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USE OF SYNCHROTRON RADIATION FROM THE VEPP-3 STORAGE RING FOR X-RAY STRUCTURAL STUDIES

BY

T.D. MOKUL'SKAYA, M.A. MOKU'LSKIĬ, A.A. NIKITIN, V.V. ANASHIN, G.N. KULIPANOV, V.A. LUKASHOV AND A.N. SKRINSKIĬ

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INTRODUCTION

Synchrotron radiation is an important factor in shaping the orbit of electrons and positrons in storage rings for those particles. It ensures compression of the beam (reduction of its phase volume) and creates the conditions for storing particles in orbit.[1-4] As early as 1956, Tombulian and Hartman in their survey article[5] pointed up the great possibilities of using synchrotron radiation for spectroscopy in the region of the vacuum ultraviolet and soft x-rays in connection with a synchrotron beam having an electron energy of 300 MeV.

The building of synchrotrons having an energy of 1 GeV and above has substantially widened the spectrum of the occurring synchrotron radiation, having shifted the spectrum peak into the region of a few angstroms--the most interesting for diffraction-structure studies. At the same time, the radiation intensity has greatly increased. In recent years the interest in using synchrotron radiation for physical, chemical and biological research has risen sharply.

Today laboratories using synchrotron radiation have been or are being built in conjunction with all operating synchrotrons. Large-scale projects for utilization of synchrotron radiation are under way at the laboratories associated with the 7.5-GeV DESY synchrotron in Hamburg, and much work has been done with the 3.5-GeV CEA synchrotron in Cambridge, Massachusetts. In a number of countries (the U.S., Britain, West Germany et al.) programs have been initiated to develop large laboratories in conjunction with the existing synchrotrons and to build specialized storage rings to work exclusively with synchrotron radiation (storage rings as sources of synchrotron radiation having various advantages over ordinary synchrotrons). There is a vast literature on the varied applications of synchrotron radiation in physical, radiochemical, medical and other fields of research.[6-8]

One of the most important uses of synchrotron radiation is in the area of diffraction-structure research. The possibilities that open up here are very attractive, but as yet we find no new published results achieved through the use of synchrotron radiation. The reported results pertain only to method. We read descriptions of systems of channels for extracting the radiation beams, of arrangements of monochromators, collimators and what not, and data on the obtained radiation intensities.[10]

In this paper we report the first results of the work being done jointly by the Siberian Division of the Academy of Sciences of the USSR and the Kurchatov Atomic-Energy Institute on utilizing synchrotron radiation for structural research.

In December 1972 it was decided to construct a channel for extracting the x-ray part of the synchrotron radiation from the VEPP-3 storage ring (at the Nuclear-Physics Institute in Novosibirsk) for purposes of x-ray structural research in the field of molecular biology (Biology Department, Kurchatov Atomic-Energy Institute, Moscow).

The choice of the VEPP-3 storage ring as source of the synchrotron radiation was dictated by the fact that even at electron energies $E = 1.6\text{-}2.5$ GeV the peak in the synchrotron-radiation spectrum lies in the region $\lambda = 4\text{-}1$ Å, which is the most suitable for x-ray structural studies. The long lifetime of the beam in the storage ring ensures a low level of radiation background around the machine, which makes it possible to work in the immediate vicinity of the effective radiation source (at a distance of around 2.5 m). Along with small transverse dimensions of the electron beam, this ensures a high flux density of monochromatic photons in the beam.

In July 1973 an SR channel was mounted on the VEPP-3 storage ring, and a beam of synchrotron x-rays was extracted into the atmosphere. Subsequently the first experiments were conducted to obtain x-ray photographs of various substances with an SRD machine specially designed to operate on this channel.

The threefold purpose of the initial experiments was to check the operating efficiency of all the components, ascertain the peculiarities of operating with an SR beam, and compare the intensity of the monochromatic SR beam with that of fine-focus x-ray tubes operating at the characteristic radiation of copper (λ = 1.54 Å).

1. *DESCRIPTION OF THE VEPP-3 STORAGE RING*

The schematically strong-focussing VEPP-3 storage ring[9] consists of two half-rings separated by long straight sections in which the focussing is done with the aid of quadrupole lenses (Figure 1). Mounted in the half-rings are sixteen magnets, each consisting of four parts: two enveloping magnets with a uniform field and short but strong focussing and defocussing magnets. In the enveloping magnets the radius of curvature is R_M = 6.15 m, in the defocussing magnet R_D = 9.8 m, in the focussing magnet R_F = 16.8 m. The mean radius of the particle trajectory in the half-rings is R_{mean} = 8.05 m, the total perimeter of the trajectory (including the straight sections) P = 74.4 m, the frequency of the particles' revolution in the storage ring f = 4.03 MHz.

The electrons are injected into the storage ring at an energy of E = 300 MeV from a B-4 synchrotron. Elevation of the energy in the storage ring occurs over a period of

~80 sec. The storage ring's magnetic system is designed to produce an energy of $E = 3.5$ GeV. In July 1973 the main work was done at an electron energy of $E = 2$ GeV, determined by the existing HF-feed system. The energy will be increased to $E = 3$ GeV in 1974.

The mean vacuum along the length of the storage ring was $\sim 10^{-8}$ torr, which ensured an electron lifetime of $\tau = 3$ hr at low current. However, with a current $I = 10$ mA and $E = 2$ GeV the lifetime dropped to $\tau = 20$ min because of the strong outgassing of the walls of the vacuum chamber under the influence of the synchrotron radiation. We hope in future to eliminate this sharp drop in the lifetime and to raise the working currents to $I = 100$ mA keeping a normal lifetime.

The current in the storage ring is measured by using a photomultiplier to record the SR intensity. Calibration is done by measuring the SR intensity from one electron. Integrated pickup electrodes are also used to measure the current when it is above 100 μA.

A system of differential pickup electrodes is used to measure the position of the equilibrium orbit in the storage ring.

A special system, based on recording the visible part of the SR, makes it possible to obtain oscillograms of the beam-density distribution in the radial or vertical direction. At an energy of $E > 0.8$ GeV, the radial dimension of the electron beam in the storage ring is determined by the quantum fluctuations of the synchrotron radiation, and is $2\sigma_r(\text{mm}) = 5 \times 10^2 \sqrt{\beta(\text{cm})E}$ (GeV). In the enveloping magnet the betatron function is $\beta = 250$ cm. The beam's vertical dimension was found by measurement to be $\sigma_z = 0.1\ \sigma_r$. In our experiments these quantities were $2\sigma_r \sim 1.5$ mm and $\sigma_z \sim 0.08$ mm.

2. *THE VEPP-3 STORAGE RING'S SYNCHROTRON-RADIATION CHANNEL*

The VEPP-3 storage ring was designed on the assumption that SR would not be extracted beyond the limits of the vacuum chamber. The vacuum-chamber structure includes an SR receiver comprising a gold-plated water-cooled tube placed on the outer radius in the circular part of the storage ring. Hence only in the segments where the half-rings are butt-joined to the straight sections can SR be extracted without altering the structure of the vacuum chamber in the magnets and that of the magnets themselves.

It was one of those places that was selected for insertion of the SR channel (Figure 2). The radiation is extracted from the enveloping magnet, from the segment of the trajectory lying at a distance of 45 cm from the magnet's edge. The channel axis is at an angle $\alpha = 4°$ to the axis of the straight section. The channel length is $L_{ch} \sim 2.5$ m.

The channel contains:

a) dowel-type radiation receivers, which can completely cover the SR channel;

b) a high-vacuum valve, behind which is connected the

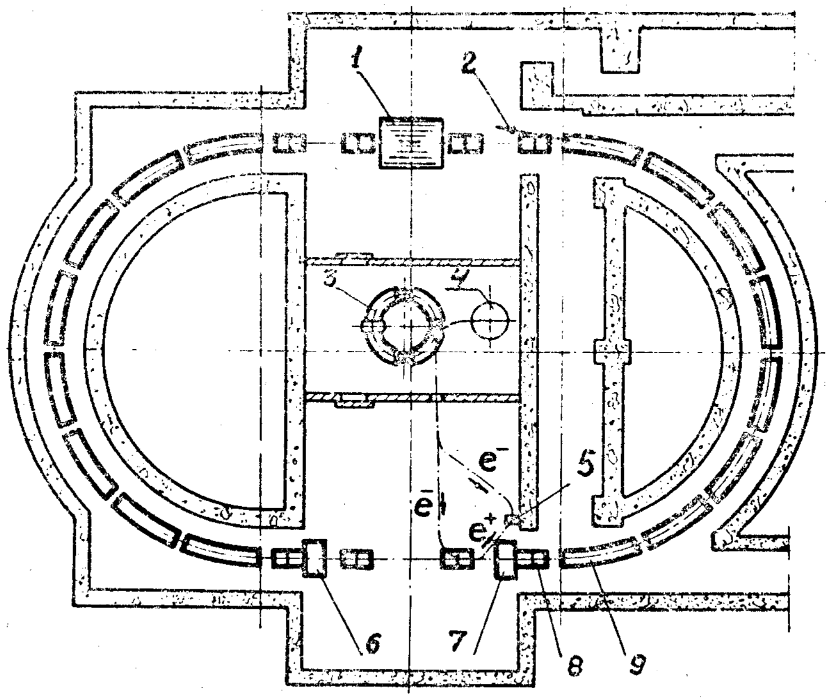

FIGURE 1: Schematic of the VEPP-3 storage ring.

1- Recording system for colliding-beam experiments; 2- synchrotron-radiation exit (the storage ring's vacuum chamber is not shown); 3- B-4 synchrotron injector; 4- foreinjector; 5- converter for obtaining positrons; 6 and 7- resonators; 8- doublet of quadrupole lenses; 9- the storage ring's enveloping magnet.

SR channel's output unit;

c) 1- and 3-mm diaphragms for narrowing the SR beam at the exit foil;

d) a variable-thickness beryllium filter placed in front of the exit foil; when introduced into the SR beam, it cuts off the long-wavelength part of the spectrum so as to reduce the thermal load on the exit foil;

e) a MERN-150 magnetic discharge pump to pump out the gas that evolves under the influence of the SR from the

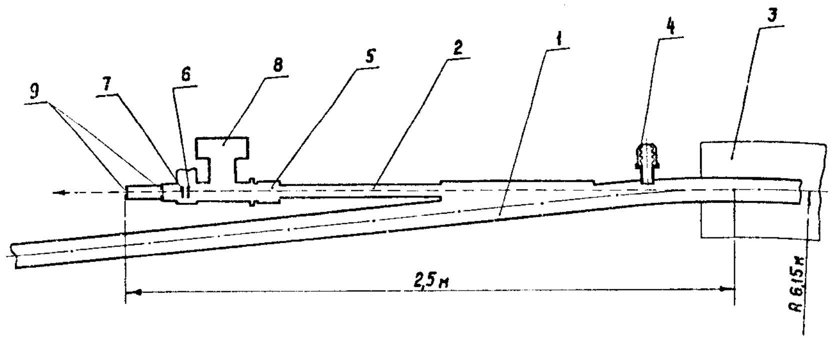

FIGURE 2: Schematic of channel for extracting synchrotron radiation from the VEPP-3 storage ring (SR channel).

9- Beryllium exit foil 0.15 mm thick; 7- attenuating beryllium filter; 6- diaphragms; 8- MERN-150 magnetic discharge pump; 2- SR channel; 4- dowel radiation-receiver; 3- the storage ring's enveloping magnet; 1- the storage ring's vacuum chamber; 5- forevacuum volume of the exit section.

diaphragm, filter and exit foil;

f) an exit window of 0.15-mm-thick beryllium foil;

g) a forevacuum volume and a second exit foil of 0.15-mm-thick beryllium, their purpose being to protect the VEPP-3 vacuum chamber against the entry of air from the atmosphere, should the exit foil suffer accidental or radiation damage.

When the storage ring operated at an energy of $E = 2$ GeV, the beryllium filter was not used, and the SR beam always exited into the atmosphere through beryllium foils having an aggregate thickness $\alpha = 300\ \mu$. The diameter of the exit foil is 9 mm; if need be, the exit foil can be enlarged to the dimensions of the SR channel, whose exit diameter is 30 mm.

The SR-channel exit and the apparatus for obtaining x-ray photographs are situated near the storage ring, and have no special shielding against hard gamma quanta and neutrons. However, even with a relatively short lifetime of the electrons in the storage rings $\tau = 40$ min, a current $I = 10$ mA and an energy $E = 2$ GeV, the maximum level of the radiation due to hard gamma quanta is only ~ 0.2 μR/sec in the storage ring's median plane, situated at the level $H = 2.2$ m above the floor.

A much greater danger is presented by the SR beam itself, but the relatively low energy of the photons in the SR beam makes it possible to remove the scattered photons in the vicinity of the SR-channel exit with the aid of a light-weight local lead shield 2 mm thick.

3. *THE PARAMETERS OF THE SR BEAM*

The basic parameter determining the time needed to obtain an x-ray photograph is the number of monochromatic photons incident on 1 mm^2 of specimen per second. This quantity depends on the storage-ring current and electron-beam cross-section, on the transmittance of the exit foils, on the length of the SR channel and on the quality of the monochromator used:

$$N(\lambda)\ \frac{\text{photon}}{\text{mm}^2\,\text{sec}} = I_{mA} \cdot \frac{dn}{d\lambda} \cdot \frac{1}{h_{mm} L_m}\ \eta(\lambda)\,\xi(\lambda)\,\Delta\lambda ,$$

where I_{mA} is the current in the storage ring; $\frac{dn}{d\lambda}$ is the photon flux (integrated over all vertical angles) emitted by a current of 1 mA into a radial angle of 1 mrad $\left(\frac{\text{photon}}{\text{sec}\cdot\text{Å}\cdot\text{mA}\cdot\text{mrad}}\right)$; L is the length of the SR channel (in meters); h is the height, i.e., vertical dimension, of the beam at the SR-channel exit (in millimeters); $\eta(\lambda)$ is the transmittance of the SR-channel exit foils; $\xi(\lambda)$ is the reflectance of the monochromator crystal; $\Delta\lambda$Å is the width of the band transmitted by the monochromator.

The value of $\frac{dn}{d\lambda}$ is calculated with sufficient accuracy using the well-known formulae[5]:

$$\frac{dn}{d\lambda}\ \frac{\text{photon}}{\text{sec}\cdot\text{Å}\cdot\text{ma}\cdot\text{mrad}} = 7.9 \times 10^4\ \frac{E^7_{\text{GeV}}}{R^2_m}\ G(y)\,\lambda(\text{Å}),$$

where E is the energy of the electrons in the storage ring (in GeV); R is the radius of curvature at the point of emission (in meters); G(y) is a tabulated function[5] in which

$$y = \frac{5.59 \cdot R_m}{E^3_{\text{GeV}} \cdot \lambda\text{Å}}\ .$$

The beam height h at the SR-channel exit is a less determinate quantity, and depends on the dimension of the electron beam $2\sigma_z$ in the storage ring, on the angular spread in the electron beam ψ_{el}, on the angular divergence of the SR beam ψ_z, and on the channel length L:

$$h = \sqrt{4\sigma_z^2 + L^2(\psi_z^2 + \psi_{el}^2)}\,.$$

Because of the smallness of the vertical dimension of the electron beam in the storage ring, in determining the height of the SR beam one can almost always neglect the dimension and angular spread of the electron beam. For wavelengths λ at which $y \lesssim 2$ the SR beam's angular divergence does not depend on the electron energy and is found with the expression:

$$\psi_z \text{ mrad} = 5.75 \times 10^{-4} \left(\frac{\lambda Å}{R_m}\right)^{1/3}.$$

Then $h_{mm} = L_m \psi_{mrad} = 0.575 \left(\frac{\lambda Å}{R_m}\right)^{1/3}.$

In our case, for $\lambda = 2$ Å we have a beam height $h \sim 1$ mm.

Figure 3 shows curves characterizing the intensity and spectral distribution of the synchrotron radiation at the SR-channel exit of the VEPP-3 storage ring for energies of 2, 2.5 and 3 GeV with a current of 1 mA. The channel length, i.e., the distance from the point of a photon's emission to its exit into the atmosphere, is ~2.5 m.

4. *APPARATUS FOR RECORDING THE SYNCHROTRON-RADIATION DIFFRACTION PATTERNS*

The apparatus for recording the synchrotron-radiation diffraction pattern, the SRD-1 (see Figures 4 and 5), consists of a monochromator, an x-ray camera and a number of auxiliary devices. The SRD-1 unit is fastened with adjusting and clamp screws to a platform suspended from the storage ring's bending magnets.

Fastened to the SRD unit's main rack are the

FIGURE 3:

The number of photons at the exit of an SR channel of length L = 2.5 m as a function of the wavelength for different electron energies: solid-line curve is the emission spectrum prior to passage through the exit foils; broken-line curve is the emission spectrum after passage through beryllium foils having a total thickness of 0.3 mm. The beryllium's absorption coefficient for different λ is calculated with the Johnson formula.

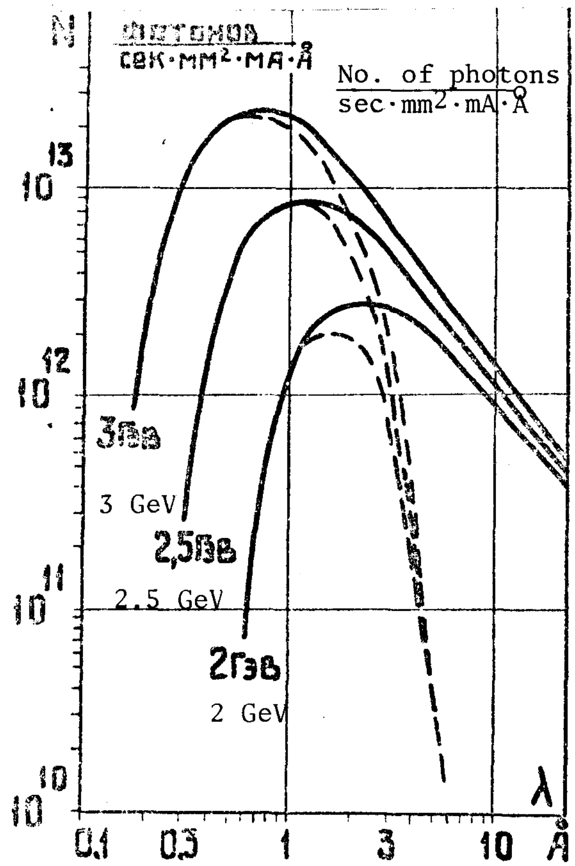

FIGURE 4:

Schematic of the SRD-1 unit:
1- main rack; 2- monochromator crystal; 3- rotating bench;
4- x-ray camera; 5- radiation scintillation detector;
6- adjusting and clamp screws;
7- platform; 8- SR-channel exit segment.

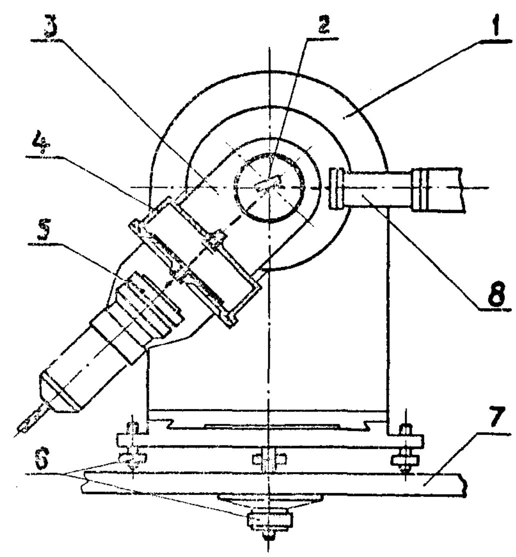

FIGURE 5:

The SRD-1 unit.

monochromator-crystal holder and a rotating bench. The crystal and bench can be rotated independently of one another (via worm gears) about a horizontal axis common to both, which is perpendicular to the SR beam. Fastened to the bench are an x-ray camera and an "Araks" radiation scintillation detector. Used as diffraction monochromator was a single crystal of quartz (cut parallel to the $10\bar{1}1$ plane with an interplanar spacing $d = 3.34$ Å).

When the quartz crystal is rotated through an angle θ, the bench through an angle 2θ, with respect to the median plane, the straight SR beam exiting from the channel hits the surface of the crystal at an angle θ. The reflected (monochromatized) beam goes down from the median plane at an angle 2θ, passes through the inlet collimator of the x-ray camera, hits the specimen, then, after passing through a hole in the x-ray film, reaches the detector inlet.

This experimental geometry, with extraction of the beam from the median place, is in some respects more convenient than the other geometry involving a vertical axis of rotation of the crystal and bench with the reflected beam remaining in the median plane. In the latter case, because of the polarizing effects, a reflected ray will be extinguished when the radiation is reflected from the crystal at an angle $\theta = 45°$. In our case, the electric vector of the incident wave and reflected wave is perpendicular to the plane of incidence, and this effect is absent.

The SRD unit permits operation over a broad range of angles θ, from 0 to 70° (2θ = 0-140°), which corresponds to a range of wavelengths of the reflected radiation from 0 to 6 Å. The practical lower limit of the operating range (of λ) is determined by the spectrum of the synchrotron radiation, and for an electron energy of $E \sim 2$ GeV is in the region of 0.5 Å. The spectrum's upper limit is determined by the transmittance of the beryllium foils and is in the region of 4.5 Å (see Figure 3). The spectrum of the radiation reflected from the crystal consists of the fundamental harmonic λ and of the upper harmonics $\frac{\lambda}{2}$, $\frac{\lambda}{3}$, ... (according to the Bragg formula, $2d \sin\theta = n\lambda$). In our case, for the quartz crystal the relative intensity of the harmonic $\frac{\lambda}{2}$ is 8%, the other harmonics being somewhat weaker. The share of the second harmonic sharply increases when one operates with radiation of $\lambda = 3$ Å and above, for then the fundamental harmonic is strongly absorbed by the beryllium.

The spectrum width $\Delta\lambda$ of the fundamental harmonic, governed by the transmission band of the monochromator and divergence of the beam of synchrotron radiation, is estimated by us to be 10^{-3} Å.

The x-ray camera has as collimator a lead-glass capillary 0.15 mm in diameter, and the distance between the specimen and the film can be varied from 9 to 45 mm. The desired water-vapor pressure can be maintained in the camera by placing inside it a special tray of saturated salt solution. This makes it possible to photograph with the camera biological preparations, whose structure is strongly dependent on the atmospheric humidity. The diffraction pattern is recorded on the x-ray film.

5. *FIRST DIFFRACTION-PATTERN EXPERIMENTS*

The diffraction patterns were photographed under different storage-ring operating regimes (electron energy 1.6-2 GeV, current ranging from fractions of a milliamp to 10 mA), hence the radiation intensity was different in the different experiments. The exposure-time data given below were obtained by conversion to the regime: $E = 2$ GeV, $I = 2$ mA. The experiments that were run are enumerated below (Figures 6-8).

a) Diffraction of the continuous-spectrum radiation: The x-raying was done by the ordinary Laue method. The specimens were mica and aluminum foil; the exposure time ranged from 12 sec to 1 min.

b) <u>Diffraction of the monochromatic radiation</u>: All three specimens--wood, polyethylene and DNA*--had axial textures. The wood had a natural orientation; the polyethylene films and DNA fiber were oriented by drawing. The following x-ray photographs were obtained:

FIGURE 6: Laue pattern from the aluminum foil.

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*Used was a sodium salt of DNA from the thymus of a calf.

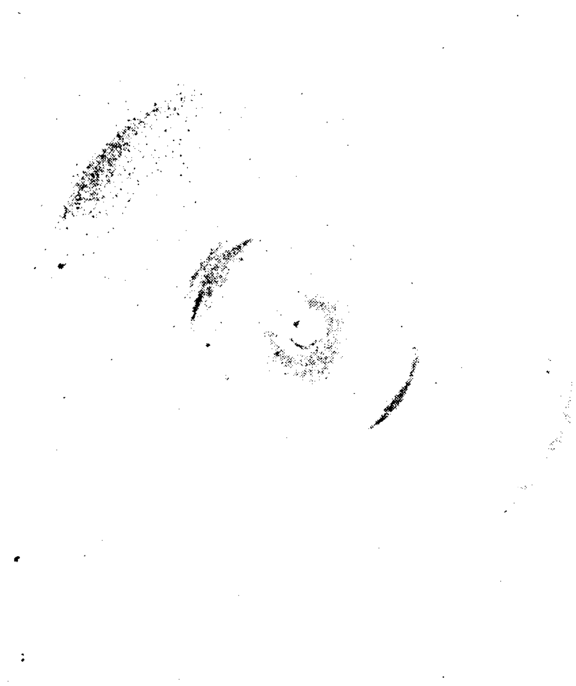

FIGURE 7: X-ray photograph of the polyethylene. The axis of draw was horizontal. One sees equatorial reflections of the fundamental harmonic (3 Å) and second harmonic (1.5 Å).

1) Wood: λ = 2 Å; exposure time 60 min.

2) Polyethylene: λ = 2 Å; exposure time 50 min; visible in the x-ray photograph were faint reflections produced by radiation having a wavelength of 1 Å (second harmonic).

3) Polyethylene: λ = 3 Å; exposure time 60 min. The reflections produced by the second harmonic (λ = 1.5 Å) became strong.

Comparison of the x-ray photographs of the polyethylene taken at λ = 2 Å and 3 Å showed that the 3-Å wavelength is closer to optimal for x-raying that specimen. Actually, the number of quanta of radiation having a wave-

FIGURE 8: X-ray photograph of the NaDNA (λ = 2 Å; A-shape).

length λ = 3 Å for the same storage-ring current is smaller by a factor of roughly 3 than when λ = 2 Å, but with equal exposure times we then get x-ray photographs with similar densities.

4) DNA: λ = 2 Å; exposure time 135 min. The specimen had a high degree of crystallinity. The relative atmospheric humidity in the camera was 75%; the DNA was A-shaped.

An estimate of the density and resolution of the obtained diffraction patterns permits a qualitative estimate of the effect of shortening the exposure time, achieved with the storage ring and SRD unit used. For photographing in monochromatic radiation in the VEPP-3 storage ring operating with an electron energy $E = 2$ GeV and current $I = 2$ mA, the exposure time is roughly equal to that needed for photographing in unfiltered CuK_{α} radiation using a fine-focus x-ray tube with a copper anode. Using a nickel-foil filter (to weaken the CuK_{β} line) increases the exposure time in the x-ray tube by a factor of 2-3. In our experiments the current in the storage ring reached 10 mA, hence the exposure time was shortened by approximately one order of magnitude relative to that with the nickel-filter x-ray tube. These experimental estimates agree well with the calculated values of the spectral density of the synchrotron radiation and radiation of the x-ray tube.

DISCUSSION OF THE RESULTS AND OUTLOOK

The results obtained enable us to draw certain conclusions concerning the prospects for developing diffraction-structure research using the synchrotron radiation of the VEPP-3 storage ring.

1. *The Radiation Intensity*

At the outlet of the storage ring operating at the rated $E = 3$ GeV and $I = 100$ mA, the spectral density of the radiation greatly increases, and the exposure time becomes greatly shortened in comparison with the x-ray tube. A substantial increase in the number of quanta hitting the specimen can be achieved by using a monochromator with a broader bandwidth $\Delta\lambda$ and greater reflection factor (within that band). Some deterioration in the beam's monochromaticity (increase of $\Delta\lambda$ to 3×10^{-3} Å) is entirely admissible in most x-ray structure studies. The use of focussing devices may further increase the radiation intensity by several times. It therefore appears quite feasible to use synchrotron radiation to shorten the recording time of the x-ray diffraction pattern by a factor of 10^2 in comparison with the better rotating-anode x-ray tubes. This in itself opens up very important new possibilities for structure research, affording in particular a real prospect of obtaining x-ray photographs of specimens weighing 10^{-9} g and less, which would be of enormous significance in many areas of biological research.

2. *The Radiation Spectrum*

The possibility of conducting diffraction studies at any radiation wavelength, from tenths of an angstrom to several angstroms, will permit substantial development of direct methods of determining the atomic structure of matter. Actually, as shown in a number of studies (e.g., ref. 12), precise measurements of the intensities of diffraction of radiation of different wavelengths near the edge of the K-band of absorption of one of the atoms will permit solution of the phase problem without resort to the method of isomorphic derivatives.

Diffraction studies with radiation having a wavelength of 3-6 Å, virtually unrealizable with the aid of ordinary x-ray tubes, will facilitate studying structures with greater periods (hundred of angstroms), and will be helpful in the investigation of diffraction from small specimens (e.g., biological specimens measuring some 30 μ; the optimal wavelength, corresponding to the shortest exposure, being $\lambda \sim 5$ Å). In the 4-6 Å range lie the K-bands of the anomalous dispersion of the atoms of phosphorus and sulfur that go into the nucleic acids and proteins. Diffraction studies at these wavelengths appear most promising. Extraction from the storage ring of radiation with a wavelength of 4-6 Å is entirely possible.

Of general physical interest are precise measurements of the total complex function of atomic scattering. Progress in this area has hitherto been slowed by obstacles involving method, specifically by the absence of good sources of radiation with a continuous spectrum.

3. *Natural Collimation and Polarization of the Synchrotron Radiation*

Good collimation of the synchrotron radiation makes possible a radical shortening (by several orders of magnitude) of the duration of small-angle studies of amorphous bodies, solutions, biological structures. In conjunction with the polarization, it affords the possibility of conducting on a new level the structural studies of matter in strong magnetic and electric fields, and under other conditions in which the use of ordinary x-ray tubes is impossible.

SUMMARY OF THE RESULTS

1) A beam of synchrotron radiation in the x-ray range has been extracted from the VEPP-3 storage ring.

2) An apparatus has been built for recording the patterns of diffraction of monochromatic synchrotron radiation at different wavelengths.

3) Patterns of diffraction of synchrotron radiation from specimens of different types (single crystal, metal, fibrillar polymers) have been obtained on photographic film.

REFERENCES

1) J. O'Neil: CERN Symp., 1956.
2) C. Bernardini et al.: The Frascati Storage Ring. Nuovo Cimento, vol. 18 (1960).
3) G.I. Budker et al.: *Materialy Mezhdunarodnoĭ konferentsii po uskoritelyam* ("Proceedings of the International Conference on Accelerators"), Dubna, 1963.
4) W. Barber et al.: ibid.
5) D.N. Tombulian and P.L. Hartman: Phys. Rev., 102, 1423 (1956).
6) E.M. Rowe: Research Using Synchrotron Radiation. Nucl. Sci., vol. NS-20, N 3, 973.
7) *Sinkhrotronnoe izluchenie v issledovanii tverdykh tel* ("Synchrotron Radiation in Solid-State Research"). Collection of papers edited by A.A. Sokolov. Mir, Moscow (1970).
8) H. Winiok: Synchrotron Radiation at the CEA. Nucl. Sci., vol. NS-20, N 3, 984.
9) G.I. Budker, I.Ya. Protopopov and A.N. Skrinskiĭ: *Ustanovka so vstrechnymi elektron-pozitronnymi puchkami na energiyu 3,5 Gev (VEPP-3). Trudy YII Mezhdunarodnoĭ konferentsii po uskoritelyam* ("The VEPP-3 Machine with 3.5-GeV Colliding Electron-Positron Beams. Proceedings of the 7th International Conference on Accelerators"), Yerevan (1970), vol. 2, p. 37.
10) G. Rosenbaum, K.C. Holmes and J. Witz: Nature, vol. 230, N 5294, 434 (1971).
11) M.A. Blokhin: *Fizika rentgenovskikh lucheĭ* ("The Physics of X-Rays"). GITL, Moscow (1957).
12) A. Herzenberg and H.S.M. Lau: Acta Cryst., 22, 24 (1967).