ing only. This shows that the S-wave scattering is of the magnitude expected from a Yukawa or exponential potential with the parameters fixed by the low-energy scattering. Figure 11 gives a comparison of the data with distribution curves to be expected from the potential proposed by Christian and Noyes.[22] It has been suggested that the discrepancy in the 90° values between the curves and the experimental point is not too important since a slight change in one of the available parameters could shift the curve vertically without any considerable change of shape. However, it is seen that the shape of the singlet square well plus triplet Yukawa tensor interactions is not satisfactory. The shape of the Gauss error potential plus triplet tensor interactions is satisfactory.

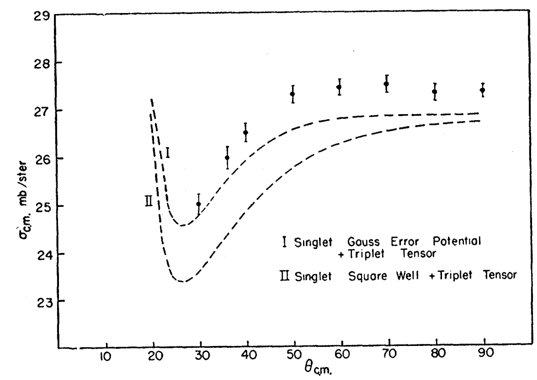

FIG. 11. Comparison of the experimental data with the potential proposed by Christian and Noyes (see reference 4).

ACKNOWLEDGMENTS

We are indebted to Dr. G. Breit for several very helpful discussions both on the experimental procedure and the interpretation of the data. The theoretical distribution curves given in Figs. 7, 8, and 9 were checked by Dr. M. H. Hull, Jr., Miss Smolen, Dr. Thaler, and Mr. Bengston. The assistance of Dr. J. C. D. Milton in the earlier stages of this work and of Mr. K. W. Brockman, Jr. in the taking of the data is gratefully acknowledged.

Most of the equipment was constructed in the shops of the Palmer Physical Laboratory. We are heavily indebted to the technical staff of the laboratory for their cooperation and many helpful suggestions.

[22] We are indebted to Dr. R. Christian for the calculation of the theoretical curves.

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Time-of-Flight Measurements on the Inelastic Scattering of 14.8-Mev Neutrons*

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Measurements have been made of the energy spectra of neutrons inelastically scattered from 14.8 Mev into the interval 0.5–4 Mev. Carbon, aluminum, copper, tin, and lead scatterers were used. 100-kev deuterons were extracted from a cyclotron and allowed to strike a target of tritium absorbed in zirconium. The resulting reaction $T^3(d,n)He^4$ (17.7 Mev in the center-of-mass system) yielded a 14.8-Mev neutron accompanied by a recoil 3-Mev alpha particle. A scintillation counter within the vacuum system, subtending a solid angle of $4\pi/100$ at the target, detected recoil alpha particles with ∼100 percent efficiency, delivering a fast signal whenever a neutron started on a path within a cone chosen to avoid scattering material for a distance of several meters. Within the cone and close to the target a scatterer was placed. The inelastically scattered neutrons emerged from the scatterer with approximate isotropy, while few elastically scattered neutrons were deflected through large angles. A proton-recoil neutron counter placed at ∼90° to the cone axis was thus prevented from detecting almost all undesired neutrons. The distance from the scatterer to the counter was 50 to 100 centimeters, and neutron energies were obtained from the measured flight times over this path length, with the recoil alpha signal serving as a time zero. The flight times, which were from 20 to 65 millimicroseconds, were measured by a time analyzer having nine 4.7×10^{-9} second channels, recording directly on mechanical registers. Experimentally, neutron energies after scattering could be approximated by number/unit energy $E=E\exp(-E/T)$ with T, the "nuclear temperature" in Mev obtained from the raw data being: Pb, 0.75; Sn, 0.62; Cu, 0.84; Al, 1.06; C, 0.93. These results are in general agreement with photographic plate data. The experimentally observed angular distributions were isotropic within the limits of error of ∼15 percent. Over-all limits of error of ±15 percent in the nuclear temperatures are assigned.

1. INTRODUCTION

IN studies of the internal structure of nuclei, measurements of inelastic neutron scattering (INS) are especially useful. Since neutrons do not interact with the Coulomb fields of nuclei or with atomic electrons, their scattering is a measure of nuclear properties alone and can be interpreted with few ambiguities.

In a complete inelastic scattering experiment, nuclei would be bombarded by monoenergetic neutrons, and the energy distributions of all subsequently emitted particles would be measured as functions of the angle from the incident neutron direction. For bombarding energies between 0.5 and 15 Mev, in all but the lightest

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elements, charged particle or gamma emission is far less probable than the emission of one or two neutrons, followed by gamma rays from the decay of nuclei which are not of sufficient excitation to emit more neutrons.

Compound-nucleus models are based on the assumption that in any inelastic interaction the incoming neutron very quickly shares its energy with all or most of the nucleons in the target nucleus, forming an excited state which lasts for a time long compared with the transit time ($\sim 10^{-21}$ second) of a neutron through the nucleus. When this state finally decays, the emerging particle has a direction uncorrelated with the incident neutron direction. The emergent particle energy depends only on the matrix element for the transition from a bound to a free state, and on the density of available final states for the excited nucleus and the free particle.

This experiment was designed to check the compound-nucleus model at the high bombarding energy of 14 Mev, where, if anywhere, this model should be a good approximation. If all or a large number of the nucleons participate in the scattering process, and if they act as Fermi particles within a potential well of nuclear size, it can be shown[1-3] that the outcoming neutrons should have approximately the energy distribution $dN/dE = Ee^{-E/T}$, with T a constant for a given nuclide and excitation. In this energy distribution, with T between 0.5 and 1 Mev, most of the outcoming neutrons have energies between 0.5 and 5 Mev.

In the present experiment, only one excitation energy (14.8 Mev + the binding energy of one neutron) was used for each element. Thus changes in T with excitation were not measured. There was some evidence of the alternative shell-model mode of interaction in neutrons above 5 Mev, but resolution was not good enough to permit measurements on these neutrons. The experimental accuracy was also insufficient to allow the detection of effects due to $(n,2n)$ interactions.

2. METHOD

Measurements of neutron energy spectra in the Mev region are relatively difficult, since the individual neutrons can only be detected through their infrequent interactions with nuclei. Of several possible techniques for neutron energy measurement, that of time-of-flight (TOF) offers certain advantages and the following disadvantages.

(a) In the Mev region, flight times are very short, of the order of a few $\times 10^{-8}$ second for dimensions of the order of a meter.

(b) Since $dE/E = 2dt/t$, measurements of the flight time must be made with twice the relative precision of the resulting energy measurement.

(c) Two measurements on the neutron must be made, to establish the zero as well as the arrival time. In practice, it has been customary to use a pulsed neutron source to establish the time zero. For the required very short pulses, heavy and complex equipment is required. In the method to be described, the time zero is obtained without pulsing, and this disadvantage is avoided.

(d) The energy *vs* flight time conversion is very nonlinear, high energies being compressed to a small range of flight times.

Against these disadvantages, the TOF method can be made to have high efficiency, high resolution if intensity and background problems are overcome, and an energy sensitivity that is relatively easy to calculate. It is inherently clean since energy is measured in terms of the fundamental dimensions length and time.

For the experiment described here, the TOF method, in conjunction with a specific reaction for neutron production, was chosen. The technique[4] was: 100-kev deuterons were extracted from a cyclotron and used to bombard a T-Zr target. There the reaction $T + D \rightarrow n + He + 17.7$ Mev (center of mass) yielded 14.8-Mev neutrons accompanied by 3-Mev recoil alpha particles. A scintillation counter within the vacuum system, subtending a solid angle of $\sim 4\pi/100$ at the target, detected recoil alphas with nearly 100 percent efficiency. The alpha signals thus supplied a time zero for 14.8-Mev neutrons and selected only those neutrons having directions within a cone free, for several meters, of all material except air, the vacuum chamber walls, and the desired scatterer. Within this cone a scatterer (S) was placed. The neutron counter, containing an organic scintillator, was placed outside the coincidence neutron beam, at a large angle from the cone axis so that most of the elastic scattering was avoided.

The advantages of this technique are:

(1) The time zero is obtained without the use of a pulsed neutron source, and with an uncertainty dependent only on electronics and on the alpha-path geometry.

(2) A beam of neutrons having a known and controllable direction is obtained without the use of absorbers and collimators. Thus the neutron beam is still monoenergetic after its direction is defined.

The disadvantages are:

(1) A practical restriction to machine-made neutrons, in particular to those neutrons made in two-body reactions with energetic recoils.

(2) Restriction to thin foils or gases as neutron-source targets.

(3) A limit on the source intensity, and so on the amount of data taken in a given time. This limit exists because one type of background, random n-α coincidences, has a component proportional to the square of the neutron detection rate. Although not serious in the experiment discussed here, such a limit might become important in measurements on scattered neutrons be-

[1] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[2] D. B. Beard, Phys. Rev. **94**, 738 (1954).
[3] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).
[4] G. K. O'Neill, Phys. Rev. **92**, 853 (1953).

tween 5 and 14 Mev. A way of getting around this limit is discussed in Sec. 12.

3. APPARATUS

The target assembly (Fig. 1), placed at the end of a 36-inch snout on a small cyclotron, was provided with a beam collimator and a small metal door, operable through a vacuum seal. This door, when closed, shut off the target from the deuteron beam, and simultaneously exposed the alpha scintillator to a weak 5.3-Mev polonium alpha source. The scintillator,[5] 40 mils thick, was masked to $\frac{7}{8}$ in.$\times 1\frac{1}{8}$ in. by a brass plate and covered by a 1.09 mg/cm^2 bronze foil to stop scattered deuterons. Pulse-height spectra taken in the illustrated geometry showed a well resolved peak for the Po-alpha test source. The 5819 alpha counter was placed at the end of a 6-in. light pipe, so that a magnetic field could be maintained across the vacuum chamber. Such a field (*ca* 300 gauss) was used for a time to shield the alpha counter from the tritium beta rays, but improvements in electronics finally reduced the beta background to 500–1000 counts/second, and the magnet was removed to minimize scattering material.

The neutron counter (Fig. 1) was required to be large in volume for maximum counting rate and to be hydrogenous.[6] The housing was aluminum. Teflon (polytetrafluoroethylene) gaskets were used, since it was found that O-rings were attacked by the scintillator. Organic scintillators are strongly nonlinear, giving only weak light output for heavily ionizing slow protons, so there was also a light collection problem. At the time of construction of the counter, the high current photomultipliers (type 4646, etc.) were experimental and not yet fully reliable, so the large area type 5819's were used with subsequent distributed amplification. All three photomultipliers were operated at 1200–1500 volts, with equal dynode-to-dynode voltages and doubled photocathode-first dynode voltage. Experiments showed, however, that variations in the transit time of electrons from the photocathodes was still the most serious source of uncertainty in the entire time measuring process. The time resolution width due to transit time effects goes as (voltage)$^{-\frac{1}{2}}$, so that large area high voltage tubes would have helped this situation only slightly.

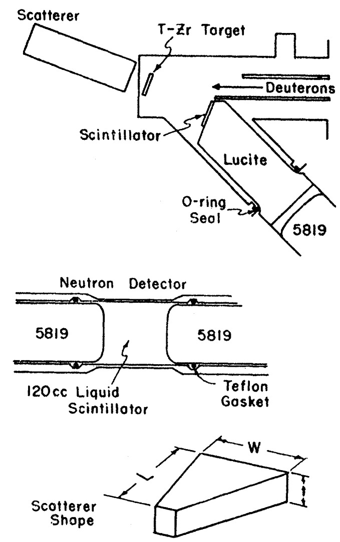

FIG. 1. Target assembly, neutron detector, and scatterer shape. (Sec. 3.)

The scatterers (Fig. 1) were made with $L\approx W$, $L\approx\lambda$, $t\approx\frac{1}{4}\lambda$, λ being the inelastic mean free path for 14-Mev neutrons experimentally observed in the photographic plate work of Graves and Rosen.[3] An upper limit of 17 cm on L was, however, set to avoid uncertainty in the time zero due to the 14-Mev neutrons' flight time through the scatterer. Dimensions for the five scatterers used are given in Table I.

TABLE I. Scatterer dimensions.

Element	Source	t (cm)	L (cm)	W (cm)	Density
C	Pile graphite	5.4	15.4	17.5	1.59
Al	2*S* (99% pure)	5.1	16.2	17.9	2.73
Cu	Electrolytic	2.5	10.0	9.8	8.99
Sn	Chemically separated ingot	3.9	15.1	13.6	7.40
Pb	Electrolytic	2.9	9.3	10.0	10.7

4. ELECTRONICS

In the design of the electronics, it was necessary to insure:

(1) Maximum speed (rise rate) of the fast pulses so that the time measurement could be made with the greatest possible precision.

(2) Easy and unambiguous measurement of all singles counting rates so that random coincidence backgrounds could be separated in measurements of the total background.

(3) Easy measurement of the minimum neutron counter pulse height accepted by the electronics, a quantity needed in the calculation of the (energy dependent) neutron sensitivity.

(4) Maximum discrimination against undesired signals. The process to be measured contributed only about 1/10^4 of the counting rate in each neutron detecting photomultiplier, so that every advantage afforded by coincidence requirements had to be taken.

To achieve these ends, discriminations, counting rate, and efficiency measurements were made by stable slow circuits (rise times $\sim 0.2\times 10^{-6}$ second). Each fast circuit was operated at a gain sufficiently high that all pulses accepted by the slow circuits were also accepted by the fast elements. The register chronotron, which made the actual time measurements, was designed in such a way that every neutron-alpha pulse pair falling

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[5] Plastifluor-B, Larco Nuclear Instrument Company.
[6] Scintillator mixing formula:

0.04 g/liter	diphenylhexatriene	(spectrum shifter)
3 g/liter	*p*-terphenyl	(scintillator)
1 liter	phenylcyclohexane	(carrier).

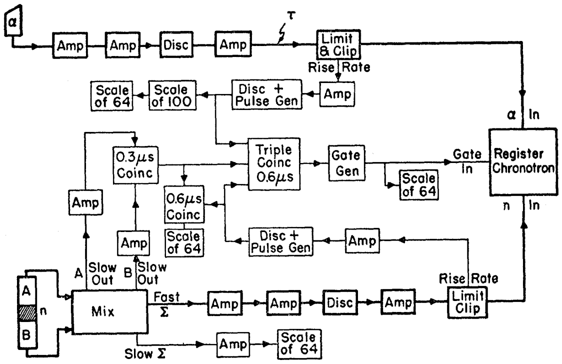

FIG. 2. Electronics, with fast (3-millimicrosecond rise time) circuits heavily outlined. The slow circuits have rise times of 0.2 microsecond. Each of the fast amplifiers has a gain of 10, each slow amplifier a gain of 10^4. (Sec. 4.)

within a 40-millimicroseconds range and accepted by the slow circuits produced one and only one register impulse. With this arrangement of the electronics, the fast neutron and alpha gains could each vary by ± 50 percent without changing the over-all counting efficiency for neutrons.

In the block diagram (Fig. 2) fast circuits are indicated by heavy lines. The chronotron will be discussed in the following section.

The alpha particles, having energies of about 2.2 Mev at the scintillator, were in the energy range of complete saturation (i.e., pulse height proportional to range and independent of energy loss). They produced pulses equivalent to electrons of about 40 kev. Thus high amplification was required in the alpha line. The signals passed through two distributed amplifiers (each with voltage gain of 10) to a fast discriminator of constant impedance. This device stopped all signals below a certain height V and passed all larger signals after subtracting V from their heights. It was designed so that signals of all heights, above or below V, were terminated in the characteristic impedance of the signal cable, thus preventing unwanted reflections and the pileup of many small pulses. This discriminator removed most of the tube noise, the pickup from the 8-Mc cyclotron rf, and most of the beta signals. After one more amplifier, the signals arrived at the chronotron pretreatment unit. Here their rise rate (volts/millimicrosecond) was measured by an RC network, and a tube carrying 50 mils was cut off to provide a positive 5-volt signal, clipped by a 65-cm shorted stub. A stretching circuit imposed a 1-microsecond dead time after the initial pulse to cut out ringing due to amplifier saturation or mismatch, and to remove after-pulse signals from the photomultiplier. Delay cables were inserted at τ (Fig. 2) to slide the chronotron's time zero to desired points. The impedance was 170 ohms throughout the fast line from the alpha 5819 to the register chronotron.

On the neutron side, signals observed by 5819's A and B were fed to a mixer. There the individual signals were sent to high impedance slow amplifiers and were added linearly to provide a third output (slow Σ) for monitoring and pulse-height analysis. These slow outputs were obtained without loading the input pulses. A fast addition of the A and B signals was also made, followed by moderate RC clipping (25 millimicroseconds) to prevent amplifier saturation. The rest of the fast circuits were nearly identical to those in the fast-alpha line.

The slow circuits operated as follows: alpha signals exceeding a fixed rise rate initiated uniform blocking oscillator pulses, which were applied to a triple coincidence circuit and simultaneously monitored for counting rate. Similar neutron-initiated signals were applied to the lowest input (Fig. 2) of this circuit. The individual A and B signals were sent through slow amplifiers to a faster coincidence circuit having pulse-height discriminators on its inputs. The output of the AB coincidence circuit led to the middle input of the triple coincidence circuit. An output of the latter unit fired another blocking oscillator (Gate Gen.) whose signal was used by the chronotron to initiate the various internal gate wave forms it required. Thus a gate fed to the chronotron implied:

(1) Fast rising pulses on both neutron and alpha lines.

(2) The presence of a neutron-side signal not due to photomultiplier noise.

In addition, the counting rates of alphas and AB coincidences were continuously monitored.

5. REGISTER CHRONOTRON

The chronotron, whose function of precise time interval measurement was basic to the entire experiment, was largely a new design but contained elements of a number of ideas found in the literature of fast electronics. It has been described in detail in an article, not yet published, for another journal.

Basically, the chronotron consisted of two fast-delay lines, one for the neutron and one for the alpha signal, arranged side by side with the neutron and alpha signals traveling in opposite directions. At intervals of 2.3 millimicroseconds on each line, a 6BN6 coincidence tube grid was attached. There were ten such tubes. When a pulse pair arrived, about three or four of the 6BN6's gave output signals, the largest indicating the point on the fast delay lines where the neutron and alpha signals most nearly met. These 6BN6 outputs were coded in time, amplified, and suitable circuits measured the position of the largest coincidence signal. After decoding, one of nine mechanical registers, each corresponding to a 4.7-millimicroseconds interval, fired. A tenth (Σ) register fired also, once for each pulse pair measured. The channel boundaries were stable to within 3×10^{-10} second. It was an essential property of the design that each channel register impulse corresponded to one and only one detected event in the neutron counter.

In order to test and adjust the chronotron, a sliding double pulser was built. This consisted of a wire-wound delay line with an internal grounded metal core. The coil was wound on threaded polystyrene tubing, had a length of 30 cm and a delay of $\sim$1.5 microsecond/cm. The ends of the delay line were connected through an impedance matching network to cables which could be plugged into the chronotron's pretreatment unit inputs. A fast rising pulse, supplied by a thyratron or by a mercury switch, was introduced to the delay line by a sliding tap, whose position could be adjusted and read to 0.5 mm by a lead screw and a fixed 30-cm scale. Thus by moving the sliding tap through a 15-cm distance, the time difference between test pulses could be moved without jitter through the chronotron range of 40 millimicroseconds. The additional 15-cm range of adjustment allowed testing the behavior of the chronotron on pulse pairs falling just outside its nominal range and allowed movement of the whole time scale by the insertion of cables.

The calibration of chronotron channel widths and the absolute time measurements were made with the help of lengths of 170-ohm coaxial cable, fitted with standard cable connectors. The delay per unit length in these cables had been measured to $\sim$1 percent in another experiment by Weil and Luckey.[7] The physical length of each cable was measured, and the electrical length calculated using the conversion factor measured in the experiment mentioned above. The delay introduced by the connectors was measured directly, and, as a further check, several pairs of these cables were compared for electrical length.

The chronotron time scale was measured in the following way: using the sliding double pulser, the pulser position for each of the ten channel boundaries was measured to $\sim 3\times 10^{-10}$ second. One of the standard cables was then inserted between the pulser and the pretreatment unit, sliding each of the 10 channel boundaries by the same fixed amount. After a remeasurement of the boundaries, the process was repeated with a different length of standard cable. Four such measurements were performed. None of the four results differed by more than 3 percent from the average value of 4.7×10^{-9} second/chronotron channel, and indicated a delay of 0.5 ± 0.1 millimicrosecond for each cable connector. Other measurements with the sliding double pulser confirmed the absence of gaps between channels of the chronotron. In the neutron energy measurement, five changes of the chronotron time zero were made to cover an interval longer than the chronotron total width and to average out small variations in individual channel widths. Thus the γ-ray peak, from which the time zero was obtained, and the neutron peak were measured in the same chronotron channels, so that the absolute time measurement depended mostly on the standard cables, relatively little on the chronotron channel width measurement.

6. ERRORS 1—BACKGROUND

Backgrounds may be divided into two groups, arising from scatterer-in and scatterer-out processes. The first group consists of register counts in the INS time region which are not the result of the desired process, single inelastic scattering in S, but which do depend on the presence of the scatterer. This background is difficult to measure and must, in general, be computed. The following processes contribute to it:

(1) Multiple scattering in S. Elastic processes contributed to a spread in the time resolution (by changing the total path length in S) but did not change the measured energy spectra. However, after a first inelastic scattering, a neutron might suffer a second. Assuming a constant INS cross section and a plane infinite slab geometry, the probability of a double INS was calculated by numerical integration. For this geometry, the only parameter required in the calculation was t/λ, the ratio of the slab thickness to the inelastic scattering mean free path. The probability that after a first inelastic scattering at a depth x, a neutron would emerge without suffering a second was calculated as a function of x for various t/λ. For the scatterer thicknesses used in this experiment, the fraction of once-scattered neutrons suffering a second scattering was found to be nearly $t/2\lambda$. Using the λ measured at 14 Mev by other experimenters,[3] the fraction of double scatterings was calculated to be 0.10–0.15. However, the most probable neutron energy after a first scattering is quite low ($\sim$1 Mev) and the INS cross section is known to decrease rapidly with decreasing energy. Thus an estimated upper limit of 5 percent on the double scattering ratio is reasonable.

(2) Processes in which a neutron scatters once in S, and again in nearby material (target assembly, cyclotron, floor, or walls). The nearest walls were at a distance of about 3 meters. This was far enough so that the earliest arrival time for a γ ray initiated in a wall was later than the arrival time for the latest neutron of interest. The walls were therefore neglected in the calculation. Processes in which a neutron scatters elastically in S may be estimated in the following way: Coon[8] has measured the angular distribution of the elastic scattering of 14-Mev neutrons and has found that less than 20 percent of the scattering is through angles of more than 20°. In the present experiment, all scatterings of less than 30° would have resulted in second scatterings at distances of not less than 3 meters. Gamma rays from such a scattering would have been outside the INS time region.

For the 20 percent or so of large angle elastic scatterings, an isotropic angular distribution was assumed. It was also assumed that when a 14-Mev neutron

[7] D. Luckey and J. W. Weil, Phys. Rev. 85, 1060 (1952).

[8] J. Coon, Phys. Rev. 94, 785 (1954).

TABLE II. Calculated double scattering backgrounds.

Source	Contribution
Floor	2%
Cyclotron	4%
Target assembly	1%
Total	7%

entered a thick slab of material it produced a secondary (gamma ray or neutron) with probability P of one. Further, such secondaries were assumed to be isotropically distributed and to escape the material without interaction.

For the low-energy neutrons from inelastic scatterings in S, the same assumptions were made except that P was taken to be $\frac{1}{2}$. The above assumptions are probably in error in such a direction as to cause an overestimate of these backgrounds.

The ratio of the number of inelastically scattered neutrons leaving S to the number of recoil alpha particles detected was calculated, including the effects of elastic outscattering; it was found to vary from 0.55 in Pb to 0.40 in C. Combining these calculations and estimates, the following (Table II) are the estimated double scattering backgrounds, with the location of the second scattering noted. The relative probability for this type of background event is roughly proportional to d, the distance between the scatterer and neutron counter. A distance of 50 cm was used in the estimate made in Table II. The uncertainty of this correction, as well as the falloff of counting rate with d, were the limiting factors on the useful working distance.

The scatterer-out backgrounds were measured directly, and are mentioned in a later section on experimental results. Since singles rates were monitored, these backgrounds could be computed; the computed backgrounds were in fairly good agreement with the measurements. One can distinguish:

(1) Background due to scattering of neutrons in the target backing and the vacuum chamber. This counting rate varied between 5 and 8 percent of the INS rate, and had a similar distribution in time.

(2) Random coincidences of alpha counter pulses with neutron signals. This was important mainly at the longer working distances and was uniformly distributed in time.

(3) Processes in which one 14-Mev neutron was received in the n counter in random coincidence with an alpha particle from a second neutron.

Since the deuterons of the cyclotron beam emerged in bunches at the cyclotron rf frequency, this background was somewhat peaked around the zero of time.

Under the operating conditions of this experiment, the background of type 2 was the most important. The total S-out background exceeded 20 percent of the true INS peak counting rate only at the longest working distance (100-cm flight path) and in angular distribution measurements on carbon.

7. ERRORS 2—ENERGY SENSITIVITY

Since measurements of the INS spectrum involved observations of neutrons over the energy range from 1 to 4 Mev, the apparatus had to be designed to allow easy calculation of the over-all efficiency. The effects to be considered are:

(1) Alpha counter efficiency. There was no correlation between scattered neutron energy and the recoil alpha direction, so no alpha counter effects needed to be considered.

(2) Probability of interaction in the n counter. The counter liquid was a mixture of hydrocarbons of known properties, so the number of C and H nuclei per cc was also known. The cross sections for both C and H are known and $n-p$ scattering is isotropic below 10 Mev.[9] Since the first excited state in carbon is at 4.5 Mev,[10] only elastic scattering had to be considered for the energies of interest. The maximum C^{12} recoil energy can be calculated immediately from momentum conservation, and is (neutron energy)/12.

(3) Pulse-height sensitivity and the response of organic scintillators. To make the calculation of efficiency as easy as possible, the neutron counter was designed and operated to have nearly uniform sensitivity over its entire volume. The relative sensitivity of the counter as a function of position was measured with a collimated radium gamma-ray source. For both the $\Sigma\epsilon$ and the AB counting systems (Sec. 4 and Fig. 2) there was less than a 15 percent variation in counting rate as the collimated beam was moved over the active length of the counter.

The fact that the response of organic scintillators to heavily ionizing radiation is nonlinear has been known for some time and a thorough experiment on the subject has been reported.[11] By assuming the liquid scintillator here employed to be stilbene-like, the relation of total pulse height (H) to particle energy for electrons, protons, and alpha particles was calculated from the data of reference 11.

Below 10 Mev for alphas, there is complete saturation (i.e., H proportional to range and independent of dE/dx). In order to compute H for C^{12} elastic recoils, it was necessary to know a range-energy relation for C^{12} nuclei. This was obtained by interpolation from the range-velocity relations for alphas, light fission fragments, and heavy fission fragments.[9]

In finding the sensitivity of the neutron counter as a function of energy, one quantity, the minimum scintillator pulse height accepted by the electronics, was measured directly. The relative response of the scintillator to protons from 0.3 to 14 Mev and to C^{12} nuclei from 0.5 to 5 Mev was calculated, and depends on

[9] *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. I, p. 487.
[10] *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).
[11] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. 84, 1034 (1951).

measurements of the response of solid organic scintillators. All effects due to geometry were calculated.

The measurement of minimum accepted pulse height was made in the following manner: the neutron counter photomultiplier voltages were adjusted so that the sensitivity was nearly uniform over the counter volume. Then, two measurements were made using the $\Sigma\epsilon$ slow linear pulse addition system (Sec. 4). In the first, the pulse height corresponding to 14-Mev recoil protons was measured, using direct 14-Mev neutrons from the target. In the second, a radium γ source was brought to a standard position, and an integral pulse-height spectrum was obtained with the same $\Sigma\epsilon$ system for this source. The source provided many low-energy pulses, presumably from Compton recoils, and the integral counting rate was a steep function of the minimum recording pulse height in the $\Sigma\epsilon$ system. Thus pulse height in the low-energy region was calibrated against counting rate from the source. Finally, the AB coincidence counting rate was measured; this measurement and the calibration just described allowed calculation of the minimum acceptable pulse height in units of the 14-Mev proton height. This minimum height was 1/300 of the 14-Mev height, with limits of error estimated as ± 50 percent.

With the help of the pulse height *vs* energy relation which has already been discussed, the minimum detectable proton and C^{12} energies were then calculated. They were: protons, 300 ± 100 kev; C^{12} nuclei, 1.5 ± 0.7 Mev. This most probable minimum detectable C^{12} energy was larger than the maximum recoil energy (1.2 Mev) from the most energetic neutron of interest (4 Mev).

The efficiency of the neutron counter as a function of energy was calculated, using the measured $n-p$ cross section (reference 9, pp. 486 and 507), the n-carbon cross section,[12] and the minimum detectable proton and C^{12} energies given above. The longest recoil-proton range involved (0.3 mm) was so short that no edge corrections had to be made. The probability of outscattering from the thin aluminum counter wall was also negligible ($\sim\frac{1}{2}$ percent). An upper limit on the effect of elastic outscattering by the carbon was calculated and found to be not more than 5 percent. The shape and size of the neutron counter were taken account of, and calculations of the efficiency were made on each of several assumptions as to minimum detectable pulse height.

To summarize the results of these calculations: the quantity needed in the interpretation of the neutron energy distributions was the variation in counter efficiency between 1 and 4 Mev. The effects of changing cross sections and the loss of low-energy pulses tended to cancel, and the net variation, a decrease of efficiency with increasing neutron energy, was not strongly dependent on the assumed low-energy cutoff. The calculated upper limit on the variation was about 35 percent of the mean efficiency, the lower limit about 20 percent. The variation was insensitive to the shape of the counter used in the calculation. If this were the only effect bearing on the nuclear temperature measurement, it would have had the effect of raising by not more than $\sim$8 percent the temperatures obtained from the raw data alone. As will be shown in the next section, however, another effect tended partly to cancel the error due to the variation in energy sensitivity.

[12] *Neutron Cross Sections*, U. S. Atomic Energy Commission Report AECU-2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1952).

8. ERRORS 3—TIME AND ENERGY RESOLUTION

Uncertainties in the knowledge of neutron velocity came about through errors in both distance and time measurements. Uncertainties in the distance, which gave rise to constant relative errors $\Delta E/E$ over the E range, were due to:

$D1$. The finite size of the scatterer S along the line from S to the counter.

$D2$. Finite counter size.

$D3$. The shift in the effective center of the counter with energy.

Above one Mev, the distance uncertainties were small compared to the time uncertainties; of these, the most important were:

$T1$. The finite resolution width of the electronics, mostly due to photoelectron transit time variations.

$T2$. The transit time of 14.8-Mev neutrons through the scatterer.

$T3$. Variations in flight distance for recoil alphas.

In addition to these two groups of errors, there was one error affecting the energy directly: the variation in the $T(d,n)\alpha$ neutron energy with angle. The incoming deuterons, whose mean energy was measured as 95 ± 5 kev from the known cyclotron field strength, were monoenergetic within about 2 percent. However, the finite angular width of the scatterer resulted in an effective neutron beam energy distribution having a nearly rectangular shape and a width of 90 kev.

Since the INS data were taken at a scattering angle close to 90°, it was a good approximation to assume the independence of $D1$ and $T2$. $T3$ was made small by the design of the target assembly and was computed to be $\sim 3\times 10^{-10}$ second. The remaining errors were computed, the distance errors were combined and translated into times, and the three resulting time errors were combined to form a single resolution function.

The over-all resolution function was only slightly wider than that due to errors of the type $T1$ alone. It was approximately a Gaussian, with a full width at $1/e$ value of about 9 millimicroseconds.

In order to estimate the errors caused by the finite resolution width, it was necessary to assume a form for the neutron distribution being observed. The form $dN/dE = Ee^{-E/T}$, to which the experimental points were compared, was used. In time units, $dN/dt = t^{-5}\exp[-(a/t)^2]$, a the flight time for neutrons of energy being equal to T. The measured value of neutrons/unit time, dN/dt at $t=t_0$, could be written as the fold of dN/dt and the resolution function

$$\frac{dN}{dt}(t_0)_{\text{exp}}=\int_0^{\infty} t^{-5}\exp[-s(t-t_0)^2]\exp[-(a/t)^2]dt.$$

dN/dt was expanded in Taylor series around t_0, and term-by-term integration was used. All odd terms vanished, and the fractional error caused by the finite resolution width was taken as the ratio of the 2nd to the 0th order term.

The fractional error was computed for all cases of interest. In general, only the points at lowest t_0 were affected; for Pb (in which the effect was largest) the lowest t_0 point was 10 percent high due to this effect, and other points were affected by less than 5 percent.

To summarize the calculations on errors, it was concluded that systematic errors of types 1 and 3 were each less than 10 percent and were opposite to errors of type 2 between 1 and 4 Mev. Within that range, systematic errors of types 1, 2, and 3 were calculated as totaling between 0 and 20 percent in any measured point.

Since these errors were in general smaller than the estimates made of noncalculable error limits (e.g., variations in the electronics during operation) no corrections for them were made, and the nuclear temperatures were obtained from plots of the raw data, giving little weight to points outside the 1- to 4-Mev range. Systematic errors of 20 percent in the measured points could have made errors of at most ~7 percent in the nuclear temperatures.

9. PRELIMINARY EXPERIMENTS

Before taking any INS data, several measurements on systematic errors were made. First, the neutron counter sensitivity was measured, and pulse-height spectra were taken on monoenergetic neutrons and gamma rays. With the cyclotron off, the total neutron counter rate was ~35 counts/second, mostly due to small pulses. These may have been due to slow neutron capture from sources elsewhere in the building or to radioactivity in the counter liquid. Experiments with an anticoincidence Geiger counter umbrella, and with large thicknesses of lead and paraffin shielding, showed that this background was not due to cosmic rays. However, a small (0.5 count/second) component of large pulse height was consistent in rate and height with fast mu mesons from cosmic rays.

Using the Gate coincidence circuit, the neutron-alpha angular correlation was measured and is shown in Fig. 3.

A number of measurements of time resolution were made, using mu mesons, neutron-alpha coincidences, and the double-Compton scattering of radium gamma rays. By choosing different values of the photomultiplier high voltages, the distributed amplifier gains, and the conditions on minimum rise rate, it was possible to identify and measure the following sources of time-uncertainty.

(1) Variations in chronotron channel boundary positions. This effect was small compared to the next two.

(2) The variation in the center of gravity of a clipped pulse with the rise rate of the pulse before clipping. During operation this effect was made small by using high distributed amplifier gains and requiring high values of the rise rates.

(3) Variations in the transit time of electrons from photocathode to first dynode in each photomultiplier, due to statistical fluctuations in the photoelectrons' points of origin. This effect was the largest of the three; the over-all time resolution width was measured as 9 ± 1 millimicroseconds.

A number-bias spectrum for the gamma source was taken with a linear amplifier, and was used to calibrate the minimum acceptable pulse height for the entire system, as discussed in Sec. 7. With the n counter in the coincidence cone, the Gate counting rate was measured as a function of alpha-counter voltage, a plateau was obtained, and an operating point well onto the plateau was chosen.

The first distributed amplifier on the neutron side had an adjustable gain control. This control was calibrated, and it was found that above a certain value of the gain all signals accepted by the slow AB coincidence circuit also satisfied the rise-rate criterion. The plateau above this value had a width of about a factor three in gain. Maximum gain was used in operation.

Several preliminary INS runs on lead were made. The scatterer was built up of two layers, each $\frac{1}{2}$ in. thick, and measurements were made with one and with two layers in use, the measured spectra being the same

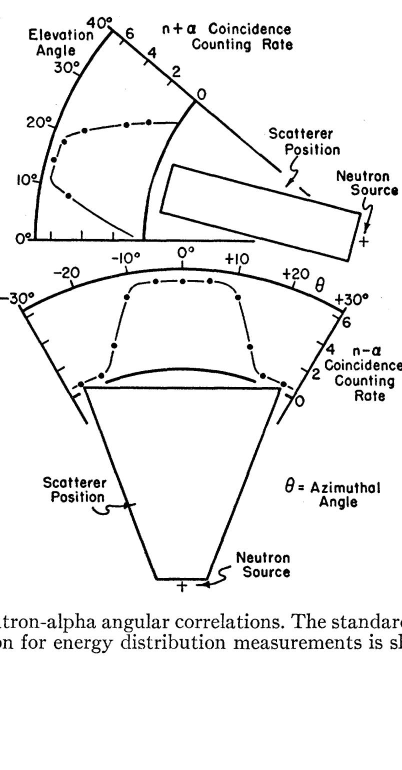

FIG. 3. Neutron-alpha angular correlations. The standard scatterer position for energy distribution measurements is shown.

within errors of ~10 percent. With a thick (1-in.) scatterer in place, $\frac{1}{2}$-in. slabs of paraffin and of lead successively were placed halfway along the INS flight path. The paraffin had no effect on the shortest delay component, which had been identified by TOF as decay gamma rays; however, the paraffin reduced both the main INS and the 14-Mev elastic groups by ~30 percent. The latter group, not resolved by TOF alone, was thus identified. The $\frac{1}{2}$-in. Pb slab had almost no effect on the neutrons, but reduced the gammas by ~70 percent.

A flight path of 71-cm average was chosen for the main energy-distribution measurements, a compromise between resolution, counting rate and scatterer-in background. Scatterer-out background was measured at the neutron-counter standard position (71 cm effective from the coincidence-cone axis, ~85° from that axis, and

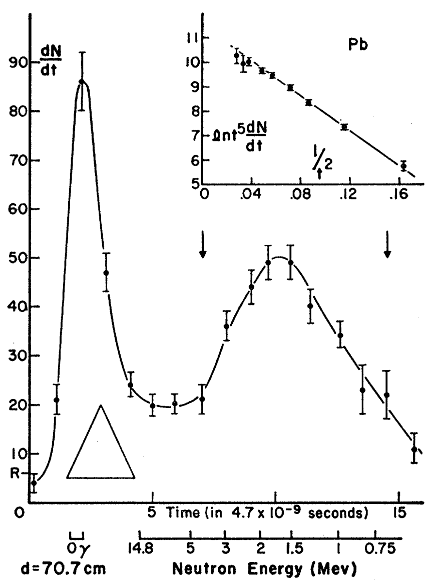

FIG. 4. Results of an energy distribution measurement with a Pb scatterer. Inset, plot for obtaining the "nuclear temperature" T from the measurement. (Sec. 10.)

160 cm from the concrete floor, the scatterer being at height 110 cm). The background was nearly uniform in time in the INS time region and consistent with the sources mentioned in a previous section. It was remeasured several times during the course of the experiment.

The external cyclotron beam was not focused and averaged 0.1 μa during the measurements. The neutron production rate was 1.5×10^5/sec, and about 1500 alpha particles/sec were incident on the alpha scintillator. Inelastically scattered neutrons were detected at a rate of ~1000 counts/hour.

Runs on each element at each distance required one day's operation, with actual data-taking times of 3 to 5 hours/day. Before each day's running an extensive schedule of standard tests was followed, in which

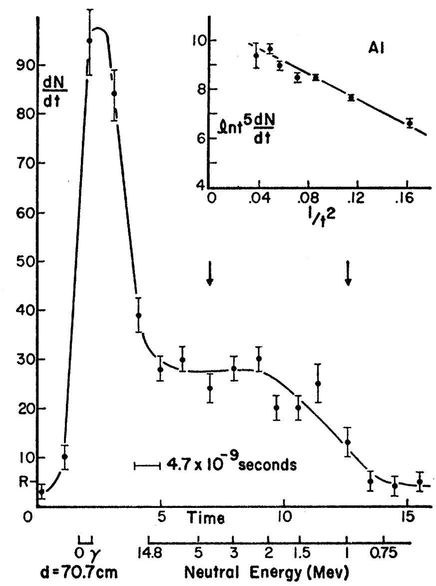

FIG. 5. Results of an energy distribution measurement using an Al scatterer. The results for Sn and Cu showed a smooth transition in the shape of the spectra from Pb to Al.

efficiencies and sensitivities were measured. This set of tests insured that the electronics was working properly before any data were taken. Although the nature of the chronotron made the INS results insensitive to running times, data were taken in units of a fixed number of detected 14-Mev neutrons, and experimental points represent the average of data from several (3 to 5) chronotron channels. No failures of the apparatus occurred during the three-week period required for collection of the data reported here.

10. ENERGY DISTRIBUTIONS

Two groups of runs were made on energy distributions. In the first, at a working distance of 71 cm, Pb, Al, Cu, C, and Sn were measured. The results for Pb, Al, and C are shown in Figs. 4–6, before subtraction of backgrounds. dN/dt for each figure is in arbitrary units, time in units of one chronotron channel width, with an arbitrary zero. The zero of time was measured by observation of the gamma rays from Pb, and was checked by the gammas from each element investigated. Below the time scale, an energy scale is given, and the time zero and gamma arrival time are noted. The equivalent resolution triangle is drawn in Fig. 4. R on the dN/dt scale indicates the measured scatterer-out background, and the arrows indicate the range of points which are plotted on the inset of each figure. The insets (plots of $\ln(t^5dN/dt)$ *vs* $1/t^2$ with backgrounds subtracted) should be straight lines with slopes equal to $-a^2$, a being the flight time for neutrons of energy equal to the nuclear temperature T, if $dN/dE=Ee^{-E/T}$. Although the experimental errors are too large to permit the detection of small deviations from linearity, the measurements are consistent with the above form for dN/dE.

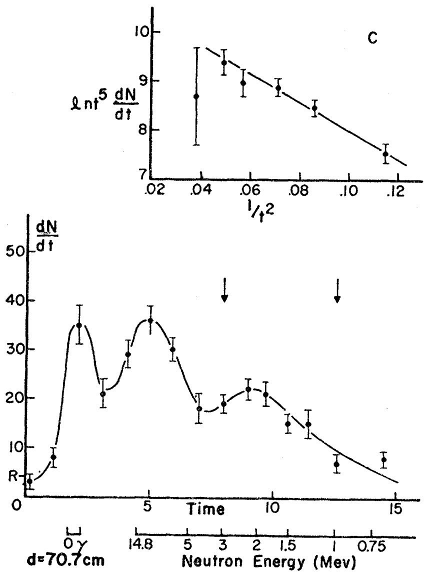

FIG. 6. An energy distribution measurement with a C scatterer. The number of observed decay gamma rays is small, presumably due to the simple level structure of carbon. The elastically scattered 14-Mev neutrons are well resolved from the gamma rays.

Another group of three energy measurements was also made, on the three lightest elements of the previous series. For Al, a working distance of 100 cm was used, with a distance of 88 cm for Cu and C. These measurements were made using different scattering angles and orientations from those of the previous measurement in an effort to obtain better resolution of the INS spectrum from the elastic scattering. An improvement was in fact obtained, but at the expense of scatterer-in/scatterer-out ratios and counting rates.

In Table III, the results of both these runs are given, together with average values which are adopted as the final results of the experiment.

It should be noted that these results come from straight lines drawn through sets of experimental points. The difference of 20 percent in the two measured values of T for Cu, and the difference of 9 percent and 6 percent for C and Al, indicate the uncertainties in drawing such lines. In order to allow for these uncertainties, estimated errors of ± 15 percent are assigned to each average value of T. Each of the average values is within 10 percent of the corresponding temperature obtained by photographic plate techniques.[3]

11. ANGULAR DISTRIBUTIONS

One of the easiest tests of the compound-nucleus model should be the measurement of isotropy in the INS. Although isotropy would not be expected for those neutron groups which do not follow an $Ee^{-E/T}$ law, the scattering of 14.8-Mev neutrons below 5 Mev should be nearly isotropic.

Using a working distance of 55 cm, with the scatterers suspended in the vertical plane, the distributions of neutrons from C, Al, and Pb were measured at laboratory angles of $\sim 48°$ and $\sim 130°$ (Fig. 7). In order to insure correct monitoring, an extra proton recoil counter was mounted in a fixed position, set at a bias of ~ 7 Mev, and used to monitor all angular distribution runs. Backgrounds were measured several times, and are shown at the top of Fig. 7. They were consistently higher at 130°, probably due to the increased n-counter rate near the cyclotron, and to the fact that for a fixed INS flight path, the T-target to n-counter distance decreased with increasing angle.

The rapid change of the 14-Mev elastic scattering with angle is clearly visible. The results for the INS in Pb were good enough to be plotted for nuclear temperature. The result (0.82 Mev) was within 10 percent of the more carefully measured value. The results for C are too poor to allow conclusions as to isotropy, but taking the sum of all counts below 5 Mev, with a positive $N(48°)-N(130°)$ difference taken as a positive effect, the anisotropy can be obtained. It is given in Table IV.

Taking into account the inequality of backgrounds at the two angles, the measurement may be taken as setting an upper limit of ~ 15 percent on the anisotropy in these three elements.

12. EXTENSIONS OF THE MEASURING TECHNIQUE

With minor modifications, it is probable that the present technique could be used to examine the interesting high-energy nonisotropic INS groups. A brief design study for a high-resolution neutron spectrometer was made and will be outlined below.

The source of neutrons would consist of a T-Zr target, held at -50 kev by a low-power dc supply. A deuteron source would supply ~ 5 to 10 μa of deuterons to the target, producing $\sim 3\times 10^6$ 14-Mev neutrons/second. This assembly would be mounted as far as possible from scattering material.

The target would be observed by two alpha counters; the first, which would be fixed, would subtend a solid angle $\Omega/4\pi$ of $\sim \frac{1}{6}$ and would apply a 0.2-microsecond anticoincidence signal whenever a neutron headed toward nearby parts of the laboratory or toward the neutron counter. Its counting rate would be $\sim 5\times 10^5$/

TABLE III. Measured nuclear temperatures.

Element	T (70.7-cm run) Mev	Distance d cm	T (run at d) Mev	Value of T adopted Mev
Pb	0.75			0.75
Sn	0.62			0.62
Cu	0.74	88	0.91	0.82
Al	1.03	100	1.10	1.06
C	0.89	88	0.97	0.93

TABLE IV. Anisotropy of inelastic neutron scattering.

Pb: $+8\pm 8\%$	Al: $-6\pm 13\%$	C: $+14\pm 18\%$

second. The second alpha counter would be a thin (slightly more than alpha range) layer of plastic scintillator on the glass envelope of a short-transit-time photomultiplier. This (coincidence and time zero) counter would be movable within the vacuum system to provide a coincidence neutron beam over a 120° range of angles, all directed away from the laboratory building. The scatterer would be outside the vacuum system. To cut down random background from cosmic rays, an array of Geiger counters in anticoincidence would shield the neutron detector.

Analysis would be carried out by a chronotron similar to the one already built, but with a channel width of 2×10^{-9} second to take advantage of the short-transit-time photomultipliers.

Estimates of the backgrounds to be expected indicate that 1000 counts/hour could be collected on a line having 2 percent of the total INS intensity, with a real-to-random ratio of 1:1. Since the main source of background would be random n-alpha coincidences, the true/background ratio could be improved in direct proportion to the time required to collect a specified number of counts. Energy resolution would be ~10 percent (full width) at 12 Mev, with a three-meter flight path.

It should be emphasized that the discussion above is the summary of a design study, not a description of apparatus already built or definitely planned.

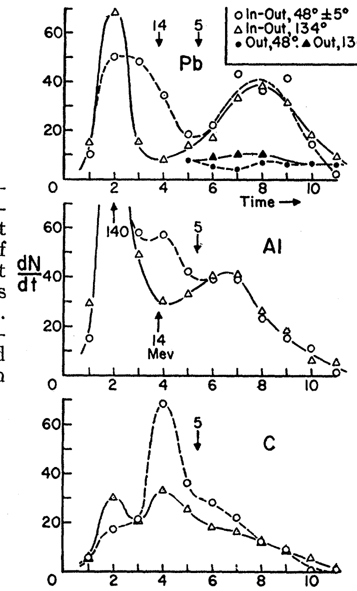

FIG. 7. Energy distributions, with backgrounds subtracted, at two angles for each of three elements. The first peak in each case is ascribed to gamma rays. The arrival time for 14-Mev elastically scattered neutrons is indicated on the graph for Al.

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Natural Radioactivity of Sm^{147}

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The half-life of Sm^{147} has been measured to be $1.25\pm0.06\times10^{11}$ years with an energy distribution corresponding to the emission of monoenergetic alpha particles.

A STUDY of the natural radioactivity of Sm^{147} has been made, including a determination of the half-life and an investigation of the energy spectrum of the alpha particles.

The activity of the samarium was measured using a 4π counter developed by Sawyer and Wiedenbeck.[1] The counter was originally designed for use in the Geiger region, but tests showed that with center wires of 4-mil diameter and a filling of 20 cm of CH_4 and 41 cm of argon it performs satisfactorily in the proportional region also. The sources were made of zapon films upon which aluminum was deposited by evaporation in a vacuum followed by a similarly deposited layer of samarium chloride. It was found that by using a molybdenum crucible quite efficient evaporation of the samarium chloride could be obtained.

When samarium chloride is evaporated, there is some question as to its final chemical composition.[2] Therefore, in order to determine the amount of samarium deposited, a spectroscopic analysis of each source was made.

A large quantity of 10 percent HCl stock solution

[1] G. A. Sawyer and M. L. Wiedenbeck, Phys. Rev. **79**, 490 (1950).

[2] L. L. Quill, *Nuclear Energy Series IV 19B* (McGraw-Hill Book Company, Inc., New York, 1950), pp. 125, 219.