just one value of the density, $\rho=6\times10^{14}$ g/cc, but has taken account of the protons' Fermi energy. His result is

$$l\simeq(7.36\times10^{4}\text{ ergs/g sec})[T/(10^{9}\,{}^{\circ}\text{K})]^{8}\quad(F=93\text{ MeV}).$$

Bahcall and Wolf[6] use distorted-wave Born approximation with empirically determined parameters, and take account of collective effects by using effective masses for the particles involved. Their result is

$$l\simeq(10^{4}\text{ ergs/g sec})[T/(10^{9}\,{}^{\circ}\text{K})]^{8}[\rho/(3.7\times10^{14}\text{ g/cc})]^{-1}.$$

Considering the different approaches used, the three results are in quite good agreement.

A rough estimate of the neutrino luminosity of a neutron star, due to this process, can be made by simply writing

$$L_\nu(\text{Urca})\simeq2Ml\simeq6\times10^{38}(M/M_\odot)(T/10^{9}\,{}^{\circ}\text{K})^{8.7}\times(F/50\text{ MeV})^{-1.9}\text{ ergs/sec}.\quad(6)$$

Here M is the mass of the star, and $M_\odot$ the mass of the sun, 2×10^{33} g. The factor 2 is inserted to account for both ν and $\bar{\nu}$ emission. For $M=\frac{1}{2}M_\odot$ and $F=50$ MeV, this result can be compared directly with the estimates of luminosities made by Chiu and Salpeter.[3] Combining Eq. (6) above with Table I of Ref. 3 gives the cooling time estimates shown in Table II. For example, if the Scorpius source is assumed to satisfy the model of Ref. 3 and to be at least 1 kiloparsec distant from us, its core temperature must be at least 10^9 °K, and so its age is at most a few decades. The present calculation is not applicable to the model used by Morton[7] in his calculations of x-ray emission, because his densities are so high ($F>100$ MeV) that meson production cannot be ignored.

TABLE II. Cooling times for model of Chiu and Salpeter (Ref. 3).

T (°K)	L_ν (Urca) (ergs/sec)	L_ν/L_γ	τ (years)
2.0×10^{9}	1×10^{41}	5×10^{3}	$\frac{1}{2}$
1.0×10^{9}	3×10^{38}	4×10^{1}	40
5.0×10^{8}	7×10^{35}	2×10^{-1}	10^{3}
2.0×10^{8}	2×10^{32}	7×10^{-4}	1.5×10^{3}

It is a pleasure to acknowledge helpful conversations with Professor D. B. Lichtenberg and Professor J. G. Wills.

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[6] J. N. Bahcall and R. A. Wolf, Phys. Rev. Letters **14**, 343 (1965).

[7] Donald C. Morton, Astrophys. J. **140**, 460 (1964).

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Gravitational Acceleration of Free Neutrons*†

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The gravitational acceleration of free neutrons from the Oak Ridge Research Reactor has been measured in the evacuated 180-m flight path at Oak Ridge National Laboratory. The transmission edges associated with the ⟨100⟩ and ⟨002⟩ lattice spacings in a polycrystalline beryllium filter have been used to define particular neutron velocities $v_{hkl}=(h/2md_{hkl})$ in the "slow beam." Boral filters permitted the selection of a "fast beam" which did not fall appreciably. The differences between the vertical positions of the slit image formed by the "fast beam" and of the two transmission edges (12.7 and 15.5 cm lower) have been determined with the aid of least-squares fits to theoretical curves. An x-ray examination of the beryllium filter established the values for $2d_{hkl}$. We find the acceleration of free neutrons due to gravity to be $g=975.4\pm3$ cm/sec^2 [(100) planes] and $g=973.1\pm7$ cm/sec^2 [(002) planes]. These may be compared with the local value $g=979.74$ cm/sec^2 and McReynolds' early result $g=935\pm70$ cm/sec^2. A recent suggestion of Spitzer that there might be a difference in g for the two vertical neutron-spin projections $\pm\frac{1}{2}$ does not appear to be present. No splitting greater than a few percent of g is found.

INTRODUCTION

THE general observation that the acceleration of gravity is a universal constant for all matter has been supported by the extremely precise measurements of Eötvös[1] *et al.* and Renner,[2] and more recently by the substantially improved measurements of Dicke and his collaborators.[3] In the latter, the comparison between the

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[1] R. V. Eötvös, D. Pekar, and E. Fekete, Ann. Physik **68**, 11 (1922).

[2] J. Renner, Mat. Termeszettud. Értesito (Budapest) **53**, 542 (1935).

[3] R. H. Dicke, Sci. Am. **205**, 84 (1961). Since the present work was completed, the following have appeared: R. H. Dicke, in *Relativity, Groups and Topology*, edited by C. DeWitt and B. DeWitt (Gordon and Breach Science Publishers, Inc., New York, 1964); P. G. Roll, R. Krotkov, and R. H. Dicke, Ann. Phys. (N.Y.) **26**, 442–517 (1964). The latter is a delightfully complete treatise on recent measurements which confirm the equivalence principle even more closely than indicated above.

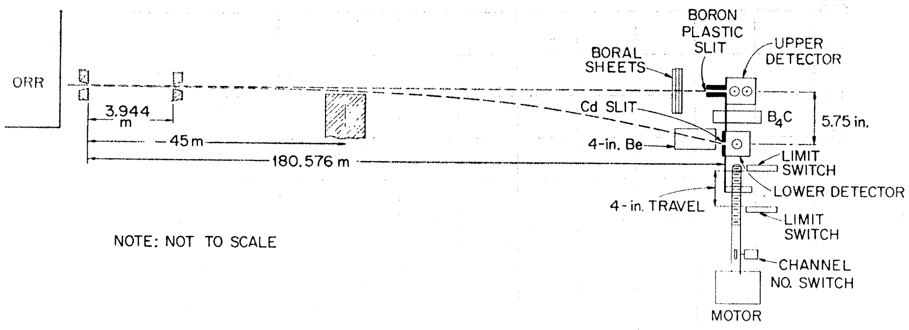

FIG. 1. Schematic diagram of experiment.

acceleration of PbCl (neutron-proton ratio $R=1.45$) and of Cu ($R=1.19$) gave results which agreed within about one part in 10^{10}. Thus, it may be concluded that neutrons and protons in nuclei, i.e., while moving at high velocities under the influence of nuclear forces, experience the same gravitational accelerations within about $2\times10^{-9}g$. Schiff, in a discussion of a number of consequences of the early experiments[4] concluded that the effect of gravity on both positrons and electrons must be closely the same as on neutral matter. A measurement by Estermann, Simpson, and Stern[5] demonstrated a gravitational acceleration of free Cs and K atoms in an atomic beam which apparently agreed within a few percent with the expected value. This work was in connection with verification of a modified Maxwellian velocity distribution within the beams. It seems quite reasonable to assume that a neutron free of nuclear forces should experience the same gravitational acceleration it experiences within a nucleus. This assumption is subject to experimental verification, however, and such a verification was the purpose of the present experiment. The measurements reported here are very crude compared to those obtained in the Eötvös-type experiments, but represent an improvement of a factor ~25 in accuracy over the only direct measurement heretofore available.[6]

METHOD AND APPARATUS

The basic approach was to provide a definite and sufficient time for the gravitational force to act on the free neutrons and to measure the deflection resulting. This was accomplished in the present instance by allowing well-collimated beams of both high- and low-velocity neutrons (which passed through the same slit system) to traverse a very long (180-m) evacuated flight path. Observation of the difference in height of the two components of the beam then allowed a determination of g. The most desirable way to determine the lengths of time involved would have been through conventional time-of-flight techniques. This method was not used, however, because of intensity considerations. Instead, the transmission edges associated with the $\langle 100\rangle$ and $\langle 002\rangle$ lattice spacings in a polycrystalline Be filter were used to determine the velocities. The sudden cessation of Bragg scattering for wavelengths λ longer than $2d_{100}$ or $2d_{002}$ allows one to define neutrons of velocities $v_i=h/m\lambda_i$, where $\lambda_i=2d_{100}$ or $2d_{002}$. The method is quite straightforward and gives high intensities as well.

The experimental arrangement is shown in Fig. 1. The collimating slits were 0.02-cm high and were tapered to reduce reflections from the jaws and were spaced as shown. They were made from two boron steel plates ~6-cm thick in the beam direction and were coated with cast tetradecanoic acid ($C_{14}H_{28}O_2$). This material is useful for suppressing total reflection of neutrons at small angles.[7] The collimating slit height was chosen to be sufficiently large that diffraction effects could be ignored. The actual choice corresponds to a Δv (along the Cornu spiral) of 7.1 at the longest wavelength of importance, which is ~4 Å in the present case; here v is of course the upper limit of the standard Fresnel integrals. At the 180-m station, the upper portion of the beam was filtered by 6.2-mm Boral[8] plus 0.75-mm Cd which transmitted a "fast" component which had not fallen appreciably. The lower portion was filtered by a 10-cm-thick polycrystalline Be block which gave the transmission edges mentioned above, and thus defined a "slow" component which had fallen ~10–20 cm. The neutrons were detected by $^{10}BF_3$ proportional counters placed behind detector slits made as shown in Fig. 1. The upper slit was 0.574-cm high; the lower 0.653-cm high. The effective vertical separation of the two slits was 14.587 cm. The entire assembly (counters, slits, and Be block) was oscillated vertically through a travel of ~10 cm by an accurate lead screw (32 threads/in.) at the rate of ~1.9 cm/min. The data were recorded by means of a transistorized multichannel analyzer of 512 channels operating in a multiscaler mode. Routing signals from the two counter amplifiers permitted separate storage of pulses into the two halves of the analyzer memory array. Through use of a cam and switch, each lead-screw revolution caused a pulse which increased by one the addresses of the channels into which counts were stored. Thus 128 channels cor-

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[4] L. I. Schiff, Proc. Nat. Acad. Sci. (U.S.) **45**, 69 (1959).

[5] I. Estermann, J. O. Simpson, and O. Stern, Phys. Rev. **71**, 238 (1947).

[6] A. W. McReynolds, Phys. Rev. **83**, 172, 233 (1951).

[7] I. R. Jones and W. Bartolini, Rev. Sci. Instr. **34**, 28 (1963).

[8] Aluminum containing ~0.2 g/cm² natural boron.

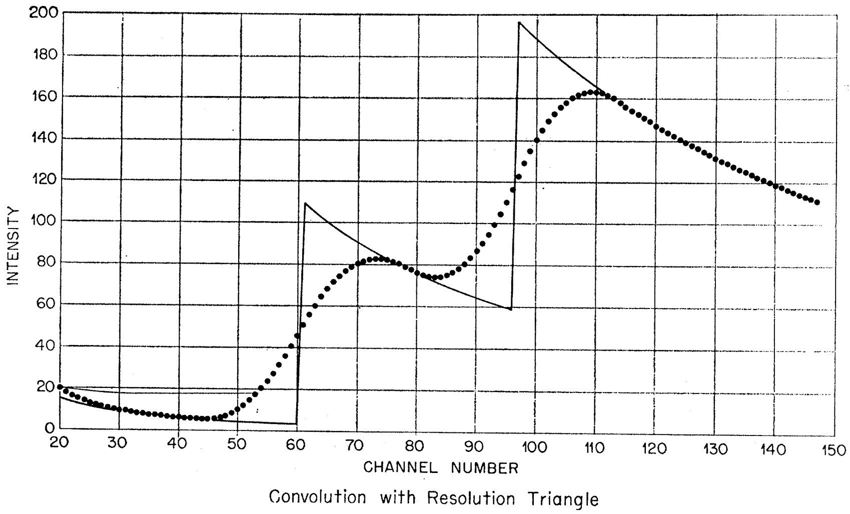

FIG. 2. Diagram of expected intensity of "slow" component versus height; increasing channel numbers are at lower heights.

responded to a 4-in. travel. The first two quarters of the memory array received counts from the lower detector during downward and upward travel, respectively; the second half was similarly used for the upper detector.

Since the counting rates in the lower detector were not large (200 counts/min at the bottom of the travel and 30-MW reactor power), care was taken to reduce the background. The massive direct-line shield at 45 m, the B_4C shield between the upper slit jaw and the lower counter, and a Cd wrapping around the lower counter case were all found necessary. Upper detector backgrounds were measured through 19-mm Boral plus 0.75-mm Cd; lower detector backgrounds were taken with 10-cm Be plus 0.75-mm Cd. Appropriate backgrounds have been subtracted from all data presented below.

DETERMINATION OF STEP AND PEAK LOCATIONS

The flux distribution of neutrons emerging from moderated reactors such as the Oak Ridge Research reactor is approximately Maxwellian. On the long-wavelength side of the peak the flux would then fall as λ^{-5}; thus the intensity as a function of height after gravitational acceleration should vary approximately as d^{-3}. Actually, because of the ubiquitous $1/v$ cross sections for absorption, a more rapid decrease of intensity with distance is to be expected. A slight increase in efficiency of the detector also occurred over the span of height, again because of the $1/v$ cross section of ^{10}B in the detector. The observed open-beam intensity distribution was consistent with these expectations. During passage through the polycrystalline Be block, neutrons with wavelengths less than twice the largest lattice spacings can fulfill the Bragg scattering condition for some crystallite in the polycrystalline filter; thus an abrupt step upward in intensity should occur as one goes to wavelengths $\lambda \geq 2d(hkl)$. Such a distribution is illustrated by the solid curve of Fig. 2. If one takes into account the finite size of the collimating slits and convolutes a resolution triangle with the curve, the closed circles of Fig. 2 give the shape expected. The advantage of separating the effects of the two steps in the Be cross section in the manner of Fig. 2 thus sets an upper limit for the collimating slit widths.

An actual curve of this type is shown in Fig. 3. The data points are shown as small crosses attached to the smooth curve. The smooth curve is a least-squares fit to the data. The two transmission edges are clearly visible. The resolution widths for the steps are closely in accord with those expected from the slit geometry. [Spitzer[9] has recently suggested the possibility that there might be a difference in g for the two vertical neutron spin projections $\pm\frac{1}{2}$. The fact that the width appears normal strongly suggests that such an effect, if it exists, is either very small (less than a few percent of g) or very large. In the latter case, it is very likely that the effect would have been seen in the early work[6] or in other experiments. We conclude that the effect is probably small or nonexistent.] In this particular least-squares fit, the parameters describing the slope between the two steps and that to the right of the second step were both free parameters in the fit. In the final data analysis, these were forced to values obtained from open-beam runs. An indication of the effect of this difference may be seen by comparing the calculated step locations in Fig. 3 with those in the first line of Table II. Each channel is $\frac{1}{32}$ in. or 0.79375-mm wide.

The location of the "fast" beam was also determined by fitting a semitheoretical curve to the observed peak in each run. In this case, a symmetric, triangular resolution peak was used as a fitting function. This is illustrated for the same run in Fig. 4. The correct theoretical curve would include the effect of the finite detector slit and the effect of the very small amount of fall in the

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[9] J. A. Wheeler (private communication).

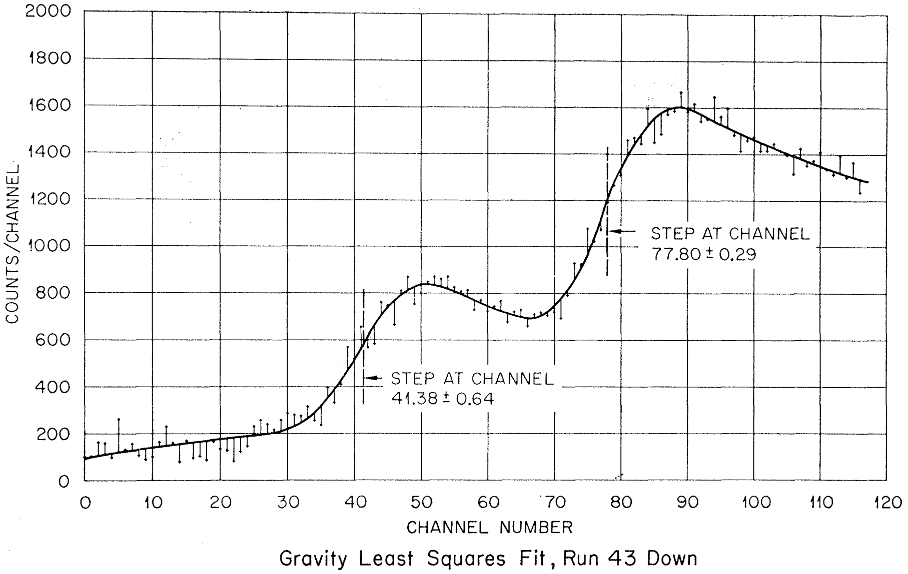

FIG. 3. Measured intensity versus height for "slow" component; curve is fitted by least squares to data points, shown as small crosses. The vertical dashed lines correspond to the locations of abrupt steps of the type illustrated in Fig. 2. The word "down" means data taken while counters, slits, and filter block were in downward motion. The least-squares fit was not the final one; see text.

gravitational field of the earth of the "fast" beam. The average deflection associated with this effect was estimated to be 0.10 mm, and was easily included separately. The data points of Fig. 4 are seen to fit the theoretical curve quite well. An indication of the distortion associated with the distribution in neutron energy is given by the shaded area. The peak of Fig. 4 was actually superimposed on a low, very broad symmetric peak which was attributed to leakage through the collimator jaws. This background was subtracted and all negative deviations from the baseline suppressed prior to analysis.

TABLE I. Lattice spacings in Be.[a]

	$2d_{100}$	$2d_{002}$
Measured (Cu K_α)	3.9558±0.0016	3.5780±0.0016
Theoretical	3.9538	3.5767

[a] Note that the observed spacings were slightly larger than the theoretical values, as might be expected for material containing a slight amount of impurities.

DETERMINATION OF CUTOFF WAVELENGTHS

After completion of the measurement runs, the polycrystalline Be block was cut into 24 pieces with a spark cutter, and each was examined by x-ray diffraction.[10] The values obtained were averaged in a manner which took into account their relative positions in the original block, and yielded the values given in Table I.

RESULTS

The distance of fall of the neutrons passing through slits at horizontal locations 0, l_1, and l_2 is given by[6]

$$s=\tfrac{1}{2}g(m\lambda/h)^2(l_2^2-l_1l_2)\,, \qquad (1)$$

and the de Broglie relation is assumed.[11] In (1), m is the mass of the neutron and h is Planck's constant.

Table II gives a resumé of the peak locations and step locations for seven runs made during the period 17–29 July, 1963. Run numbers not shown in Table II correspond to various background runs and open-beam measurements (without Be filter). One run was discarded because of convergence difficulties in the least-squares fit. In Table II are also shown the differences (in cm) between the "fast" peak and the appropriate step location. An amount 0.10±0.02 mm must be added

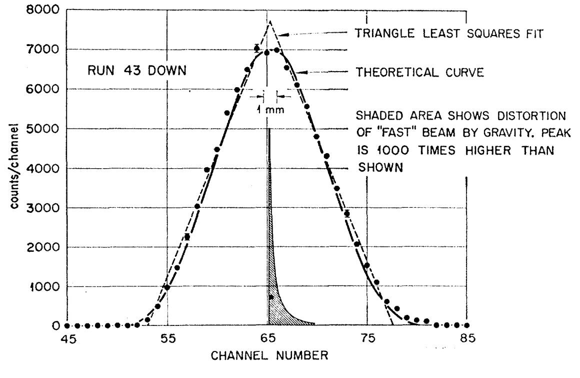

FIG. 4. Measured intensity versus height for "fast" component, as compared with triangle least-squares fit and a theoretical curve. The center of the fitted triangle is at channel 65.34±0.06. An indication of the effect of gravity on the dE/E reactor spectrum, as modified by Boral and Cd filters, is given by the shape of the shaded area. The centroid of this area is approximately 0.1 mm from the left edge.

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[10] The assistance of R. L. Sherman is gratefully acknowledged.

[11] A direct check of this assumption by neutron time-of-flight, using the (100) planes of Be has actually been made: S. Holmryd K. E. Larsson, and K. Otnes, Nucl. Instr. Methods **12**, 335 (1961). The accuracy was clearly much better than 1%, but the published information does not allow an error smaller than ~0.5% to be inferred.

TABLE II. Resumé of observations.

Run No.	Duration (h)	Center of fast peak channel No.	(002) step location channel No.	(100) step location channel No.	(002) net drop (cm)[b]	(100) net drop (cm)[b]
43 down	25	65.34±0.06	42.60±0.64[a]	77.37±0.35[a]	12.781±0.051	15.541±0.028
43 up	25	63.75±0.07	40.36±0.75	75.58±0.46	12.730±0.059	15.525±0.037
45 down	20	66.84±0.10	41.96±0.53	78.94±0.39	12.611±0.044	15.547±0.034
45 up	20	65.31±0.08	40.44±0.63	77.41±0.04	12.612±0.050	15.547±0.033
57 down	24	65.83±0.07	41.78±0.74	77.92±0.42	12.677±0.060	15.546±0.034
57 up	24	63.75±0.12	41.68±1.36	76.78±0.62	12.834±0.109	15.620±0.052
58 down	4	65.96±0.08	43.16±1.43	77.34±0.68	12.776±0.114	15.489±0.056
58 up	4	(Discarded–see text)				
Weighted mean[b]					12.685±0.031[c]	15.544±0.014

[a] These values differ from those shown in Fig. 3, which represents a preliminary analysis in which the slopes of the curve between channels 52 and 66 and above channel 90 were left free rather than forced to the theoretical value. The (002) shift due to this slope change is typical of this correction, but the (100) *average* correction was small.

[b] An amount 0.010±0.002 cm must be added to obtain the actual fall of the slow beam.

[c] Error from variance.

to each of these entries to obtain the actual drop distances for neutrons of wavelengths $2d(002)$ and $2d(100)$. The weighted means of the two net drop distances are also given.

Using Eq. (1) and the information in Tables I and II, together with the known values of l_1 and l_2 (see Fig. 1), the following mean values of the acceleration of free neutrons due to gravity were obtained from the weighted mean values of Table II:

$$g(002)=973.1\pm7.4\ \mathrm{cm/sec^2}, \tag{2}$$

$$g(100)=975.4\pm3.1\ \mathrm{cm/sec^2}. \tag{3}$$

These may be compared with the value previously obtained[6]

$$g(\mathrm{McReynolds})=935\pm70\ \mathrm{cm/sec^2} \tag{4}$$

and with the local value

$$g_{\mathrm{loc}}=979.74\ \mathrm{cm/sec^2}. \tag{5}$$

The errors quoted in (2) and (3) represent a combination of errors obtained statistically from the individual least-squares fits (or from the observed variance) in quadrature with estimates of the resultants of a number of possible systematic errors. The latter are listed, with the estimated resultants, in Table III. The most important of the items listed in Table III is item 4, which refers to a possible shift in step locations associated with the choice of two slopes in the neighborhood of the steps. The shift in the step locations was rather large when these slopes were forced to have the same values for all runs. These slopes, though they represented our best estimate of the theoretical values, may not have properly taken into account variations in the scattering cross section of Be with energy; such variations have not been well measured. The (002) slope shift was $\sim$10 cm/sec^2, and suggested strongly the possibility of a systematic error of order 5 cm/sec^2. In the case of the (100) step, the average shift was only 0.9 cm/sec^2, though the typical single run shift was ±2.1 cm/sec^2.

TABLE III. Some possible systematic errors.[a]

	(002)	(100)
(1) Lattice spacing	±1	±1
(2) Fast beam drop	±0.2	±0.2
(3) Upper detector slit droop	±1	±0.8
(4) Slope shift in analysis	±5	±1
(5) Counter location with respect to slits	±1.5	±1.2
Estimate of possible combined error	±7	±3

[a] All values in cm/sec^2.

We conclude that an appreciable systematic error probably existed, whose possible magnitude is indicated by the final entries in Table III. A shift of $\sim$3.5 cm/sec^2 in the mean values of (2) and (3) above would be sufficient to give good accord with (5). If a substantially more accurate method of measurement should become possible, it would be desirable to repeat the determination.

ACKNOWLEDGMENTS

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