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NEW INSTRUMENTS AND TECHNIQUES IN NEUTRON CAPTURE STUDIES*

W. R. Kane

Brookhaven National Laboratory

Upton, New York 11973

INTRODUCTION

There are three general topics I would like to cover in this discussion. The first deals with crystal diffraction gamma-ray spectrometers, in particular, with the highly productive GAMS spectrometers at the ILL reactor in Grenoble. While these experimental devices have been described briefly at previous meetings, they deserve a detailed description here because of their great potential for producing capture gamma-ray data of the highest quality. Future possibilities for other developments in the area of crystal diffraction spectroscopy of capture gamma rays will also be mentioned. Several papers have been submitted to this conference in the area of improved neutron beam facilities for capture gamma-ray experiments. These papers will be discussed within the general framework of the subject of the production of high quality thermal neutron beams under a variety of conditions. Finally, a magnetic spectrometer for studies of internal conversion electrons emitted after thermal neutron capture, now nearing completion at the BNL High Flux Research Reactor, will be described in some detail. Since the high performance (n,e) spectrometer BILL at the ILL research reactor in Grenoble has already been described by K. Schreckenbach in an earlier invited talk at this meeting, discussion of it here will be limited to a comparison of the ILL and BNL (n,e) spectrometers.

I. CRYSTAL DIFFRACTION SPECTROMETERS

For several reasons, the crystal spectrometer is ideally suited for studies of the (n,γ) reaction. The simultaneous requirements

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for a very strong gamma-ray source and high angular resolution are met by employing an in-pile target, particularly in a high flux reactor. At the same time, the non-specific and very prolific nature of the (n,γ) reaction produces, in most medium mass and heavy elements, a very large number of gamma-ray transitions, sometimes numbering in the thousands, so that the high resolution and precision of the crystal spectrometer are essential if individual peaks are to be resolved and energies measured with a precision sufficient to permit the application of the Ritz combination principle to the construction of reliable level schemes. Additional advantages of the crystal spectrometer are its simple response function (a single peak) and a dynamic range which exceeds that of the Ge(Li) detector by a large factor. The use of the crystal spectrometer in studies of the (n,γ) reaction is highly useful for nuclear structure investigations, since the non-specific nature of the reaction and the capabilities of the spectrometer insure that the gamma-ray deexcitation of most low-spin energy levels up to a fairly high energy, typically several MeV, can be observed. This stands in contrast to the situation that exists with many other nuclear reactions, including those involving heavy ions, which excite only those final states which possess a certain character or whose spins fall within a certain range.

For reasons of intensity, the curved crystal spectrometer, which enjoys an efficiency 10^2 to 10^3 times greater than existing double flat crystal spectrometers, is the instrument of choice for studies of the (n,γ) reaction. Of the two curved crystal geometries, the Cauchois and DuMond, which are equivalent except for an interchange of source and detector positions, the DuMond geometry, which utilizes a small source and large-area detectors, is preferable since it is usually impractical to insert in a reactor the large amounts of separated isotopes necessary for the large-area source required in the Cauchois geometry, while Na(I) detectors of sufficient size for the DuMond geometry are readily available. A 4-meter focal length Cauchois spectrometer has, however, been installed at the Joffe Institute in Leningrad by Sumbaev and Smirnov[1], and experiments carried out on several nuclides. This instrument has a relative accuracy of about 2.5×10^{-5} in the energy range of 50 to 500 keV, and 1×10^{-4} in the range of 500 keV to 1 MeV.

The most important development in recent years has been the installation of the GAMS curved crystal spectrometers at the high flux reactor at the Institut Laue-Langevin in Grenoble. While these spectrometers, having the DuMond configuration, are similar in concept to earlier devices, for example the curved crystal spectrometer formerly at the Risø research reactor[2,3], a substantially improved design combined with the higher flux of the ILL reactor lead to a very large advantage in resolution and sensitivity over earlier devices. The GAMS spectrometers consist of a single crystal,

GAMS 1, with a focal length of 5.8 meters, designed to operate in the gamma ray energy range of 20 to 600 keV, and a double crystal arrangement, GAMS 2/3, with a focal length of 24 meters, designed for the energy region 200 to 1500 keV. All three instruments view a common source situated in a through tube 55 cm from the reactor core in a flux of 8×10^{14} n/cm^{2}-sec. All of the crystals are quartz, utilizing reflection from the 110 planes. The useful energy range was determined by selecting an appropriate thickness for the quartz: 4 mm for GAMS 1 and 14 mm for GAMS 2/3. This provides rather efficient reflection over the energy range of interest; for example, for GAMS 2/3 the reflected intensity for the 411 keV gamma ray of ^{198}Au is about one third that of the primary beam. In order to obtain good resolution, the dimensions of the source are crucial. Typically a laminar shaped source is used, with a thickness ranging from 0.03 to 0.20 mm, depending upon the capture cross section. A source width of 0.1 mm contributes about 1 arc second to the instrumental rocking curve of GAMS 2/3. In addition to effects arising from the source width, small displacements of the source are also a potential source of error. For GAMS 1, a change in source position of one micron will lead to a corresponding error of $\sim$ 1 eV for a 200 keV gamma ray. This problem is dealt with on GAMS 1 through the use of an auxiliary crystal which, for a given target, is focussed on a single strong gamma-ray peak throughout the run. Changes in the position of this reflected peak with time are recorded and used during the analysis of the data to correct for source motion. In the case of GAMS 2/3 the reflecting crystals are mounted on a common axis but rotate in opposite directions. In this geometry the Bragg angle is derived from the sum of the angles of the two reflecting crystals and the effect of the source motion vanishes, since it makes equal and opposite contributions to the two angles of reflection. The Bragg angles for all of the crystals are determined by Michelson angle measuring interferometers. The light beam, provided by a laser, is split into two paths with a phase difference of $\lambda/4$, providing a means of determining the direction of rotation of the crystal. For GAMS 1, one interference fringe corresponds to 0.45" of arc, and the precision of the angle setting is $\sim$ 0.05". For GAMS 2/3 the corresponding quantities are 0.165" and 0.03", respectively. The reflected gamma rays are detected by NaI scintillators, with the output pulses routed into five single channel analyzers with windows set to record each of the first five orders of reflection. The simultaneous acquisition of data in five orders of reflection permits, for example, strong lines to be measured at high resolution and precision in the fifth order, while weaker lines are measured in the second order. For optimum conditions, the resolution of GAMS 1 is about 100 eV at 200 keV gamma ray energy and of GAMS 2/3, about 150 eV at 500 keV. The corresponding precision of the two spectrometers is about 1 eV for GAMS 1 at 200 keV and 2 eV for GAMS 2/3 at 500 keV. For weak lines and thick sources the line breadths and energy errors

may be an order of magnitude or more greater. For typical counting times the minimum partial cross section for the observation of a gamma ray is, at an energy of 600 keV, about 2 mb. In special regions of interest the sensitivity can be increased by ~ 5 by a longer counting time. In both sensitivity and precision the GAMS spectrometers represent an improvement of $\sim$10 over the Risø curved crystal spectrometer.

While the GAMS spectrometers can be expected to be very powerful tools for studies of the (n,γ) reaction, for a number of years, it is nevertheless of interest to consider what further advances might be possible in the area of crystal diffraction studies of capture gamma rays. For the curved crystal spectrometers the resolution could evidently be improved by the use of more perfect crystals, and the efficiency, by the use of crystals with a higher reflecting power. For this purpose the use of nearly perfect crystals of Ge and Au have been proposed [4] and it has been suggested that with sufficient effort large perfect crystals could be bent without any increase in the width of the rocking curve over that attainable with existing flat crystal spectrometers.[5] This improvement in the resolution would, of course, only be useful for the case of long focal length and a very narrow source, since otherwise the contribution of the finite source width to the rocking curve would be much greater than that of the crystal itself.

In an invited paper given at this conference, by E.G. Kessler, the very high resolution, high precision double flat crystal spectrometer at the National Bureau of Standards, employed for the precise determination of gamma-ray standards, has been described[6]. This instrument, which utilizes nearly perfect crystals of Si or Ge, has a rocking curve with $\sim$0.1 arc second full width half maximum at 411 keV. For the measurement of the angular positions of the crystals it employs Michelson interferometers which are capable of a precision of 50×10^{-6} arc second. A portable version of this device is now under construction. This will be available both for measurements of x-ray spectra at the NBS Van de Graaf Accelerator and for the measurement of prompt neutron capture gamma rays. Although the efficiency of this instrument is about three orders of magnitude lower than that of a curved crystal spectrometer, it should nevertheless prove very useful for the determination of new gamma-ray energy standards or for the resolution of very dense spectra in certain special and interesting cases.

In principle, it should be possible to employ much larger perfect flat crystals of Si or Ge than those presumably in use, along with targets of correspondingly large areas, and thus overtake most of the advantage in efficiency that the bent crystal spectrometers now enjoy.[5] In this arrangement the source width does not contribute to the instrumental line breadth, since each

portion of the diffracting crystal views a small portion of the source determined only by the angular width of the reflection process.

II. HIGH QUALITY THERMAL NEUTRON BEAMS

For a number of years all but a few thermal neutron capture experiments carried out have tended to be rather straightforward in that they involved macroscopic amounts of target materials (>0.1 gm) and capture cross sections usually in excess of 0.1 barn, and with the exception of tests of fundamental conservation laws, small effects were not usually sought after. For these experiments, reasonable, rather than optimum beam intensity and quality and background were ordinarily sufficient. There exists a larger class of more difficult experiments involving, for example, low cross section targets, small samples of rare or radioactive isotopes, and prompt neutron capture activation analysis of trace elements, which become possible in neutron beams of high intensity and optimum quality. Other experiments, such as the search for two-photon emission after neutron capture by hydrogen [7] also require optimum conditions. Clearly, experiments in these areas greatly expand the scope of both basic and applied neutron capture gamma-ray research. For many of these experiments the in-pile target geometry is a logical choice, since it affords a considerable advantage in flux and geometrical efficiency, but it also has certain inherent disadvantages, including a usually high gamma-ray background, heating of the target, and the inability to insert certain materials into the reactor, complication of the analysis of the results by multiple neutron capture (although this can evidently be an advantage when the study of successive product nuclei is desired) and the activation of, for example, a stable isotope target, rendering it worthless for further use in research. External beams are evidently also necessary if coincidence, angular correlation, or lifetime measurements are to be carried out.

Of the several approaches by which experimental parameters can be upgraded and extended, the careful design of beams (or in-pile targets) and the minimization of background are certainly the most feasible and cost effective. Major increases in the neutron flux from reactors or other neutron sources, or the incorporation of devices in them which enhance experimental conditions are subject to both technological and economic limitations. The improvement of experimental devices has ordinarily been carried out to the extent that techniques and resources permit. On the other hand an improvement of a factor of 2 or 3 in beam intensity through the optimum design of a beam line, or an equivalent increase in signal-to-background ratio can often be attained at a relatively low cost, particularly when compared with the cost of increasing the reactor flux or even the efficiency of detectors by the same factor.

Ideally, the best conditions for a given experiment or experimental facility are attained when the requirements of an individual experimental program are considered in detail very early in the planning of a research reactor, and the entire facility, including the reactor vessel and shielding, "built around" the various experiments planned. In practice, this procedure is rarely followed. More often a researcher will be assigned a beam port at one of several more or less standard types of research reactors which is less than ideal for his experiment and he must best adapt it to his own particular needs. Moreover, as experimental programs evolve and take new directions it is often necessary to modify an existing facility to accomodate new and different experiments.

In the design of a neutron beam facility there are five elements that may enter into consideration. They are: 1) the source. 2) collimator. 3) crystal filter. 4) neutron guide tube. 5) shielding and beam trap. In any given instance these elements are interrelated, with the character of the source usually most important in determining the choice of subsequent elements.

The source of neutrons may be a thermal column, a tangential beam tube, or in some circumstances, a radial beam tube viewing the reactor core.

The most suitable source of a thermal neutron beam of moderate intensity is certainly a thermal column, if it is available in the reactor, since it possesses a very low background of fast neutrons and gamma rays. A beam from this source, with simple collimation, is usually adequate for most purposes. A thermal column, however, usually has a considerably reduced flux of thermal neutrons compared with certain regions of the reactor moderator, making it unsuitable as a source of neutrons for intense beams. A tangential beam tube, either terminating in the moderator, or a through tube containing a suitable reflector will have much higher flux, but at the cost of a considerably higher background of reactor gamma rays and fast and epithermal neutrons, which must be dealt with if a thermal beam of high quality is to be obtained. Finally, it is well known that a radial beam tube should be avoided as a source of thermal neutrons whenever possible, because of its very high background of gamma rays and fast neutrons. But a beam from this source, if its use is unavoidable, can be upgraded to a very substantial degree by eliminating the contaminant radiations with single crystal filters, a guide tube, or both in combination.

The principles of collimation are largely self-evident. A few points, however, should be emphasized. For example, the advantages of using converging, rather than straight collimators should be considered. While for a converging collimator the penumbra surrounding the beam some distance downstream may be

somewhat greater in extent than in the case of a straight collimator, its effect can be minimized with a proper choice of target and detector geometry and the use of neutron absorbing apertures, and the increase in beam intensity can be very substantial. For example, at our monochromator facility at the Brookhaven HFBR the use of a vertically converging Soller collimator which viewed the entire inner end of the beam tube gave an increase in intensity of about 3.5 over an equivalent straight collimator, which is the equivalent of the upgrading of the reactor from 40 MW to 140 MW power at essentially no cost. A small amount of monochromator resolution was sacrificed, since the Bragg condition becomes $n\lambda = 2d \cos \alpha \sin \theta$, where α is the vertical deviation of a ray from normal incidence, but the effect was small over the angular spread of the beam and negligible for the experiments carried out.

It is important to view every element of the beam line not only as an absorber that defines the beam or removes background but also as a source of scattered neutrons and secondary radiations.

A collimator is a source not only of a highly directional neutron beam but also of both scattered neutrons and capture gamma rays, which for practical purposes, can be considered to be isotropic. There is thus some optimum distance, typically a meter or more, where the target and detector should be placed downstream from the end of the collimator, where the primary beam has not undergone a great degree of divergence but where secondary radiations from the collimator have been attenuated by the inverse square law. Evidently, the end of the collimator should be well-shielded with "quiet" neutron and gamma-ray shielding, such as $^{6}Li_2CO_3$ (or LiF) and lead. The use for collimation of materials which possess both a large capture cross section and high energy capture gamma rays, especially iron, should be strictly avoided.

Since the scattering and absorption of thermal neutrons in air reduces the beam intensity by 6 per cent per meter and also contributes significantly to background, it is worthwhile to evacuate collimators and provide beam pipes for distances of a meter or more in air. If evacuation is not feasible, filling with helium is nearly as effective.

If the beam has a significant fraction of reactor gamma rays and fast or epithermal neutrons, filtering of the beam through single crystals should be considered.[8,9] If the best obtainable crystals of bismuth, quartz or MgO are used and they are cooled to liquid nitrogen temperature to reduce thermal diffuse scattering, a high transmission for thermal neutrons can be realized along with a very large attenuation of gamma rays and fast neutrons. For example, a cooled single crystal of Bi 40 cm long should have a transmission of 0.1 to 0.3 for thermal neutrons, depending on the

degree of perfection of the crystal, while attenuating 2 MeV gamma rays and neutrons by 4×10^{-8} and 2×10^{-4} respectively.[10] The advantages of this are apparent when it is realized that the thermal neutrons remaining in the beam can be effectively and quietly stopped by less than 1 gm/cm^2 of $^6Li_2CO_3$, while the gamma-ray and fast neutron components of the beam could only be stopped by hundreds of times more material. The crystal filter also has the advantage that it can be situated in a very limited space and used with a rather divergent beam, while guide tubes, on the other hand, are only effective when they attain lengths of a number of meters, and the angular divergence of the beam is fixed by the critical angle for reflection, typically $\sim 0.15^o$ for thermal neutrons on nickel.

The excellent transmission of single crystal filters for thermal neutrons suggests that for (n,γ) experiments on targets with low capture cross sections, it might be advantageous, in a few favorable cases where the incoherent scattering is small, to fabricate the target from a single crystal. For such isotopes the limit on the thickness of the target which may be employed is usually set by the scattering of neutrons out of the beam by the target material, which in most cases has a coherent scattering cross section in the range of 3 to 10 barns. If the transmission of the target could be substantially increased, then a much thicker target could be utilized, and the number of capture events increased proportionately.

When the advantages of neutron guide tubes are considered, it is difficult to understand why they have not been more widely employed. Since the aperture depends only on the critical angle for reflection ($4\theta_c^2$ for a tube of square cross section) and reflection losses are small, typically one to two per cent per meter for nickel on glass, a beam of thermal neutrons can be transported with nearly undiminished intensity, for a considerable distance, while the undesirable, higher energy components in the beam obey the inverse square law. For long distances, a further improvement in beam quality can be achieved with the use of a curved guide tube, eliminating any direct path for contaminant radiations in the beam. For thermal neutrons, however, the radius of curvature must be so large that for an aperture with a typical width of say 2 cm, the length becomes, for most purposes, impractically long, the order of 50 meters. Nevertheless, the beam quality can be considerably improved with the use of straight quide tubes of modest length. For example, a guide tube of 2 cm square cross section 20 meters long will reduce the ratio of higher energy components in the beam to the thermal component by about 30. Both single crystal filters and guide tubes can be thought of as "low pass filters" which enhance the lower energy component of a neutron beam, each by a different mechanism. One additional advantage

they both afford is that since most thermal capture cross sections have a $1/\sqrt{E}$ dependence on neutron energy, for experiments in which there are limits on target thickness, such as, for example, in studies of the (n,α) or (n,e) reaction, the effective target cross section is increased by the weighting of the neutron beam to lower energies.

In a given situation factors such as initial beam quality, the experimental requirement for intensity and beam size, available space in the reactor hall, and the distance of the target from the source all enter into the design of the beam line, and there exists some optimum solution which may involve single crystal filters, a guide tube, or in some instances, both devices in combination. The important point is that with the proper use of these devices a very substantial improvement in beam quality may be realized, and in addition, a guide tube may afford a sizeable increase in beam intensity over a conventional geometrical collimator.

Proper design of both the detector shielding and the beam trap are also important. As in the case of collimators, they must be viewed not only as sinks for radiation but also as sources of background. For example, since some back-scattering of neutrons and other components of the beam is inevitable, not only should the beam trap be situated some distance behind the target, but it should also be designed so that the solid angle for the escape of scattered radiation from it should be as small as possible, i.e., the beam should penetrate via a deep, narrow channel well into the interior of the trap before it is stopped. In the case of detector shielding a number of processes occur which produce secondary radiation-- compton scattering, inelastic neutron scattering, slow neutron capture, x-ray fluorescence, and even accidental resonance fluorescence of iron capture gamma rays on lead. In extreme cases the placing of shielding near a detector may actually increase the background detected. Thus a thoughtful choice should be made of not only shielding materials, but also the geometry. While very compact shielding around a detector is efficient and economical, it may be a major source of background. The placement of the target and bare detectors in the middle of a large shielded gamma-ray "cave" or box, while usually more expensive, may give lower background, since the solid angle subtended by a detector for radiation scattered from the internal walls of the shield will evidently be less than in the case of a compact shield.

At the present conference there are several contributed papers which describe improved neutron beam facilities. One of these, by S. Sakamoto, describes the installation of a bent guide tube at the Kyoto University Research Reactor, a 5 MW swimming pool facility. The guide tube, of nickel evaporated on float glass, has a 1 x 7 cm cross section, a 10.8 m length, and a 833 m radius of curvature.

With these parameters, the tube is "tuned" for neutron energies somewhat below the peak of the thermal Maxwell-Boltzmann energy distribution. The beam has an intensity of $1.2 \times 10^6/cm^2$-sec and is effectively free of contamination from epithermal neutrons and core gamma rays. Capture gamma-ray studies utilizing a combined pair- and compton suppression spectrometer are underway at this facility.

An interesting example of the utility of a converging, focussing collimator is provided in a paper by F. Stecher-Rasmussen and W. Ratynski. They describe a 24 keV (Fe, Al, S) filter facility combined with a focussing collimator, which has been installed at the High Flux Reactor at Petten. The collimator consists of 90 plates, each 2m long, arranged so as to focus the beam on an area of 0.6 x 20 cm at a distance of about 5 meters from the source. The advantage afforded by this geometry is evidently very large, since each gap in the array is the equivalent of a single collimator. The 24 keV flux obtained at the target position is about 10^5 neutrons/cm^2 sec.

A paper by M.A. Lone and W.M. Inglis describes a carefully designed thermal beam facility at the NRU reactor at Chalk River. The source of neutrons for this facility is the thermal column of the reactor. The direct beam from this source may be used (flux $\sim 10^8/cm^2$.sec), or it may be brought through 15 cm long Bi and up to 30 cm long quartz filters cooled to 77°K, giving a flux of $\sim 10^7/cm^2$ sec. The Cd ratio of the filtered beam is in excess of 10^6. The use of a ^{6}LiF lining in the target tube and in the beam trap gives a very low beam-dependent background. It is possible at this facility to investigate the (n,γ) reaction on very low cross section targets. For example, capture gamma-ray spectra of high quality have been obtained for ^{17}O, for which $\sigma_c \tilde{<} 0.5$ mb.

III. THE BROOKHAVEN (n,e) SPECTROMETER

The usefulness of internal conversion data in nuclear structure studies utilizing the neutron capture reaction has long been recognized. A number of examples of the acquisition and utility of internal conversion data have already been described in an earlier paper at this conference.[11] Accordingly, we proposed sometime ago, the construction of a spectrometer for this purpose, and in 1972, about four years after work had commenced on the BILL (n,e) spectrometer at Grenoble, we received permission to proceed. In contrast with the situation at the ILL reactor, where provision had been made for an in-pile target geometry for the BILL spectrometer, the Brookhaven High Flux Beam Reactor had been designed primarily as a source of external neutron beams, so that the choice of a spectrometer to be installed at the HFBR was governed by the boundary conditions particular to the facility. These are:

1. The availability of a tangential beam tube in the D_2O moderator of 9 cm. inner diameter terminating near the reactor core. Two diverging neutron beams are brought out from this beam tube, one utilized for neutron diffraction studies of biological samples, and the other for the (n,e) spectrometer. The thermal neutron flux at the source is 6×10^{14} /cm^2 sec.

2. Space in the reactor hall for about 10 meters of beam line between the reactor and the spectrometer, and the necessity to place the spectrometer at nearly this distance from the reactor face in order to provide room for the neutron diffraction experiments sharing the beam port.

3. The presence of large quantities of structural steel and other sources of stray magnetic fields, and moderate background radiation from other experiments.

The beam tube configuration clearly calls for the use of an external beam, in view of the evident difficulty of target handling in the beam tube and the necessity to avoid perturbing the neutron beam utilized by the experiment sharing the beam port. Since this has a much smaller geometrical efficiency than the in-pile target configuration, both the beam transport and spectrometer should be as efficient as possible, even more so because the spectrometer must be placed several meters from the reactor face. These conditions require the use of a neutron guide tube rather than an ordinary geometrical collimator. The space available, however, is not sufficient to permit the use of a curved guide tube for thermal neutrons long enough to eliminate fast neutrons and gamma rays from the beam. Accordingly, a hybrid system was designed which employs both single crystal filters and straight guide tubes. The beam line consists of an initial 1.65 meter guide tube of polished nickel in the reactor beam plug, single crystal filters of quartz and bismuth, each 14 cm. long, cooled to 77°K, and seven one meter long guide tubes fabricated from float glass coated with vacuum evaporated nickel with an aperture 1.6 cm. wide and 5 cm. high. The latter were fabricated in Munich under the supervision of E. Steichele. The transmission of the crystal filter for thermal neutrons is $\sim$ 60 per cent, and the guide tubes provide a net gain of about 4 over an equivalent geometrical collimator. This beam line has now been installed and aligned. Au foil activation measurements give a neutron flux of approximately 10^9 /cm^2 sec at the spectrometer. Provision has been made for bringing a portion of this beam, up to 2 cm. in diameter, through the spectrometer to a well-shielded location where thermal neutron capture experiments can be conducted. Since most targets used in the spectrometer must necessarily be quite thin, only a small fraction of the neutron beam will be stopped in the spectrometer, and thus thermal (n,γ) experiments may usually be performed simultaneously with the

operation of the (n,e) spectrometer.

The choice of a magnetic spectrometer was governed by two considerations: The requirement for high efficiency, i.e., a large internal solid angle, and the presence of stray magnetic fields in the reactor hall. The latter preclude the use of an iron-free spectrometer, although such devices are otherwise highly desirable due to their high resolution and precision and readily calculable focusing properties. The magnet chosen was the "Colorado" $\sqrt{2}\pi$ double focusing design, first designed by A.A. Bartlett[12] at the University of Colorado. A similar spectrometer was subsequently installed at the Tristan facility at Iowa State University.[13] The performance of this device, as measured by the spectrometer luminosity (source area x solid angle) vs. resolution is actually superior to that of existing iron-free spectrometers.[14] An elevation view of the magnet is shown in Fig. 1. The design is characterized by a high vertical aperture, giving a maximum transmission of 5 per cent of 4π steradians, and an exterior, wrap-around, return flux path, which provides excellent shielding against exterior magnetic fields, eliminates problems associated with saturation of the iron, and provides, with the coils, about 25 cm. of radiation shielding. In order to make efficient use of the neutron beam available, the Brookhaven magnet was scaled up from the 30 cm. orbital radius in the Colorado and Iowa devices to 45 cm., giving an increase of 2.25 in luminosity. A schematic plan view of the magnet is shown in Fig. 2. It is designed to focus electrons from a maximum energy of 9 MeV down to as low an energy as is permitted by the counter window thickness, probably $\sim$ 20 KeV. This corresponds to magnetic fields in the range from 750 gauss down to $\sim$ 5 gauss. Consequently the most important property of the magnet is its low-field performance, in contrast to the situation with most research magnets, where the performance near saturation and a very high saturation induction are considered to be most important. For this reason, great care was taken in the selection of the iron for the magnet. Evidently, for the spectrometer to maintain good focussing at very low fields the remanent magnetization must be small. Furthermore, it is well-known that in large magnets the excitation of eddy currents is very detrimental to performance, since not only do the eddy currents decay with time constants as long as several minutes, impeding data acquisition, but they tend to concentrate near the surfaces of the pole pieces, producing a strong, non-uniform magnetization of the iron which may effectively destroy the desired focussing properties of the field. These problems are minimized if the iron is magnetically "soft", with a low coercive force, and if its electrical resistivity can be increased over that of pure iron. These properties are available in electrical sheet steel, but it is impractical to fabricate a magnet of the size and configuration required from this material. Instead, iron in bulk containing as

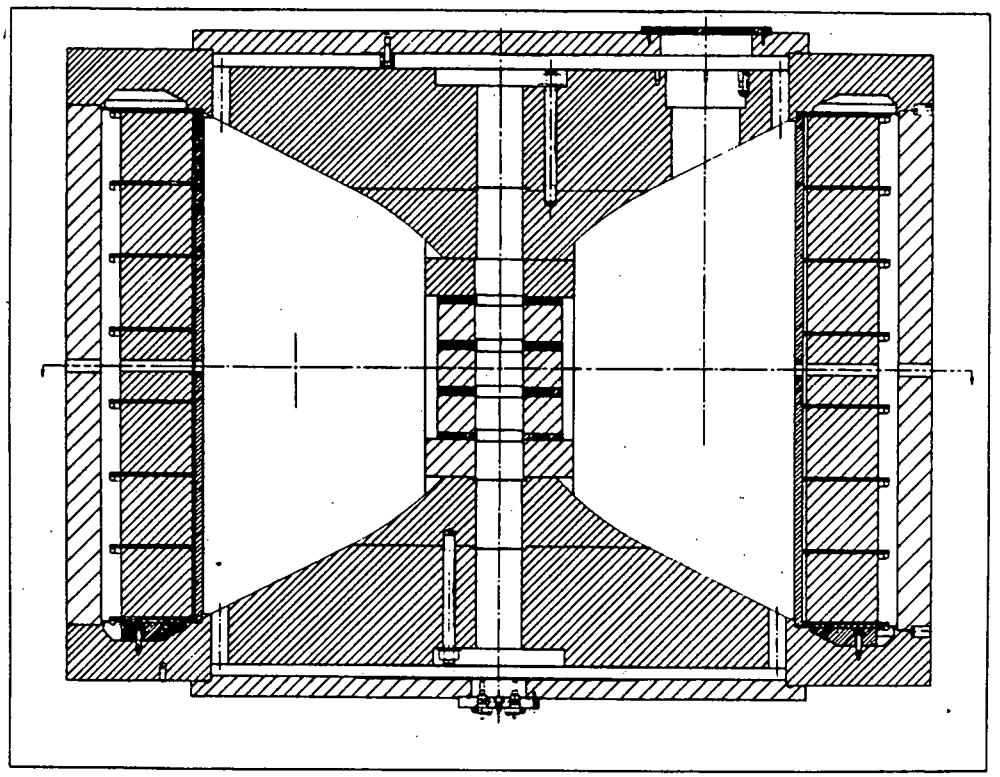

Fig. 1: Drawing of the "Colorado" design high vertical aperture double-focussing magnet employed for the Brookhaven (n,e) spectrometer.

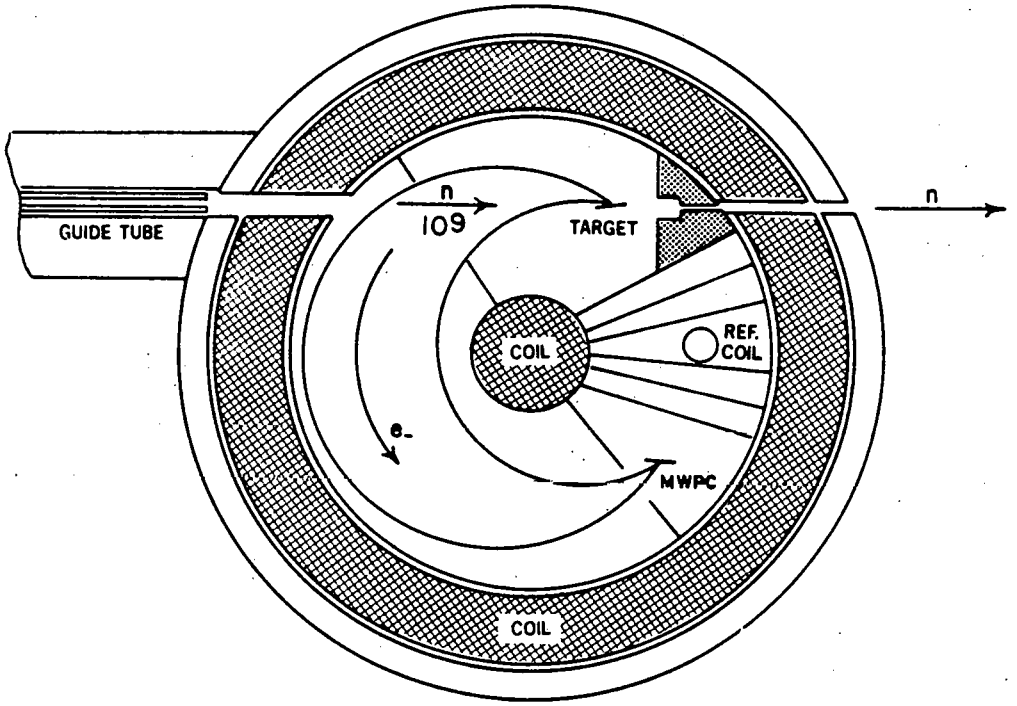

Fig. 2: Schematic plan view of (n,e) spectrometer illustrating guide tube and neutron beam, strip source, and multiwire detector.

little carbon and other light element impurities as possible and ∿ 2 per cent silicon was sought. This percentage of silicon reduces the resistivity by a factor of 4 and also improves the low-field properties of the iron, while reasonable mechanical properties of the iron are maintained. A problem arises, however, with the introduction of this much silicon in that the iron becomes extremely sensitive to thermal shock while cooling from a red heat. The fabrication of the iron for the pole pieces and yoke was undertaken by the VOEST-Alpine Co. in Linz, Austria. Difficulty was in fact encountered with the problem of thermal shock; the first pole-piece blanks shattered during flame cutting at the mill. Despite this setback VOEST-Alpine succeeded in producing sound material for the magnet essentially on schedule. The material produced contains 1.9 per cent silicon and 0.015 per cent carbon, and after special heat-treating, has a coercive force of ∿ 0.5 Oersted.

In order to obtain the most efficient possible performance of the system, two devices which greatly improve the performance of a double-focussing spectrometer are being incorporated. These devices, which rely on the use of electrostatic fields to correct for the effect of finite source width and of aberrations in the magnet, respectively, were devised by K.E. Bergqvist[14], and have been utilized in magnetic spectrometers in Sweden. The first device, the so-called "strip source", consists of a parallel array of up to 30 individual sources, each a tall narrow strip typical of the individual source ordinarily employed in a double focussing electron spectrometer. This source ordinarily must be quite narrow, since its extent in the radial, or dispersive direction of the magnet contributes to the instrumental peak width. This is evidently a severe disadvantage in a neutron beam experiment, since neutron beams cannot be focused on to a small area, as, for example, can charged particle beams. The strip source overcomes this difficulty by employing a large number of such sources. Each strip is connected to a separate point on a voltage divider, with a voltage, typically as much as 30 kV, applied to one end. In the absence of this voltage the spectrometer would produce an image of the entire strip source in the focal plane. With an appropriate voltage, which depends on the magnetic field, applied to the source, the electrostatic field provides a progressively larger increment of momentum to the electrons leaving each successive strip. This alters the radii of curvature of the electron orbits by a sufficient amount to cause the superposition of the images of all strips into one image in the focal plane which has essentially the width of one strip. In this way the luminosity of the spectrometer can be increased 30-fold with scarcely any loss of resolution. This method has already been employed in an (n,e) spectrometer at the R2 reactor in Studsvik, Sweden, by Backlin.[15] It is evidently feasible to combine the use of this electrostatic device with

preacceleration of low-energy electrons to overcome problems of counter window thickness. In addition to its utility in studies of the (n,e) reaction, the strip source should also make possible the study of the radioactive decay of very low specific activity sources, for example, certain naturally occurring isotopes, or long-lived isomers produced by thermal neutron capture, which have been impossible to investigate in the past, since the source thickness for a given amount of activity can now be reduced by a factor corresponding to the number of strips.

The second electrostatic device consists of a grid of electrodes, situated mid-way in the magnet between source and detector, which are maintained at a given electrostatic potential, again dependent on the magnetic field. Because of the shape of the grid, this device is known as the "harp". The grid is arranged so that a transverse impulse of momentum is given to an electron which depends on the distance that its orbit is off-axis. This impulse is just sufficient to correct for the second order aberration in the focussing, which depends similarly on the deviation of the orbit from the optic axis. The harp is closely analogous to a Schmidt corrector plate in a spherical telescope. It improves the luminosity of the spectrometer by a factor 3 for a given resolution; thus the strip source and harp together lead to a 100-fold increase in the spectrometer efficiency. Since the electrostatic field of the harp is essentially a perturbation which can be adjusted independently of the magnetic focussing properties of the spectrometer, it is logical first to optimize the magnetic focussing and then bring about a further improvement with the aid of the harp. In the case of the Colorado spectrometer, very good focussing is readily achieved for a very large vertical aperture but the resolution worsens rapidly with increasing radial aperture, so that the harp should be very useful in overcoming the effects of radial aberrations.

The spectrometer possesses an additional advantage, a focal surface which permits the use of an extended detector, rather than the single, narrow slit commonly used in earlier experiments. For this purpose a multiwire proportional counter has been constructed in the Brookhaven Instrumentation Department under the supervision of J. Fischer and H. Okuno. The counter is two-dimensional. Anode wires spaced 3 mm. apart run horizontally and are connected to a resistive readout circuit. These provide coarse-grid position information in the vertical (non-dispersive) direction. Cathode conductors are spaced 2.5 mm. apart and are connected to a delay-line readout, giving position information in the horizontal (dispersive) direction. This system is capable of very high position resolution. Tests with a highly collimated 200 micron wide source of 6 keV X rays showed no perceptible broadening of the position peak beyond that expected from the geometrical width of

the source. The sensitive area of the counter is 5 cm. high and 10 cm. long. This provides a momentum bite $\Delta p/p$ of 5 percent, permitting, for example, for most transitions, the counting of all three L-conversion peaks at one field setting. The use of this detector gives an improvement in spectrometer efficiency of at least 50 over point-by-point counting with a conventional detector. The two-dimensional feature of the counter is also useful in correcting for certain aberrations which introduce a small curvature into the image of the source in the focal plane, and clearly will greatly facilitate tests of focussing for a variety of conditions.

Both the control of the spectrometer and the initial data acquisition and storage are performed by a Digital Equipment Corp. PDP 11/40 minicomputor. The two-dimensional position information from the multiwire counter is routed through digital-to-analog converters and an interface to the computer, when it can be stored and processed in various arrays. The spectrometer field is controlled by a method which has become standard for double focussing spectrometers.[16,17,18] A known current is provided from a stable, programmable power supply to an iron-free solenoid placed in an unused portion of the magnet gap. For a desired field setting this current is specified by the computer and programmed via a 15-bit digital-to-analog converter. This provides a stable and reproducible field against which the field of the main magnet is compared. The probe of a flux-gate magnetometer is placed inside the solenoid, serving as the null-detecting element in a closed-loop servo system which controls the main magnet power supply. The current in the main magnet is adjusted until a null is achieved, indicating exact cancellation of the field of the solenoid and main magnet. This system evidently avoids problems of hysteresis in the iron; it is capable of achieving a stability of a few parts per million for 8 hours.[19] The electrostatic devices are also programmed in an open loop system by the computer.

A detailed comparison of the performance of the Brookhaven spectrometer with others will be possible only after it has been put into operation and some experience in its use has been acquired. The most nearly comparable system, embodying an external neutron beam, a double focussing spectrometer, and strip source, was installed by Backlin at the R2 research reactor at Studsvik, Sweden.[15] That device was capable of obtaining useful results for targets with capture cross sections in the range of several hundred barns. While similar in concept, the Brookhaven system possesses a number of additional advantages -- a large magnet aperture, multiwire counter, electrostatic focussing correction, and intense, high quality neutron beam -- which should give it an efficiency two or three orders of magnitude greater than that of the Studsvik device. A comparison with the high-performance spectrometer BILL at Grenoble is less straightforward because of

the very different configurations of the two devices. The BILL spectrometer enjoys a very high efficiency because of its internal target geometry and has very high resolution and precision. It does, however, suffer from very high background, which places severe demands on the stability of the system. Moreover, the hostile environment of the site of the target precludes the study of a number of chemical elements. The high quality neutron beam available to the Brookhaven (n,e) spectrometer should minimize background, and the external target geometry permits a wide choice of targets. The lower limit for the detection of an individual internal conversion peak should be in the range of a few hundred microbarns partial cross section. The large aperture of the magnet and target accessibility may also permit some lifetime and coincidence measurements to be made, and isomeric transitions with lifetimes down to one millisecond may be observed by chopping the neutron beam. We expect that the Grenoble and Brookhaven (n,e) spectrometers will to a great extent play complementary roles in studies of the (n,e) reaction.

At this time the installation and alignment of the beam transport system is complete and the installation of internal devices in the magnet is in progress. We expect to conduct tests of the magnet control system and the focussing properties of the magnet in the immediate future. The system should be ready for initial experiments in three to six months. As soon as our (n,e) spectrometer is in routine operation we would like to urge interested members of the nuclear physics community to consider the possibility of carrying out experiments there. Flexible arrangements can readily be made for work at our facility by outside users.

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