A FACILITY FOR STUDYING NEUTRON ENERGY SPECTRA AT INTERMEDIATE ENERGIES

Charles D. Goodman,* Charles C. Foster,** Mark B. Greenfield,+ Charles A. Goulding,+ David A. Lind,++ and Jacobo Rapaport+++

Abstract

Apparatus for measuring neutron energy spectra in the 50-200 MeV range is described. The apparatus, installed at the Indiana University Cyclotron Facility, consists of a beam swinger to change the angle of incidence of the beam on target, 100 m flight paths, large, subnanosecond neutron detectors, and a system for deriving phase stabilized timing signals.

I. Special Problems of Measuring Neutron Energies

Nuclear reactions leading to neutrons in the outgoing channels can provide important and sometimes unique information about nuclear energy levels and the nucleon-nucleon interaction, but because of the technical difficulties of measuring neutron energy spectra with good resolution, such reaction studies have been underexploited. Briefly stated, the problem is that, since the neutron is electrically uncharged, precision tools of nuclear spectroscopy, namely the magnetic spectrograph and the solid state detector, cannot be used. Neutrons can be detected by way of the charged particle recoils or charged reaction products produced when neutrons scatter from or are absorbed by other nuclei. Unfortunately, the energy signals thus produced are not proportional to the neutron energy unless a particular process is singled out, e.g., scattering from protons at a definite recoil angle. Proton recoil spectroscopy has been exploited to some extent for measuring neutron energies,[1] but the method is limited in its detection efficiency. The solid angle for detection of the recoils must be severely limited and the target must be thin in order to maintain good resolution.

The most successful technique exploited to date for measuring neutron energies is time of flight. That technique obviates the need for a detection signal proportional to the neutron energy, but it creates the need for precise time signals and long flight paths.

Figure 1 illustrates the energy resolution obtainable for 1 ns and 0.5 ns time resolution as a function of neutron energy for 50 m and 100 m flight paths. As will be discussed, the time resolution obtainable with existing accelerators, in particular the Indiana Cyclotron, is better than 1 ns and worse than .1 ns. The range of energy resolutions shown in fig. 1 is representative of the present state of the art. For high precision spectroscopy, flight paths of at least 100 m are desirable. These values for time resolution and path lengths set the scope of the technical problems of measuring neutron spectra at Indiana Cyclotron energies. The following discussion is divided into three sections to describe solutions to three problems: 1) long flight paths cannot reasonably be swung around the target; another method of changing the angle of observation must be used. 2) At large distances the solid angle subtended by typical detectors is very small, so detectors must be made large and 3) the accelerator time reference must be stablizied as well as possible. The ways in which we have handled these problems are discussed in the following sections in the above mentioned order.

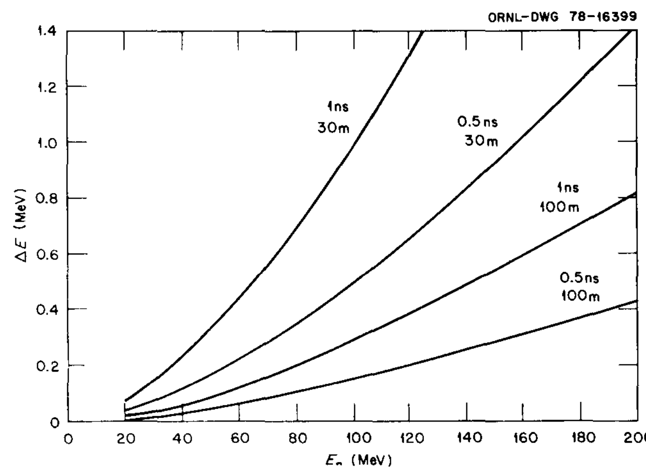

Fig. 1. Energy resolution as a function of neutron energy.

II. Beam Swingers

When the flight path is long it is generally not feasible to measure angular distributions by moving the detector around the target. This is true not only because of the large space required but also because the flight paths must contain carefully placed shielding to insure that the detector sees neutrons only from the target. In addition, the range of high energy protons in air is sufficient to allow scattered protons from the target to reach the neutron detector (the range of 124 MeV protons is 100 m in air). A magnet is necessary near the beginning of the flight path to sweep the scattered protons out of the path.

Bending magnets to change the angle of incidence of a beam on a target and thereby to change the effective scattering angles for fixed flight paths have been used at several laboratories. At Livermore[2] an 18° bend can be inserted or removed to shift the effective angles of a large number of detectors by that amount. At Oak Ridge, Greenfield[3] placed a target on a movable support inside a bending magnet to provide a range of possible scattering angles with a fixed flight path.

At Colorado a complete beam swinger system has been built that provides complete 360° rotation of the angle of incidence of the beam on target.[4] The Colorado system consists of two magnets mounted on a rotatable cradle. The axis of rotation is along the original beam direction. The first magnet bends the beam away from the axis and the second magnet bends it back to recross the original axis at a right angle. The target is placed at the recrossing point. As the plane of the magnets is rotated about the original beam line, the angle of incidence is changed. The new scattering plane is vertical. A similar

*Oak Ridge National Laboratory, Oak Ridge, TN 37830.
**Indiana University Cyclotron Facility, Bloomington, IN 47401.
+Florida A and M University, Tallahassee, FL 32307.
++University of Colorado, Boulder, CO 80309.
+++Ohio University, Athens, OH 45701.

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system has been constructed at Michigan State University.[5]

The present system originally built at Oak Ridge National Laboratory and now modified and installed at the Indiana University Cyclotron Facility employs three magnets which remain fixed. The geometry is illustrated in fig. 2. The first magnet bends the beam away from its original path and the second magnet bends it back towards the target. The pole faces are large enough to accommodate a range of paths that impinge on the target over a range of angles.

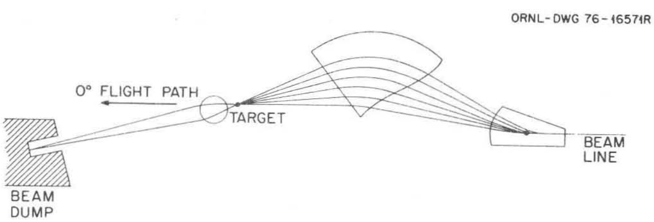

Fig. 2. Magnet layout for beam swinger

The third magnet steers the beam into a dump. The use of the third magnet allows the beam dump to remain fixed as the angle is varied. This is an advantage at high energies since massive shielding is required around the dump to keep the neutron background low. The third magnet also makes it possible to observe neutrons at 0° scattering angle where certain important nuclear processes are most readily observable.

The first and second magnets were designed for use in Oak Ridge with 65 MeV protons and a 45° angular range. The layout and the shape of the pole of the second magnet were chosen so that the radius of curvature in the second magnet is constant for all paths. This condition insures that the system is always horizontally focusing and that the beam spot will not wander off the target if a small adjustment is made in the field of the first magnet to make a small change in angle. The special pole edge shape was achieved with a specially cut pole shim that is attached to the straight edge of the pole itself.

In order to accommodate the higher rigidity particles (up to 200 MeV protons) at IUCF, the angular range had to be reduced and the layout was changed. The original pole shim was retained, however. In the compromise geometry the angular range is 26° and some variation in the radius of curvature of paths in magnet 2 is tolerated.

The operating conditions can be parametrized in terms of the radii of curvature in the two magnets, ρ_1 and ρ_2, as functions of the scattering angle θ. Thus, to set the system for a given angle, one looks up $\rho_1(\theta)$ and $\rho_2(\theta)$ in a table and sets the fields B_1 and B_2 to correspond to the magnetic rigidity, $B\rho$, of the incident particle.

Figure 3 shows $\rho_1(\theta)$ and $\rho_2(\theta)$ as measured with the floating wire technique. Although $\rho_2(\theta)$ departs considerably from being constant we feel that this will not cause operational problems and we do not plan to cut a new shim for the Indiana geometry. Although the focusing conditions vary somewhat with angle, ion optics calculations show that the beam spot will always be contained within a 1 cm diam circle for all angles without readjusting the quadrupoles.

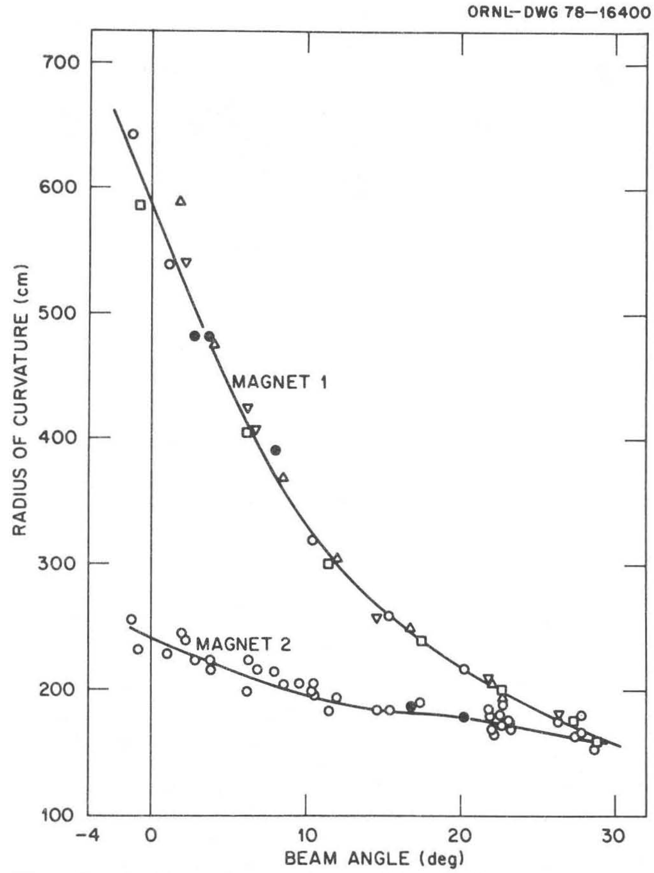

Fig. 3. Radius of curvature of trajectory as a function of angle of incidence of beam on target.

The angle is measured with a motor-driven slit on an arm that pivots around the target position. The slit is used only while the beam is being focused and the angle measured. The slit is retracted during data runs to avoid neutron background from it.

Figure 4 shows the floor plan of the cyclotron and beam swinger. The swinger is placed at the north end of the building to allow the use of long flight paths outside the building. Placing the swinger so far from the cyclotron introduces a spread in transit times of the protons due to their energy spread. Beam transport calculations lead us to believe that the increase in the spread is insignificant. With a nominal value for the phase space volume of a beam bunch the calculations show that the time width is 177 ps at the first quadrupole, 183 ps at the entrance to Magnet 1 and 186 ps at the target.

The choice of the non-moving magnet design rather than a larger version of the Colorado system was made in part because the low beam height and low ceiling at the original location at the Oak Ridge Isochronous Cyclotron precluded the mechanically swinging design. In the new setting at IUCF the Oak Ridge design has even more important advantages. Because all the magnetic bends are in the same plane as the cyclotron, the beam swinger can be used with polarized protons without solenoids to rotate the polarization as the scattering angle is changed. A second advantage is that with a horizontal scattering plane multiple flight paths can be used with all detectors at ground level regardless of the path length.

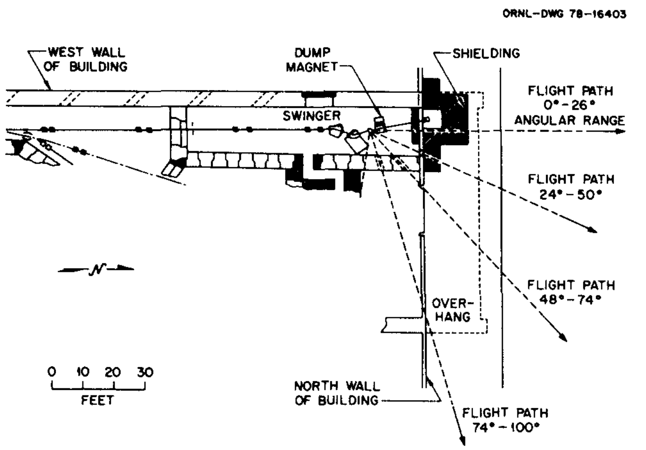

Fig. 4. Floor plan for beam swinger at IUCF.

III. Detectors

To establish a scale of reference for comparison with charged particle spectroscopy, consider that a 50 mm^2 (typical) solid state detector at 22 cm (typical) from the target subtends about 1 msr. At 100 m, the same solid angle would imply a detector area of 10 m^2. The problem is further exacerbated by the fact that neutron detectors are less than 100% efficient. The obvious imperative is to make detectors as large as possible, but one must be careful not to degrade the time resolution in the enlargement, lest one lose faster than one gains by requiring yet longer flight paths to compensate for the loss of time resolution.

The attainable time resolution for neutron detection with rf timing is about 0.5 ns. Light travels about 10 cm in plastic scintillator in 0.5 ns. Therefore, we cannot ignore the time distribution introduced by the range of geometrical light paths when the scintillator has a dimension comparable to or larger than 10 cm. In general, if the scintillator is large, the measured time of detection of a neutron depends on the position at which the scintillation event occurs. Since we must make detectors larger than those for which we can ignore position effects, we are left with two possibilities, 1) measure the scintillation position and record it along with the time data for later correction, or 2) use a compensation technique.

We are not now equipped to handle the complexity of recording both the position and time, so we are using analog compensation techniques. One form of time compensation is described in detail elsewhere.[6,7] We provide a brief description here.

In a long scintillator the light path length, s, from a scintillation to the phototube depends on the angle, θ, that the ray makes with respect to the scintillator axis. If x is the axial distance to the phototube, $s = x/\cos\theta$, and the time, $t = nx/c \cos\theta$, where n is the index of refraction, and c is the velocity of light in vacuum. The light begins to arrive at time $t_o = nx/c$ and, were the light flash instantaneous, would continue to arrive until $t_{max} = nx/c \cos\theta_{max}$, where θ_{max} is the angle at which total reflection no longer takes place at the scintillator surface (see ref. 6). The light arrival profile is altered by the finite decay time of the phosphor (about 2.4 ns).

Figure 5a shows how the light arrival profile changes with scintillation position. The parameters assumed are n = 1.6, the scintillator length is 1 m and the decay time 2.4 ns. Tilting the detector with respect to the neutron direction alters the relative time displacements of the curves for different positions. In particular, we can choose the tilt angle so that the curves for different positions start at the same time point as shown in fig. 5b. Physically, what has been done is to choose the ratio of neutron path to photon path so that the summed times are independent of position. Under this condition, which can apply exactly only for a particular neutron energy, one achieves detection pulses that have the correct time origins, but have different shapes. It is then necessary to compensate for discriminator triggering time variations that occur as a result of shape differences.

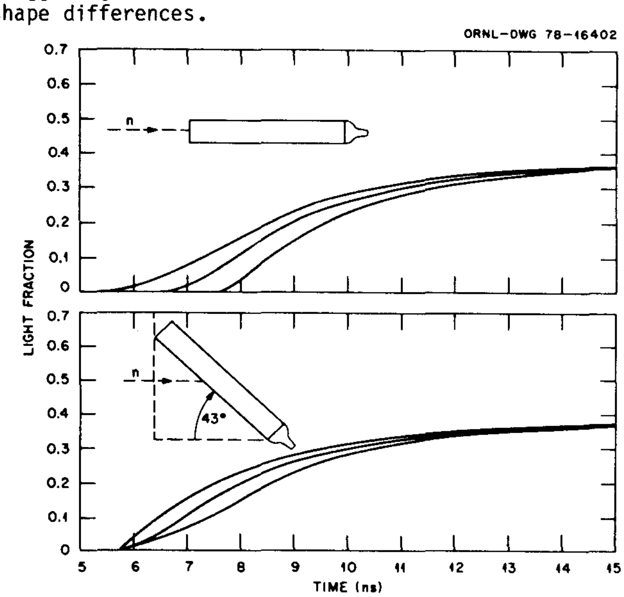

Fig. 5. Light arrival profiles for head on and tilted scintillator orientations.

It can be shown that constant fraction timing is not logically correct in such a situation and we use, instead, what we call quadratic extrapolated zero timing. To understand this extrapolation, consider a Fourier series expansion of the pulse shape. The height as a function of time can be written as

$$h(t) = A_o + A_1\cos(t/a) + A_2\cos(2t/a) + \ldots\ldots$$

where we have ignored terms in sin(nt/a) because we require that $h(o) = (dh/dt)_o = 0$. If the risetime is near the bandwidth limit,

$$h(t) \approx A\,[1 - \cos(t/a)],$$

which for small t is $h(t) \approx A(t/a)^2$. This expression can be inverted to $t(o)\ t(h)-[t(4h)-t(h)]$, which is independent of both A and a. We obtain t(o) experimentally by using two discriminators set respectively at h and 4h and generating analog signals for the lower level crossing time and the time difference with time-to-amplitude converters and subtracting the difference signal from the lower level signal. A block diagram of the electronics is shown elsewhere.[7]

We have achieved subnanosecond time resolution with tilt compensation and quadratic extrapolated zero timing with a 15 x 15 x 100 cm scintillator viewed by a single 5" phototube. Folding in the efficiency, we find that such a scintillator has an effective area

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for 100 MeV neutrons of about 10^{-2} m^2, so we are still a factor of 10^4 smaller than the 1 msr example at 100 m. However, we can stack several detectors. Two such detectors that we have already used make many experiments possible.

IV. RF Timing with Phase Drift Compensation

The absence of an electric charge on the neutron rules out the possibility of detecting the neutron twice to time its flight between two points. We must instead use a bunched proton beam and a single detection of the neutron at the end of its flight path. The timing uncertainty then cannot be smaller than the bunch width. In practice we find that phase drifts are much larger than the bunch width.

In principle we could derive a time signal from each bunch from an electromagnetic pickup. However, with beam currents between 10-100 na, pickup signals are weak and noisy. In contrast, a timing signal can be derived very cleanly and precisely from the rf signal. We have chosen to derive the basic time signal from the rf and provide a phase correction to compensate for phase drifts between the accelerating voltage and the proton bunches.

The Indiana Cyclotron is a three stage system consisting of an ion source, a preaccelerator cyclotron and the main stage cyclotron. In normal operation there are 4-6 bunches per orbit in the cyclotrons. The time separation of the bunches is too small for time of flight use with long paths, so we must eliminate all but one bunch per orbit. Unless single turn extraction can be achieved, the only satisfactory mode of operation is one bunch per orbit, because other modes spill protons into unwanted time buckets.

A pulse selector and buncher are located on the beam line between the ion source and the first cyclotron. Selection is accomplished by sweeping the beam across an aperture in a lissajous figure. To achieve one bunch per orbit, the beam is swept in a circle with a subharmonic of the cyclotron frequency, f_0. Because of the small tuning range of the sweeper, the frequency must be close to f_0, so it is necessary to use, for example, $(3/4)f_0$ or $(5/6)f_0$ for 1 of 4 or 1 of 6 selection respectively. These choices of sweeping frequencies, unfortunately make it impossible to take full advantage of the phase acceptance of the buncher while still maintaining clean rejection of unwanted bunches. Therefore, when the ion source output limits the maximum beam, the beam loss due to pulse selection is greater than 3/4 or 5/6, for example.

The time reference for the time-of-flight system is taken from a phase coincidence between the f_0 signal from the cyclotron master oscillator and the subfrequency. Thus, the time reference is locked to the bunch injection time. If the magnetic fields on the two cyclotrons were perfectly stable, the proton transit time through the accelerator system would be constant and the time reference would be completely valid. In reality, drifts of the order of a few nanoseconds occur, and compensation is essential for subnanosecond resolution.

The compensation method we have chosen is illustrated in fig. 6. Scattered protons are detected with a fast scintillation counter. A proton signal triggers a discriminator which generates a pulse with a width of about 1/2 the rf period. This pulse opens a diode bridge current gate. If the opening time is centered about the crossover point of the rf sine wave, the net charge passing through the gate is zero. However, if there is a phase drift, the net charge is no longer zero, but may be positive or negative depending on the direction of the drift. The output of the gate is integrated with a time constant of about 1 sec, and the integrated output is used as an error signal into a phase shifter that shifts the phase of the rf signal going to the stop pulse generator.

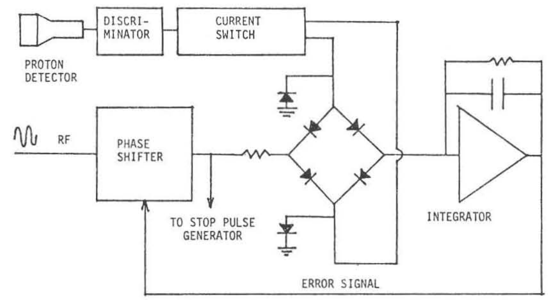

Fig. 6. Block diagram of phase drift compensator.

With this form of time compensation and the detectors described above, we have observed overall time resolution in neutron spectra of 0.8 ns FWHM. We hope to improve the time resolution somewhat by more careful trimming of our electronics.

V. Conclusions

The technical difficulties special to neutron spectroscopy can be overcome in a reasonable way using a beam swinger, large detectors, and phase stabilization. We have built apparatus for neutron spectroscopy which promises to provide us with better quality data than had been heretofore obtainable.

Acknowledgements

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** DISCUSSION **

R. BONDELID: Did you consider the use of a passing horn to set your timing signal for the proton beam burst?

C. GOODMAN: Yes. Ed Kowalski has designed electromagnetic pickups to derive phase signals from the passing beam. Such pickups can give a good measure of the time averaged phase of the beam bunches. We used a proton detector because it was easy.

T. CAHILL: Do you plan to use the prompt gammas for timing purposes?

C. GOODMAN: Perhaps. Our new beam dump has a hole through which a well shielded gamma ray detector can see the gammas from the Faraday cup. We plan to try the gamma signal as a phase reference.

H. BLOSSER: How does your "quadratic zero" timing system compare with a Munich-style system which puts phototubes at both ends of the neutron detector and averages the arrival time?

C. GOODMAN: Quadratic extrapolated zero timing reduces the time walk from position and amplitude variations. With phototubes at both ends of the scintillator it is desirable to use extrapolated zero timing at both ends. With phototubes at both ends it is also possible to obtain position information and to remove the position time walk in a computer. That is, however, a more complicated scheme of unproven value. Time averaging of the kind you speak of is applicable only to transverse scintillators which are too thin to contain the recoil tracks. That condition is undesirable both for threshold setting and for signal to background ratio.

P. MILLER: Can you tell us the reason for the drift of the timing signal with respect to the beam pulse when feedback from the proton detector is not applied?

C. GOODMAN: Our time reference is tied to the injection of the bunch into the first cyclotron. Very small drifts in the magnetic fields can cause changes in the overall transit time as large as we observe. We think the phase drifts are caused mainly by field drifts.

M. CHAUDHRI: It is generally very difficult to measure neutron spectra below 1-2 MeV. On the other hand, there is a great deal of need to know neutron spectra accurately down to the lowest possible energies. Does your special set-up for neutron spectrometry allow measurements below 1-2 MeV?

C. GOODMAN: No. Our emphasis has been on developing apparatus to enable us to measure high energy neutron spectra. For low energy one should use short flight paths and long separations between beam bursts. Low energy neutron spectroscopy is a well-developed technology.

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