designated as (5), however, the strongest line by far is the L_5, shown by legend in Fig. 2. The accompanying K line is very much weaker, although the gamma-energy is about 30 kev above the K threshold. Perhaps this energy difference is not sufficient to allow for maximum probability of K-electron emission.

Mr. R. G. Shreffler and Mr. A. D. Weaver assisted very materially in this investigation.

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Neutron Cross-Section Studies with the Rotating Shutter Mechanism*

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It has been possible to extend the usefulness of the rotating shutter mechanism of Fermi, Marshall, and Marshall for velocity selection of neutrons by increasing the number of photoelectrically activated gate circuits. With the modifications here described data can be obtained simultaneously in six well-resolved velocity intervals. In this way the cross sections of gold, gadolinium, and dysprosium have been measured as a function of velocity for low energy neutrons.

1. INTRODUCTION

AN improved velocity-selector system for low energy neutrons, giving data for six energy intervals simultaneously, has been built around the rotating shutter used by Fermi, Marshall, and Marshall.[1] The shutter consists of a series of laminae, alternately 0.006-in. thick cadmium and 0.030-in. thick aluminum, mounted axially inside a thin cylindrical steel case. As this is rotated in a neutron beam (with its axis perpendicular to the beam), two bursts of neutrons are released per revolution. Neutrons reaching a detector some distance away are registered on different scaling circuits according to the time elapsed since the shutter was open (i.e., the time of flight of the neutron). The detector used in these experiments consisted of a suitably shielded proportional counter filled with BF_3 enriched in the B^{10} isotope. The general form of the apparatus is shown in Fig. 1.

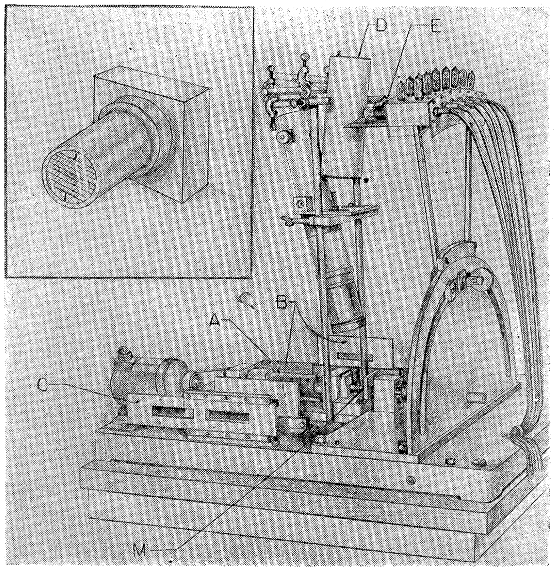

FIG. 1. Rotating shutter neutron-velocity selector. *A*—shutter; *B*—slits (cadmium); *C*—sample holder; *D*—light source; *E*—photo-cells; *M*—mirror. Insert—shutter, showing cross section. Dark areas—cadmium; crosses—aluminum; outer case—steel.

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* This report is based on work done under the auspices of the Manhattan District at the Argonne National Laboratory, the University of Chicago in 1945–1946. The information contained in this document will appear in Division IV of the Manhattan Project Technical Series as a part of the contribution of the Argonne National Laboratory.

[1] E. Fermi, L. Marshall, and J. Marshall, Phys. Rev. **72**, 193 (1947).

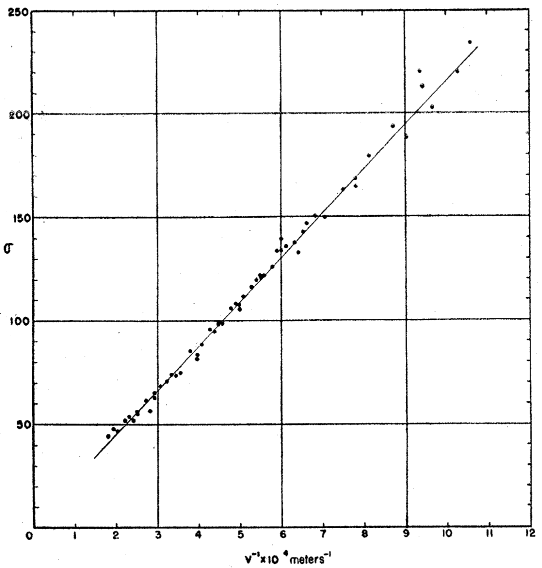

FIG. 2. Total slow-neutron cross section of gold as a function of energy.

To measure the rate of revolution and to actuate the gate circuits for registering the neutrons, a double mirror is mounted on the end of the rotating shutter at an angle of 45° to the laminae. The light beam reflected by this mirror from a strong tungsten source falls, successively, on seven photoelectric cells mounted 4° apart on a carrier whose position can be varied about the axis of the shutter. Six of these are used to open the gate circuits at known time intervals after the shutter is opened. The time intervals are determined by the angle through which the light beam rotates and its angular velocity, which is twice that of the shutter. The seventh photo-cell operates a special electronic tachometer to measure the rate of rotation of the shutter.[2] The rate used is 180 revolutions per second except for data for very slow neutrons, which are taken at 60 r.p.s. As the tachometer compares these rates to the line frequency it is possible to hold the shutter speed within 0.5 percent of the desired value and thus contribute no appreciable error to the measurement of neutron velocity. The gate circuits are each held open electronically for 31 microseconds (4° rotation of the light beam,

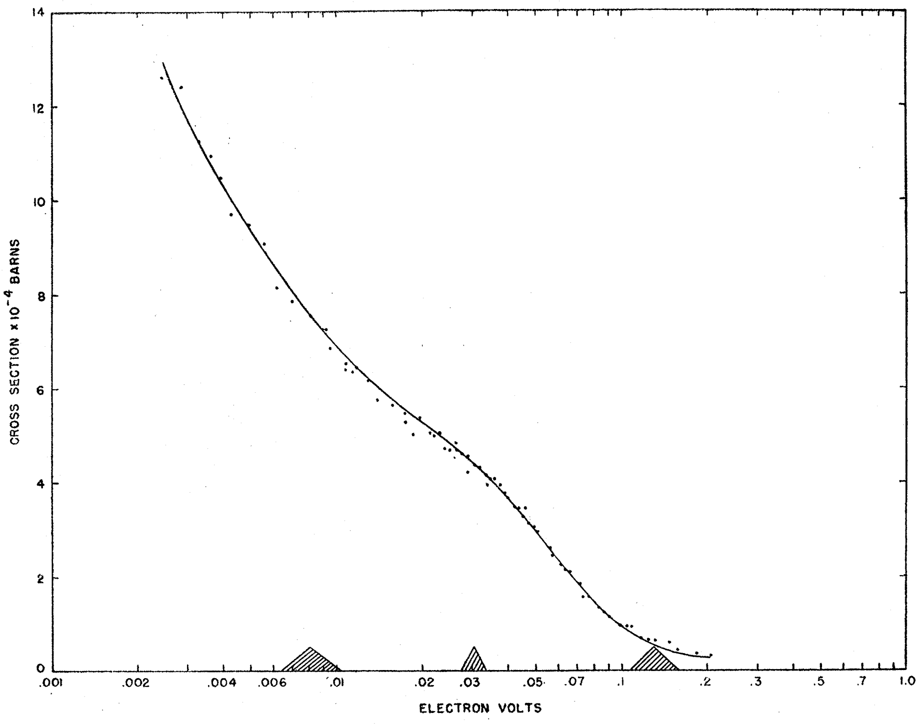

FIG. 3. Slow-neutron cross section of gadolinium. Plotted points are experimental values; solid curve, Breit-Wigner relation with $\sigma_0 = 45{,}000 \times 10^{-24}$ cm^2, $E_0 = 0.028$ ev, $\Gamma = 0.118$. Triangles show resolution width of instrument.

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[2] A separate photo-cell is not necessary for this purpose—the signal from any of the others could be used.

or 2° rotation of the shutter at normal operating speed). The shutter itself is open (partially or completely) for about 3° of its rotation.

2. EXPERIMENTAL PROCEDURE AND RESULTS

In use, this instrument is set up before the thermal column of the Argonne heavy-water pile and a collimated beam of slow neutrons is allowed to fall upon the rotating shutter. The sample is placed in its holder with appropriate cadmium collimating slits. The counter, in a heavy boron shield, is set up with its axis parallel to that of the shutter and at a measured distance from it (usually 1.5 meters). A transmission measurement is then made for the particular energies as determined by the photo-cell position settings. The background is measured by stopping the shutter with the light beam striking the photo-cell corresponding to the desired energy and counting the total output of the detector (without the gate circuits). Knowing then the gate time, the background may be taken quite accurately in a short time. The photo-cell positions are then reset and the procedure repeated.

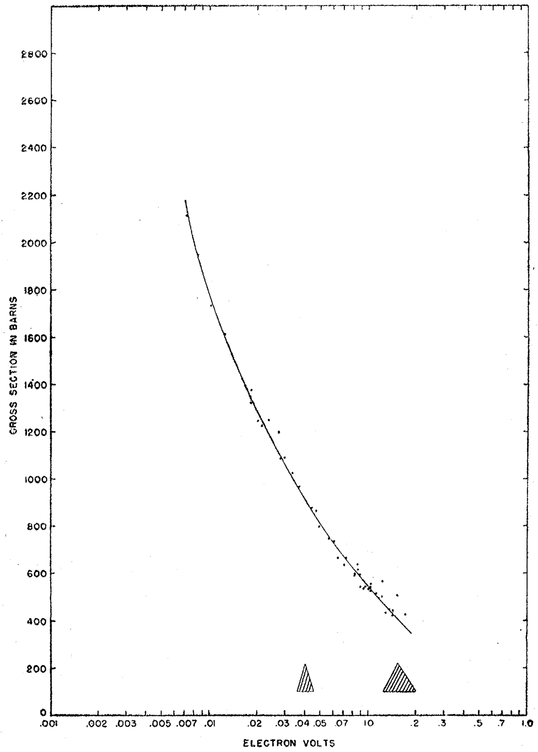

FIG. 4. Slow-neutron cross section of dysprosium. Triangles show resolution width of instrument.

A. Gold

The transmission of a gold plate 1.674 g/cm^2 in thickness was measured over a range of neutron velocities of 900 to 5700 meters per second. Total cross sections (Fig. 2) calculated from these transmissions show a very slight departure from a 1/v behavior, possibly due to the wing of the resonance level[3] at 4.8 ev.

A measurement of the transmission of the gold sample, standardized in this manner and made in the flux of polyenergetic neutrons emitted by the thermal column, indicated a resultant cross section of 100×10^{-24} cm^2/atom. This corresponds to an effective velocity of 2200 m/sec. for neutrons in equilibrium with graphite at room temperature.

B. Gadolinium[4]

Very accurate quartz cells were made up and filled with known heavy-water solutions containing various amounts of gadolinium. The transmission of the cell containing gadolinium was compared to that of a similar cell containing only the heavy water. These measurements were made in the region from 0.002 ev to 0.2 ev. The observed cross sections—the plotted points on Fig. 3—showed a resonance at about 0.028 ev. The Breit-Wigner relation with the constants $\sigma_0=45{,}000\times 10^{-24}$ cm^2, $E_0=0.028$ ev, and $\Gamma=0.118$ ev is drawn in as a solid line. These values are not in agreement with those reported by Borst, Ulrich, Osborne, and Hasbrouck;[5] however, as has been pointed out[5,6] this energy lies in a region where second-order effects cause considerable difficulty in measurements made with the crystal spectrometer.

C. Dysprosium[4]

The cells used in the measurement of the gadolinium cross section were cleaned and filled

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[3] J. Rainwater and W. U. Havens Jr., Phys. Rev. **70**, 154 (1946).

[4] These elements had previously been studied in the energy region above 0.04 ev with the aid of the crystal spectrometer by W. J. Sturm. Paper to be published.

[5] L. B. Borst, A. J. Ulrich, C. L. Osborne, and B. Hasbrouck, Phys. Rev. **70**, 557 (1946).

[6] W. J. Sturm and S. Turkel, Phys. Rev. **70**, 103(A) (1946).

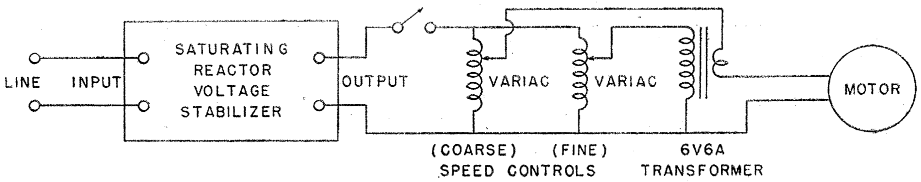


FIG. 5. Speed-control circuit.

with solutions containing dysprosium. This cross section was measured in the energy region from 0.007 to 0.15 ev (Fig. 4). No resonances were found; however, the cross section deviates somewhat from a 1/v behavior, indicating a resonance somewhere in the low energy region.

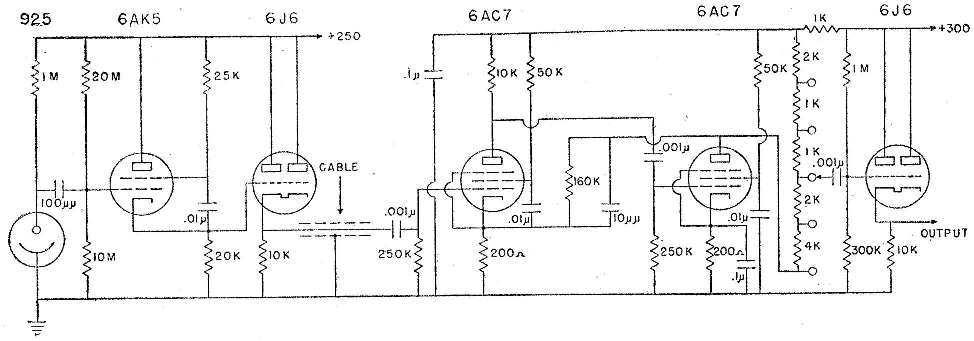
3. DETAILS OF THE INSTRUMENT

The shutter, mounted on ball bearings, is belt-driven by a high speed, series-wound grinder motor. The speed is controlled by varying the motor voltage, and a saturating, reactor-type voltage stabilizer minimizes the effects of varying line voltage upon speed. Vernier control is provided, as indicated in Fig. 5.

Type 925 vacuum photo-cells were used in this experiment. A type 6AK5 tube, mounted close to each photo-cell and used as a cathode follower with its screen by-passed to cathode, prevented capacitive loading of the photo-cell. This was followed by a type 6J6 cathode follower to drive the cable to the amplifier. As the photo-cell signal was only about 10–20 millivolts, a gain of about 500 was necessary in the amplifier used. The photo-cell and amplifier system for one channel is shown in Fig. 6.

The instrument has been simplified and improved since this experiment was performed by replacing the photo-cells with type 931-A multiplier cells. This eliminates the need for any voltage amplifier and for the double cathode-follower preamplifier—only the 6J6 is now used. In addition, excellent signal-to-noise ratio can be obtained with only a conventional galvanometer lamp as a light source instead of the much larger source previously used. A voltage of 450 volts—or 50 volts per stage—on the dynodes of the 931-A gives signals of 8–15 volts. This system is shown in Fig. 7.

Figure 8 shows one gate circuit. The first trigger pair, operated by the photo-cell signal, provides uniform pulses for the second, which is self-timed. This insures that the "on" time of the second is independent of the input signal. The gate tube itself is a twin cathode follower with separate inputs and a common output. As the cathodes essentially "follow" the more positive grid, a negative signal from the second trigger pair opens the gate by allowing the cathodes to follow the other grid, which receives negative pulses from the counter amplifier. A cathode follower prevents loading the gate tube,



Ω = OHMS
K = THOUSAND OHMS
M = MEGOHMS
μ = MICROFARADS
μμ = MICROMICROFARADS

FIG. 6. Early photo-cell and amplifier system (one channel).

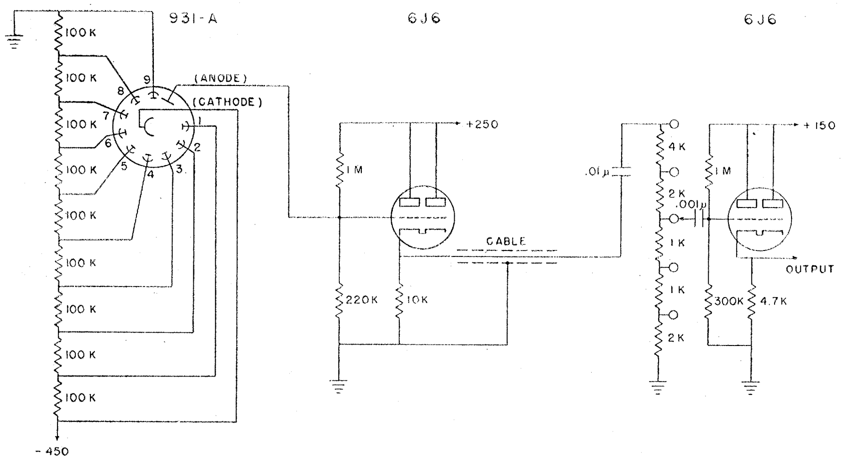


FIG. 7. Improved photo-cell and amplifier system.

and an output trigger pair provides a convenient signal for the scaler. To eliminate any dependence of the gate time upon line voltage, the power for the gate-determining trigger pairs is regulated—the plate supply electronically, and the heater supply by a 6.3-volt constant-voltage transformer.

The tachometer unit (Fig. 9) consists of a direct-reading electronic frequency meter and an oscilloscope tube having, on a 60-cycle circular sweep, a spot of light corresponding to each photo-cell pulse. Thus, if the shutter speed is a multiple of 30 revolutions per second (30 rather than 60 because the mirror has two faces) a set of spots appears to stand still on the face of the oscilloscope, one spot for 30 r.p.s., two for 60 r.p.s., and so on. If the shutter speed is not quite an exact multiple of 30 r.p.s., the ring of spots appears to rotate with a velocity proportional to the difference between the actual speed and the exact multiple. Thus, very accurate measurement of the shutter speed is possible.

The frequency meter is a trigger pair passing a fixed quantity of charge per photo-cell pulse. The resulting (averaged) current operates a meter, which registers the shutter speed directly

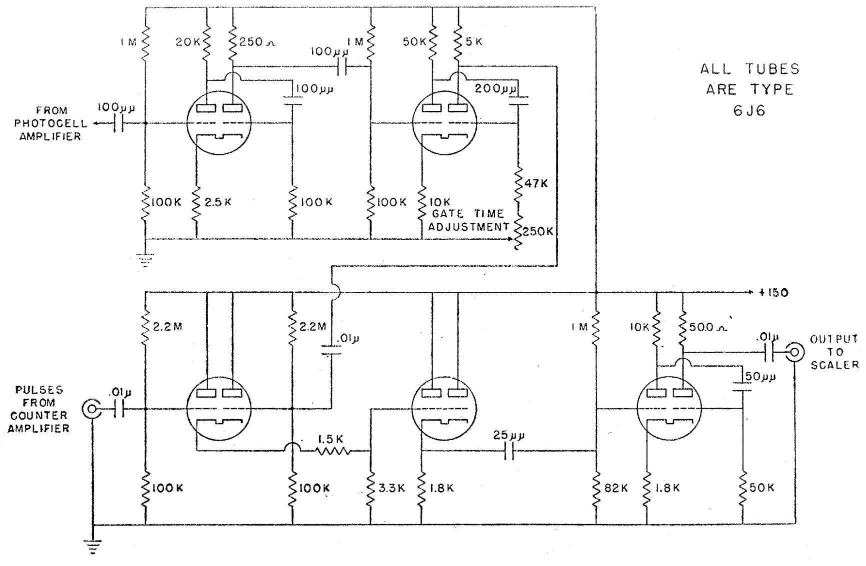


FIG. 8. Gate circuit.

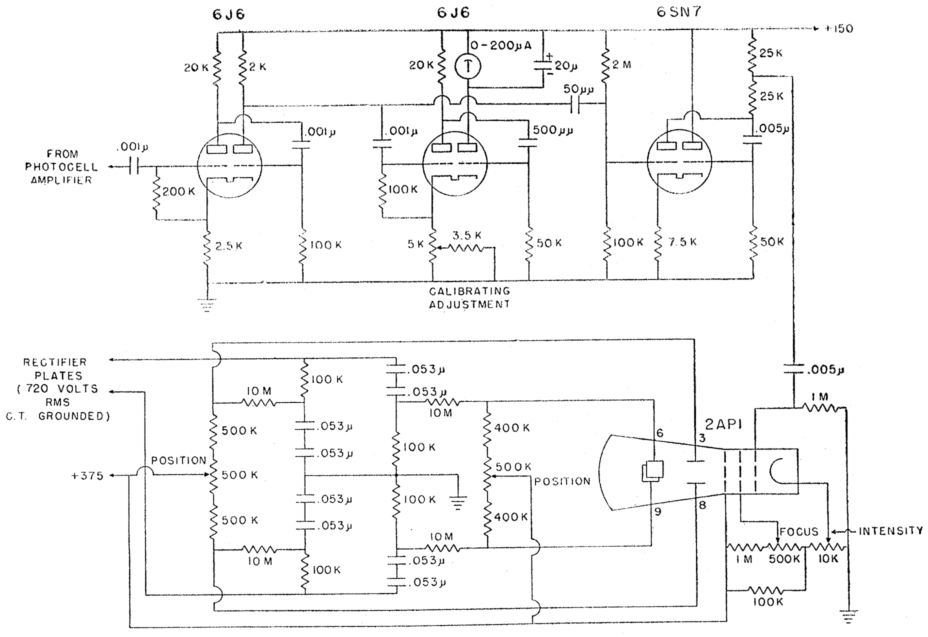


FIG. 9. Electronic tachometer.

in revolutions per second. Here, as in the gate circuits, an input trigger pair is used to eliminate any change in the pulse width of the self-timing trigger pair, and regulated supplies prevent dependence upon line voltage.

Another improvement (added since the experiments described were performed) is a synchronizer unit to "lock" the shutter to the line frequency. An iron bar on the end of the shutter rotates between the poles of an electromagnet fed with 60-cycle pulses. At present, the magnet coil is merely plugged into the line so that the synchronizer works only at 60 r.p.s. (and lower). It is planned to power this magnet with short duration pulses (1 or 2 milliseconds) synchronized with the line frequency so that the shutter speed can be locked to any multiple of 30 r.p.s.

The authors are indebted to the Ryerson Shop for its excellent machine shop work, to the Optical Shop for manufacture of the accurate quartz cells, and to the operating personnel of the Argonne pile for their cooperation and assistance in performing these experiments.

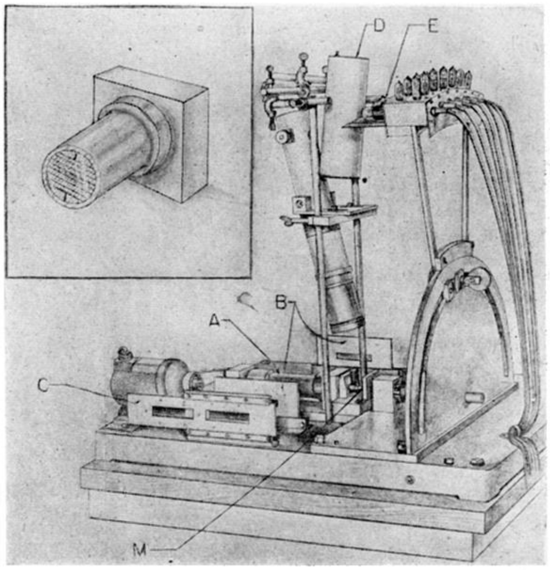


FIG. 1. Rotating shutter neutron-velocity selector. *A*—shutter; *B*—slits (cadmium); *C*—sample holder; *D*—light source; *E*—photo-cells; *M*—mirror. Insert—shutter, showing cross section. Dark areas—cadmium; crosses—aluminum; outer case—steel.