2-in. width of spacers, is 50%. Where beam widths of only one inch are desired, a simple slit system which gives 90% transmission at 12,000 rpm can be used. As mentioned above, shims of borated fiber glass epoxy as well as borated polyethylene have been used in the chopper slit system. The polyethylene was used only because the material was readily available in high B^{10} content before suitable boron loaded fiber glass epoxy shims could be fabricated. Rotor speeds had to be held down to about 6,000 rpm with the polyethylene, and this accounts for most of the test data presented in this paper being at 6,000 rpm or less. The borated fiber glass sheets are strong and stiff enough to permit operation at speeds of at least 18,000 rpm. The measured neutron attenuation at 0.25 eV and normal incidence is 52% and 26% for 32 mils of the borated fiber glass and polyethylene, respectively. For average angles of incidence associated with the transmission of 2nd order neutron energies, the borated fiber glass will attenuate 1.0 eV neutrons by a factor of 20 or more. The over-all transmission of the chopper for unwanted neutrons is not entirely determined by the transmission of the borated shims, since the edges of the main rotor body also chop neutrons, and transmission through the massive walls of the rotor is essentially zero for thermal neutrons.

D. Crystal Rotors

Functionally, the crystal rotors provide a spinning mount for

the neutron monochromating crystals. The rotor structure must have all the necessary strength and rigidity to withstand rotational stresses and operate at a constant speed. Construction must be such that there is no appreciable attenuation of the incoming and outgoing Bragg reflected neutrons. Since the target can see the monochromating crystal and parts of the crystal rotor, attention must be given to reducing incoherently scattered neutrons to a minimum. The best arrangement for a crystal rotor is one where only the monochromating crystal can see both the entrance and exit beam collimators.

The crystal rotor in Fig. 2 is constructed of two stiff end-plates, in which are imbedded the rotor shafts and four hollow pillars that are welded so as to join the corners of the square end-plates. Construction is of aluminum alloy (6061-T6); the design operating speed is 18,000 rpm. Two 10-mm precision bearings are used to support the rotor, whose weight is around 12 lbs depending upon the crystal and crystal mount used. Motor mounting is similar to that on the chopper. The hollow supporting pillars are placed sufficiently far from the rotor center line, about 3 in., so that they do not intercept the Bragg beam for the normal range of energies taken from one type of cubic plane. Incoherently scattered neutrons from these pillars cannot reach the scattering sample, since the pillars are too far off center to be viewed by entrance and exit collimators simultaneously. Spacing between the crystal rotor end-plates is enough to accommodate a 4-in.-high monochromator. If shorter crystals are used, aperatures are placed in the

first collimator to limit the slow-neutron irradiation to the crystal. Crystal mounts are also cadmium plated to reduce neutron scattering.

Mounts to hold the crystals in the rotor are of varied design. For spherical crystals like the one shown in Fig. 2, a simple socket arrangement is used to retain both ends of the crystal. This permits complete flexibility of crystal orientation. The socket arrangement can also be used with a cylindrical crystal that has spherical ends. A simple clamp with a limited range of tilt adjustment is used with flat plate type crystals. To prevent any motion of the ends of a plate shaped crystal, and to provide better strength against bending, the ends were glued or potted with borated epoxy.

E. Rotor Housings

A schematic of the chopper-rotor housing is shown in Fig. 3. The body consists of 3/8-in. steel tubing that is welded to a 1-in. base. The motor is mounted on a 1/2-in. cross member that is recessed to provide accurate alignment of the motor. To insure dimensional stability, the rotor housing is carefully annealed after welding and before final machining. The bottom bearing pocket and the motor aligning recess are machined in one setup to a precision of about 0.0002 in. A removable top-can covers the rotor housing. Lead-ins are provided in this cover for evacuation, electrical connections, and water cooling for the motor. Portholes in the sides of the housing let the neutron beam through.

A burst shield consisting of 1/4-in. steel pipe is set into

the rotor housing and around the outside of the chopper with a clearance of about $1/32$ in. This sleeve has cutouts for passage of the neutron beam under normal circumstances. In the event of a serious rotor failure, the chopper or parts of the chopper could be expected to impart some rotational energy to the sleeve which would then rotate a few inches until it closed the beam passage. This system is designed primarily to give some protection to the reactor gas seal. The close proximity of the shield to the rotor will also tend to slow the chopper down by rubbing before this rotating mass can get very far off the axis and produce large unbalanced forces.

The stator of the synchronous drive motor is mounted in a thick aluminum shell to provide good heat dissipation. A precision ground steel sleeve is used to house the upper chopper bearing. A small spring provides the required preload on the outer bearing race. Precision bearings for the rotors are usually hand fitted to give a snug sliding fit. Machining tolerances and bearing tolerances are such that the rotor shaft run-outs are kept within about 0.0002 in.

A considerable amount of heat, several hundred watts, may be dissipated in the motor rotor and windings. Cooling water flows through channels in the aluminum motor housing to reduce the operating temperature of the bearing and motor parts. When the rotor housings are completely evacuated, all heat generated in the motor rotor must be dissipated by conduction through the bearings. This has a detrimental effect on the lubrication and bearing life and

can result in damage to the motor rotor. With the rotor systems used on the RXS, it has been found that operation in vacuum is marginally feasible. However, to reduce the heat dissipation problem, the rotors are operated in an environment of helium gas. Helium pressures of 3 to 10 cm-Hg provide a very substantial cooling effect and the resultant increase in drag has not prevented the attainment of synchronous speeds in excess of 10,000 rpm. As is evident in Fig. 2, the rotors are presently not streamlined. If higher rotational speeds are ever desired and the motive power proves inadequate, a large reduction in drag could easily be achieved by using thin sleeves of aluminum to streamline the outside of the rotors.

The rotor housing for crystal rotors is similar to but smaller than that for the coarse chopper. In addition, it has a 1/16-in.-thick aluminum window that permits the Bragg reflected neutrons to exit over an angular range of 90° .

F. Rotor Driving and Control Circuits

The chopper and crystal rotors are driven by identical two phase, eight pole synchronous motors. These motors¹⁴ are of unusual design in that they combine the characteristics of induction motors for starting, and the characteristics of hysteresis and salient pole motors for pulling into and maintaining synchronous speed. At 6,000 rpm and 400 cps excitation they require approximately 100 watts input per phase for an output torque of 20 oz-in. Motor efficiency is approximately 50%. Power is derived from electronic power amplifiers of the type used in public address systems. The power

amplifiers have rated outputs of 225 watts and 150 watts per phase for chopper and crystal rotors, respectively. These amplifiers are the only circuits used with the RXS that presently make extensive use of vacuum tubes.

Figure 4 shows a schematic of the electronic circuitry required to operate the RXS. A stable tuning-fork oscillator is the frequency standard for driving the synchronous motors. The fork has a frequency of 3,600 Hz and is divided down by a scaling circuit to a number of discrete output frequencies ranging from 120 to 900 Hz. The reduced frequency signal is passed through a vernier phase-shifter which generates two outputs of adjustable relative phase. The vernier phase-shifter permits the accurate adjustment of the relative rotor phase once both rotors have reached synchronous speed. Each output of the vernier shifter is fed to a phase splitter which provides the necessary 90° phase angle between the two windings of a motor. The split signal is applied to the separate motor windings after passing through the audio amplifiers. Phase shifting and splitting, since it is done at low power levels, is simply accomplished with a few transistors.

Relative rotor phase is measured with the aid of magnetic pickups in the rotor housings and timing pins placed in the tops of the rotors. One timing pin is used in the chopper and four are placed 90° apart in the crystal rotor. A timing pulse is required each time the rotating crystal comes into Bragg. The signal from these magnetic pickups approximates a single oscillation of a sine wave which has a period of 100 to 200 μ sec. To provide an accurate

measurement of the time the magnetic pickup crosses the timing pin, the signal is passed through a pulse shaping circuit which incorporates a cross-over detector. At typical operating speeds the jitter associated with these timing signals is less than 0.1 μ sec. A counter-timer is used to measure the relative rotor phase.

Safety circuitry includes temperature and vacuum gauges as well as a phase monitor. Temperature is usually measured at the outer race of the top rotor bearings. Vacuum gauges are located in the shielded step-plug and the rotor housings. A phase monitor circuit determines if the rotor phase is being maintained within a preset range. The vacuum and temperature gauges, as well as the phase monitor, have associated circuitry that will cut off the power to the rotors and stop the accumulation of experimental data if preset levels of temperature and pressure are exceeded or if the rotor phase varies out of preset tolerances.

G. Crystal Monochromator and Resolution Considerations

Most of the considerations which apply to the choice of a monochromator for stationary crystal work also apply for a RXS. However, there are important additional requirements for the latter type. The rapidly rotating single crystal must monochromate the polyenergetic reactor beam and it must chop the monochromated beam into suitably short time bursts so that time-of-flight spectroscopy may be employed. The intensity of the pulsed monochromated beam depends upon the reflectivity integrated over crystal angle and upon the number of crystal planes of a given type that come into Bragg during one crystal revolution. Energy width of the primary

neutron beam is determined by the collimation and the crystal lattice spacing. The resolution for measuring neutrons scattered from a sample depends upon the energy and time width of the primary beam. Correlations exist between these widths and the intensity produced by the crystal.

Elements which contribute to the time width of the initial neutron pulse are crystal size and mosaic, collimator angles, energy width of the primary neutrons, doppler effect, rotor speed, target size, and orientation, as well as any other path length uncertainties.

The burst time due to collimation and crystal mosaic is given by

$$\Delta t_{\omega}^2 = \frac{\Delta\theta_C^2 + \Delta\theta_M^2}{\omega^2}, \quad (1)$$

where $\Delta\theta_C$ is the collimator angle of one of the equal collimators, $\Delta\theta_M$ is the crystal mosaic, and ω is the rotational speed. The velocity spread in the incident beam produces a time spread

$$\Delta t_E = \frac{0.7 \Delta\theta_C \cot\theta_B}{v_0} \left(L_0 + L_1 \left(\frac{v_0}{v_1} \right)^3 \right), \quad (2)$$

where θ_B is the Bragg angle, L_0 is the distance from crystal to target, v_0 and v_1 are the initial and scattered neutron velocities, and L_1 is the distance from target to detector. The 0.7 factor takes approximate account of the better average collimation seen by a rotating crystal. For large ratios of initial to downscattered energy, the element in Eq. 2 becomes dominant.

The doppler effect produces a time width in two ways. Parts of

the crystal that are off the axis of rotation will reflect neutrons of higher or lower velocity than the mean, depending upon the relative direction of the neutron and the moving crystal plane at the reflection point. Associated with this velocity shift is a change in crystal angle for which the Bragg condition is satisfied. For neutron energies in the thermal and subthermal range, the velocity shift is appreciable and by judicious choice of rotation direction can be used to oppose the effects of Bragg angle shift, or other correlated resolution elements. However, for the relatively high neutron energies with which the Battelle rotating crystal usually operates, the doppler shifts are small. This time spread is given by Eq. 3, which utilizes a result of Shull and Gingrich¹⁵,

$$\Delta t_D = 2 \frac{R}{v_o} \sin^2 \theta_B \left[\tan \theta_B \cos \alpha + \sin \alpha \right] - 2 \frac{R\omega}{v_o^2} \sin \theta_B \sin(\theta_B + \alpha) \times \left[L_o + L_1 \left(\frac{v_o}{v_1} \right)^3 \right], \quad (3)$$

where R is some appropriate mean radius of the crystal, and α is the angle between the neutron velocity vector and the normal to the diffracting plane. It is interesting that the Bragg angle shift, which is the first term in Eq. 3, is independent of ω . For the crystal and collimator configuration of Fig. 1 and counter-clockwise rotation, the neutrons originating from the side of the crystal furthest away from the sample will have their speed increased, but the Bragg condition will occur later than for neutrons reflected at the crystal axis.

Path length uncertainties caused by crystal size, target

inclination, and detector size will produce a time spread

$$\Delta t_{\ell} = \frac{X_{x\ell}}{v_o} + \frac{X_T}{v_o} + \frac{X_{\text{det}}}{v_1} - \frac{X_T \sin(\pi/4 - \phi)}{v_1} . \quad (4)$$

The effective thicknesses of the crystal and target in the direction of the incident beam are $X_{x\ell}$ and X_T , respectively. The scattered neutron detector thickness is X_{det} . The path uncertainty in the scattered neutron beam resulting from the target inclination is $X_T \sin(\pi/4 - \phi)$, where ϕ is the angle between the initial and the final neutron direction.

The doppler effect can often be used to reduce the time spread associated with the crystal size. Under such circumstances Eqs. 3 and 4 can be combined to give

$$\Delta t_{\ell} = \frac{X_{x\ell}}{v_o} - \Delta t_D + \frac{X_T}{v_o} + \frac{X_{\text{det}}}{v_1} - \frac{X_T \sin(\pi/4 - \phi)}{v_1} . \quad (5)$$

Additional time widths are introduced by the channel width, Δt_{ch} of the TOF analyzer, and the electronic time jitter of the scattered neutron detector Δt_{det} . Brockhouse² has found that a number of other elements influence the resolution of a RXS. These elements are in general small for our conditions of operation and will be neglected here.

If we assume that all resolution elements are uncorrelated, we can obtain the time width of the neutron burst by root mean square addition

$$\Delta t^2 = \Delta t_{\omega}^2 + \Delta t_E^2 + \Delta t_{\ell}^2 + \Delta t_{\text{ch}}^2 + \Delta t_{\text{det}}^2 . \quad (6)$$

Energy resolution of a scattered neutron is determined by

$$\frac{\Delta E_1}{E_1} = \frac{2\Delta t}{t} \quad (7)$$

where t is the TOF from target to scattering detector. The resolution on energy change, which is the more significant quantity for inelastic scattering experiments, is given by

$$\frac{\Delta \epsilon}{\epsilon} = \pm \frac{\sqrt{\Delta E_0^2 + \Delta E_1^2}}{E_0 - E_1}, \quad (8)$$

where the energy change $\epsilon = (E_0 - E_1)$ and ΔE_0 is the energy width of the incident beam given by $\sqrt{2} E_0 \Delta \theta_C \cot \theta_B$.

Crystals that are suitable for use on the RXS can be characterized by

1. d spacings in the 1-2 Å range
2. High peak reflectivity
3. Mosaics of 0.1-0.5 degree
4. Adequate strength for operation at high rotational speeds
5. Low incoherent scattering cross section
6. Suitable size.

Most of the scattering experiments to date have been made using a copper single crystal cut in the form of a plate 2.5 in. wide x 3.25 in. high x 0.30 in. thick. It was cut with the [200] plane on the face of the slab; it is rotated about the crystallographic C axis. This permits the use of the [200], [220], and other smaller d spacing planes. Normally the [220] planes are used in

transmission to produce four neutron bursts per revolution. This copper crystal like others we have tested has a good peak reflectivity but a mosaic that is smaller than the optimum. Incoherent scattering and attenuation of the slow neutron beam is considerable in copper even for the 0.3-in slab. However, the phased chopper decreases the time during which incoherent scattering can occur and keeps the ratio of Bragg to non-Bragg neutrons high. To increase the integrated reflectivity of our copper crystal slabs, we have made sandwiches of several thin slabs of crystals. This approach for providing a greater effective mosaic has increased the integrated reflectivity 50% for a two- versus a one-slab configuration. Large increases in mosaic and integrated reflectivity can sometimes be obtained by squeezing, bending, or thermal shocking of a crystal that is too perfect. Increases of 25 to 40 in the integrated reflectivity have been reported by Barrett, Mueller, and Heaton¹⁶ for hot pressed germanium monochromators. We feel we are conservative when we estimate that the present intensities of our rotating crystals will eventually be increased by more than a factor of two as we obtain better monochromators.

In addition to the copper plate we have used a spherical aluminum crystal. Spheres have the unique advantage, when used with the type of mount shown in Fig. 2, that they can be oriented in any fashion. This arrangement gives versatility in the choice of the reflecting plane, as well as in the symmetry with respect to the axis of rotation. For example, tilting of a given plane can decrease reflection from all but the desired plane. Since aluminum

has a low enough incoherent scattering cross section, solid spheres or cylinders up to several inches thick can be used.

III. ANALYZING SECTION

Scattering experiments are performed in a completely shielded scattering chamber that surrounds the sample, detectors and scattered neutron flight paths. In common with all crystal spectrometers, the sample is out of the main reactor beam. This makes it simpler to obtain a good ratio between coherent time correlated neutrons and background neutrons. As indicated in Fig. 1, detectors can be placed at 1.0 m and 1.5 m. Maximum detector height is 15 in. at 1.5 m. A longer flight path would have been desirable to fully utilize the two inch wide beam that can be produced by the monochromating crystals, and at the same time maintain a small fractional path uncertainty between sample and detectors. Unfortunately, space limitations in our experimental area preclude larger flight paths. For this reason the width of the beam on the sample is usually stopped down to 1.5 or 1.0 in. to make the uncertainties in analyzing path length comparable to the other resolution elements.

Scattered neutrons can be measured at 11 scattering angles simultaneously. At present, each TOF detector consists of a bank of 1 in. x 10 in., 2 atm, 96% enriched BF_3 counters. These counters have an electronic time jitter¹⁷ of 0.7 μsec and a good pulse height distribution when operated at 5,600 volts. Each detector bank is an integral unit which can mount a maximum of seven counter tubes in parallel. The detector banks can be positioned at any angle between 15 and 165 degrees.

High transmission ion chambers are used to monitor the neutron flux incident on and transmitted by the sample. Uranium-235 and B^{10} have been used as the sensitive element. Absolute efficiencies are known to $\pm 5\%$. One monitor is placed at the exit end of the last collimator and the other approximately one meter beyond the sample. The area under the TOF peak in the first monitor provides a measure of the neutron flux incident on the sample. Widths and relative positions of the peaks in the two monitors are used to determine the incident neutron energy and to monitor the time and energy resolution of the monochromated beam during a scattering experiment.

Fast-neutron dose rates in the area of the rotating crystal spectrometer are 0.5 mrem with an average energy of about 0.7 MeV. Shielding¹⁸ for the scattering chamber was optimized to conserve space and provide sufficient attenuation to reduce the background neutron count-rate to approximately the inherent counter background comprised of alpha counts and some electrical noise counts. A minimum of 4 in. of a one-to-one mixture by weight of boric acid and paraffin followed by 1.5 in. of B_4C close to the counters and cadmium lining of all surfaces seen by the counters reduces the gross background rate to about 1 cpm per BF_3 tube. This is about twice the inherent background for these counters, so that little could be gained from additional shielding.

The counting circuits associated with the TOF counters and the beam monitors are almost completely transistorized to provide maximum reliability. A Hanford-built¹⁹ time-of-flight analyzer (TOFA) is used to store the TOF data. This analyzer accepts counts at 12

separate inputs simultaneously. Each detector input has two subgroups of 256 time channels for storage of sample-in and sample-out data. Channel widths of 2, 4, 8, and 16 μ sec are provided. The clock in the TOFA is started by four equally spaced timing signals derived from timing pins placed in the crystal rotor. A digital delay is provided in the analyzer to permit delaying the start pulses so that the desired range of scattered neutron energies can always be made to coincide with the 256 channel time sweep. Data readout from the TOFA is by printer and by binary coded decimal punched tape. An oscilloscope analog display is also available. The punched tape is usually read onto magnetic tape for direct input to a large digital computer. Doubly differential cross sections and the Egelstaff Scattering Law²⁰ are then obtained from a suitably programmed IBM-7090 computer.

IV. PERFORMANCE

A. Rotor Phasing

The phased rotor system for the RXS has been developed to operate without feedback phase control or frequent manual phase adjustment. The usual mode of operating the spectrometer requires inspection of the apparatus no more than once every day or every second day. Small manual phase adjustments can be made at these times, but there must be a high probability that the rotors do not have large phase variations over periods of time corresponding to the length of a typical scattering experiment, i.e., several days to a week. Phase changes of about a degree or less merely decrease the monochromated flux, while larger phase changes will significantly

degrade the quality of the monochromated beam. The phase monitoring circuits are set to stop data acquisition in the event of a large phase change. Data acquisition time is then lost until manual adjustments are made.

Rotor phase stability and jitter have been more than adequate to meet the above requirements. Measurements of the phase jitter between crystal rotor and coarse chopper under typical operating conditions are given in Fig. 5. This distribution was obtained with a TOFA that was gated on for a short period of time every 10 minutes; and, during this on-time, it measured the interval between trigger signals derived from timing pins in the two rotors. No phase adjustments were made during the 10-day test period. The width of the jitter distribution is small enough to ensure that the maximum intensity of first order neutrons will arrive at the monochromating crystal when it is in Bragg.

The performance of the coarse phased chopper in eliminating unwanted reflections, higher order and background neutrons is illustrated in Fig. 6. A $0.3 \times 2 \frac{1}{2} \times 3 \frac{1}{2}$ -in. copper crystal was used. The crystal had the [200] plane on the face of the slab so that [220] neutrons were obtained in the transmission mode. With the chopper stopped in the open position, the TOF distribution of neutrons reaching the target axis was obtained with a $1/v$ detector. Without the chopper the neutron beam contains strong contributions from the [200] and [240] planes as well as a number of neutron energies corresponding to higher order reflections. In addition to the contamination from

coherent Bragg neutrons, there is a continuum of neutrons originating primarily from incoherent scattering in the copper crystal. With the chopper turning and phased for maximum transmission of first order [220] neutrons, all unwanted reflections, including the higher order neutrons from the [220] planes, have been eliminated. As a measure of the signal to noise in the monochromated beam, we have computed the ratio of the neutron counts in the Bragg peak to the number in a 500 μ sec interval directly following the Bragg peak. The 500 μ sec interval corresponds to the time range that will include the downscattered neutrons of interest in most experiments. With the chopper phased the S/N increases from 2.6 to 40. This is already a useful S/N, but it can be improved upon. The crystal used for the measurements of Fig. 6 is more than twice as thick as required to produce an optimum Bragg intensity. A decrease in thickness to about 1/8 in. would more than double the value of S/N. Aluminum and beryllium crystals could be used that would increase the value of S/N a factor of 2 or more. No use was made in Fig. 6 of low cut-off filters like gadolinium or cadmium that are very effective in improving S/N for Bragg energies above the peak of the reactor Maxwellian. Finally, the effect of neutrons incoherently scattered from the crystal can be completely subtracted in a separate background experiment, where the crystal and chopper are dephased so that no coherent reflections can take place. This is equivalent to the standard practice of putting the crystal off Bragg when it is desired to measure background with a stationary crystal

spectrometer. It is anticipated that this small background correction will not be required for the usual neutron scattering experiments, since good S/N can be obtained with proper choice of crystal and filters. Consideration of this feature of the RXS does, however, point up an advantage not possessed by multiple-rotor chopper systems, where it is sometimes difficult to correct for time uncorrelated neutron backgrounds.

Removal of higher order contamination from the Bragg beam depends upon the coarse velocity selecting action of the chopper. The chopper burst width and the flight path between chopper and crystal determine the range of second-order neutron energies that can be successfully chopped against. For the chopper slit configuration shown in Fig. 3, the chopper should be barely closed for second order $[440]$ neutrons of 2.0 eV for a rotor speed of 6,000 rpm. Figure 7 presents the results of measurements made by TOF techniques for neutrons reaching the target axis under the above conditions. For a chopper-rotor phase that ensures maximum transmission of the first order $[220]$ neutrons, the intensity of $[440]$ neutrons has dropped from maximum by a factor of 5. A small additional increase in rotor speed would cause a considerable further reduction in second order neutrons. The slit system used to measure the curves in Fig. 7 had sheets of borated polyethylene loaded with B^{10} and sandwiched between steel sheets to accomplish the neutron chopping. Better shims of high boron content epoxy fiberglass are now used that have 5 times more attenuation at typical grazing angles. The shims in the coarse chopper do not

extend all the way through the chopper since there are two beam channels at right angles that intersect at the center of the rotor. This causes the small steps and satellite peaks on the sides of the main neutron peaks in Fig. 7. Different average slopes on the two sides of each neutron peak result from the asymmetric slit spacing shown in Fig. 3 that produces a faster rate of decrease on the low energy side of the $[440]$ peak, where it is most needed, while permitting the use of a minimum number of neutron attenuating shims in the slit package.

B. Resolution

The separate elements, which combine to produce the over-all spectrometer resolution, have been discussed in section IIG of this paper. To verify the expressions for some of the resolution elements, we have performed experiments that separate the effects of one element from the others and that test the rms method of combining separate elements. Equation 2 gives the dependence of burst width on the initial velocity spread. If the time spread due to initial energy spread is uncorrelated with the other resolution elements, the measured burst width of the incident neutron beam should vary with distance from the crystal according to

$$\Delta t^2 = k^2 \ell_0^2 + \sum_i \Delta t_i^2, \quad (9)$$

where $k = 0.7 \Delta \theta_c \cot \theta_B / v_0$ and $\sum_i \Delta t_i^2$ includes all other resolution elements. In Fig. 8 we have plotted the measured burst widths squared (Δt^2), versus the detector-to-crystal distance squared (ℓ_0^2). The incident neutron energy is 0.5 eV with equal collimators of 0.18° . The beam width was reduced to 1/2 in. to decrease fixed

resolution elements due to crystal size. The slope of a straight line fitted to the data in Fig. 8 should be related to the collimator angle according to Eq. 2. The data fit a straight line reasonably well indicating that the rms addition is probably adequate. The collimation angle computed from Fig. 8 is $0.22^\circ \pm 0.02^\circ$. Another similar experiment at 0.15 eV gave a collimator angle of $0.187^\circ \pm 0.015^\circ$. The geometric collimator angle was 0.18° in both cases. This constitutes experimental verification of Eq. 2 and indicates that Δt_E is not strongly correlated with other resolution elements. With fixed detector position the burst width can be measured as a function of rotor speed. Similarly if Δt^2 is plotted versus $1/\omega^2$, this curve should have a slope, given by Eq. 1, of $(\theta_C^2 + \theta_M^2)$. We have made this sort of measurement and have compared the value of $(\theta_C^2 + \theta_M^2)$ with the width obtained from stationary crystal rocking curves. Agreement is within $\pm 10\%$.

The intercept of Fig. 8, at $1/\omega^2 = 0$ determines the magnitude of the resolution elements other than the initial velocity spread. The remaining resolution elements of Eq. 6 can be computed and the result compared with the measured value. The reciprocal rotor speed is 27.8 $\mu\text{sec}/\text{deg}$; the measured crystal rocking curve is 0.22 deg FWHM; the channel width is 2 μsec ; and the effective size of the crystal in the direction of the monochromated beam is 2.6 cm. The sum of the squares of the separate resolution elements from these parameters is 47 μsec^2 compared to the measured value of 48 μsec^2 as found in Fig. 8.

Using Eqs. 1-7 the resolution on downscattered neutron energy,

E_1 , and the resolution on energy change, $E_0 - E_1$, has been computed for typical operating conditions of the RXS. Figures 9 and 10 represent the resolution functions for an incident energy of 0.20 eV and for two sets of typical operating conditions. With the 1 m analyzing flight path, the resolution is a strong function of scattering angle since the uncertainties of scattered neutron path lengths contribute a large resolution element. In Figs. 12 and 13 similar resolution functions are represented for an incident energy of 0.50 eV.

The principal purpose of the RXS as presently set up is to measure energy change by downscattering. Figures 10 and 12 indicate that resolutions on energy change ranging from 10% to a few percent are attainable over a considerable range of downscattered neutron energy. This resolution is available up to energies around 0.50 eV at present, and will probably be pushed to higher energies in the future.

C. Intensities

Intensity can be traded for resolution with every type of slow-neutron spectrometer. With the RXS, changes in resolution and intensity can be effected very simply by changes in collimation, rotor speeds, and selection of different crystal planes. Table I presents resolutions and intensities for various energies, rotor speeds, and crystal planes. Collimation is 0.18° , which can be decreased to 0.08° if desired. The flux of 1×10^5 neutrons/min at 0.30 eV and 6000 rpm was attained with initial operation of the spectrometer. A conservative estimate, based on empirically determined crystal

reflectivities and chopper transmission, indicates that this flux can be increased considerably by using higher rotational speeds and more optimum crystals. With a rotor speed of 12,000 rpm and for neutron energies up to 0.5 eV the transmission of the chopper slit system can be approximately doubled. Further improvements in monochromated flux are likely since the crystals that are now being used are known to have integrated reflectivities that are significantly less than the best that have been used on the Battelle²¹ stationary crystal spectrometers.

D. Scattering Experiments

Initial scattering experiments were performed with vanadium. The known total scattering cross section of 5.13 barns is used to compare measured counter efficiencies and solid angles with calculated values. The operating points of the detectors are tested before each experiment, either with a vanadium scattering experiment or by use of a constant intensity (α -n) source.

As an example of performance in down-scattering measurements, we are including some preliminary results²² on zirconium hydride. Complete results will be published elsewhere. A well-defined vibration level, with $hw \approx 140$ meV, dominates the inelastic slow-neutron scattering from ZrH. For incident energies large enough to excite single or multiphonon events, the scattered neutron spectra exhibit discrete peaks corresponding to the neutrons scattered from the vibration levels. If the inherent widths of these vibration levels is much less than the resolution width of a spectrometer used to measure them, the measured widths will correspond

to the spectrometer resolution. If the spectrometer resolution and natural widths are comparable, the measured width can be corrected for spectrometer resolution to obtain the true width. The scattering sample was in the form of a metal sheet 1.5 x 2 x 0.034 in. with a Zr:H atom ratio of approximately one. Sample inclination was 45° , or symmetric to the forward and backward detector quadrants. Incident neutrons of 0.180 eV from Cu[220] were used to study the first vibration level. $\Delta E_0/E_0$ was 1.6% and the width of the elastically scattered neutron burst was 12 μsec at the 1 m detector positions. Figure 13 shows the time-of-flight data for the 15-degree scattering detector. The calculated resolution for scattered neutrons in the neighborhood of the vibration peak is 17.5 μsec , while the observed width of the vibration level is about 110 μsec . Thus this resolution is more than adequate to accurately determine the true width.

Figure 14 shows the TOF spectrum of neutrons scattered at 57° from the same ZrH sample, but with an incident energy of 0.50 eV. $\Delta E_0/E_0$ was 2.7% and the neutron burst width of the unscattered neutrons was 10 μsec at the 1 m detector positions. Sample transmission was about 90% and the sample-in running time was 175 h. This running time could have been cut in half without decreasing the resolution if a longer sample had been available. In fact, the continuous background, which is seen to be rather large in Fig. 14, would have been substantially reduced relative to the vibration peaks, since there are a number of components in the continuous background that depend on running time and are not much influenced by target size. Calculated resolutions are indicated by the triangles placed above the

1st, 2nd, and 3rd vibration peaks. The inset of Fig. 14 shows the TOF data in the region of the 3rd phonon peak with counts summed over 5 channels.

Figure 15 shows the TOF data for 0.180 eV reduced to partial cross sections with the aid of a digital computer. The centroid of the first vibration peak occurs for an energy change of 140.5 ± 2.5 meV. The measured width of the level is 27 meV while the resolution unfolded width is 26.4 ± 0.6 meV.

Partial cross section data for a run at 0.5 eV incident energy are shown in Fig. 16. Results are given for scattering angles ranging from 15 to 105° . At larger angles the cross sections become negligible. The resolutions for the various vibration levels are indicated by bars. The bar under the elastic peak indicates the equivalent time spread due to incident energy spread only; whereas, the total resolution widths are given at the vibration peaks. For the first vibration peak the resolution of the spectrometer completely determines the width and the calculated resolution width is about equal to the measured width. For the second and third phonon, however, the instrumental resolution can be unfolded to give the true width of the level. The centroids of the three vibration peaks correspond to energy changes of ≈ 140 meV, 283 ± 13 meV, and 411 ± 19 meV. Reduced widths of the second and third levels are 53 ± 5 meV and 72 ± 6 meV, respectively. A more accurate measurement on the second vibration peak using an incident energy of 0.386 eV gave results in agreement with the 0.5 eV experiment for the width of the second vibration level. This is

additional evidence that the calculated resolutions are correct.

V. CONCLUSIONS

In this paper we have described in some detail the design of a rotating-crystal spectrometer that is well suited for downscattering studies in the fractional eV range. The main characteristics and performance relative to other spectrometer types are summarized below. A report to be published by R. M. Brugger and Y. D. Harker²³ was an aid in making this comparison.

- A. The range of incident energies available with good resolution, good signal-to-noise ratio, and adequate intensity for doubly differential scattering measurements, extends from about 15 meV to more than 500 meV. Multirotor phased chopper systems are most successful at energies below several tenths of an eV. Slow-neutron spectrometers based on pulsed linear accelerators have a much higher upper energy range but are more difficult to use at energies approaching thermal. The most interesting range of incident energies for studying the motions of bound atoms or molecules by downscattering is just the range covered by the RXS.
- B. The best energy resolution in the monochromated beam is 2 to 4 times better, in the several tenths eV range, than existing phased chopper systems or pulsed linac systems. Burst widths obtainable are as good as those for choppers using comparable beam sizes and are achieved at conservative rotor speeds. Resolutions can

conveniently be varied with changes in the collimation and by selecting different crystal lattice planes.

- C. Intensities are adequate to measure the doubly differential cross sections of 10% scatterers with a running time of about a week at 0.5 eV, and in considerably less time at lower energies. By going to high pressure He^3 in our TOF detectors, count-rates 4 to 5 times higher are achievable. Some existing phased chopper systems have approximately 5 times higher output fluxes in the low tenth eV range, while the linac systems produce comparable monochromated fluxes in this range. At higher energies typical thermal-reactor sources cannot compete with the under-moderated spectral distributions obtained with the pulsed linacs.
- D. Considerable floor space is required by the movements of the scattering chamber to cover a large range of incident energies. If there are space limitations, as there were in this case, compromises may have to be made in the choice of analyzing flight paths and beam widths. For example, to reduce path uncertainties we normally operate with a 1-in.-wide beam even though this reduces the incident flux to 65% of that obtained with a 2-in.

beam at our spectrometer. At a research reactor where large beam cross sections could be obtained, a 3-in. wide by 6-in. high beam would present no great design problems.

- E. In actual cost of construction the system described here is probably less costly than most multirotor phased chopper systems. Rotor design is simpler and requirements regarding phasing are less severe than for systems using mechanical choppers only. Obtaining monochromating crystals is no real problem. However, it can be rather difficult to obtain a monochromator that has close to the optimum characteristics.

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Table I. Typical resolutions and intensities^a

Crystal plane	E_o eV	$\frac{\Delta E_o}{E_o}$	rpm	Δt_d μsec	$\frac{\Delta t_d}{t_d}$	I_o n/min
Cu[200]	0.107	0.015	6000	13	0.039	
Cu[220]	0.107	0.009	6000	12.5	0.038	
Cu[220]	0.107	0.009	12000	7.5	0.022	
Cu[220]	0.300	0.021	6000	11	0.056	1×10^5
Cu[220]	0.300	0.021	12000	7.3	0.037	3×10^5
Cu[220]	0.500	0.027	6000	10	0.065	
Cu[220]	0.500	0.027	12000	7.2	0.047	

^aFor 2.5×10 cm beam, 0.18° collimator angles, and 1.5 m flight path.

Δt_d is FWHM of unscattered neutron burst at TOF detectors.

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FIGURE CAPTIONS

Figure No.

- 1 Schematic view of the rotating-crystal phased chopper spectrometer that is in operation at a Hanford production reactor.
- 2 Coarse chopper fitted with asymmetric slit system for suppression of unwanted crystal reflections and second order neutrons. A crystal rotor with spherical aluminum single crystal is also shown.
- 3 Rotor housing with coarse chopper. A similar housing and driving arrangement is used for the crystal rotor.
- 4 Electrical schematic of the rotating crystal spectrometer
- 5 Typical rotor phase jitter for a 10-day run at 7800 rpm
- 6 The time-of-flight distributions for neutrons diffracted from a cubic crystal rotating about its C-axis shown for equal counting times, both with and without the phased chopper in operation. Chopper and crystal rotors were operated at 4500 rpm and the Cu[220] reflection produced 0.15 eV neutrons.
- 7 Transmission of monochromating section for first order and second order neutrons as a function of chopper-crystal phase. The Cu[220] reflection is used to produce 0.50 eV and 2.0 eV neutrons in first and second order, respectively. Rotor speeds 6000 rpm, borated polyethylene inserts

Figure No.

- 8 Neutron burst width vs distance from crystal
- 9 Energy resolution on downscattered neutrons for an incident energy of 0.20 eV
- 10 Resolution on energy change for an initial energy of 0.20 eV
- 11 Energy resolution on downscattered neutrons for an incident energy of 0.50 eV
- 12 Resolution on energy change for an initial energy of 0.50 eV
- 13 Time-of-flight spectra of 0.18 eV neutrons from Cu[220] scattered off ZrH. Rotor speeds 6000 rpm
- 14 Time-of-Flight spectra of 0.50 eV neutrons from Cu[220] scattered off ZrH. Rotor speeds 6000 rpm. Sample-in running time 175 h
- 15 Partial differential cross-section data for zirconium hydride with an incident energy of 0.180 eV and a 15° scattering angle
- 16 Partial differential cross-section data for zirconium hydride with an incident energy of 0.50 eV

PLAN VIEW ROTATING CRYSTAL SPECTROMETER

Fig-1

Fig. 2

NEUTRON CHOPPER

Fig. 3

Fig-4

Fig. 5

Fig-6

Fig. 7

Fig-8

Fig. 9

Fig. 10

Fig. 27

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig-16