than about 10^{-13} sec, we would have incoherence and all interference terms in Eq. (8) must be set equal to zero. In this situation we would have

$$\mathbf{p}_\Lambda \leqslant \tfrac{1}{3}\mathbf{p}_\Sigma.$$

D. $P \rightarrow P$ Transitions

The structure of the T operator in this rather complicated situation is as follows:

$$\begin{aligned} T=(\tfrac{3}{4})^{\frac{1}{2}}\{&3d_1[4\mathbf{N}\cdot\mathbf{n}X_t-3i\mathbf{S}\cdot(\mathbf{N}\times\mathbf{n})-\mathbf{n}\cdot\mathbf{S}\mathbf{N}\cdot\mathbf{S}] \\ &+d_2[i\mathbf{S}\cdot(\mathbf{N}\times\mathbf{n})+\mathbf{n}\cdot\mathbf{S}\mathbf{N}\cdot\mathbf{S}] \\ &+\sqrt{2}i\mathbf{S}'\cdot(\mathbf{N}\times\mathbf{n})(d_3X_t+d_4X_s) \\ &+2d_5\mathbf{N}\cdot\mathbf{n}X_s+\tfrac{2}{3}d_6[\mathbf{N}\cdot\mathbf{n}X_t-\mathbf{n}\cdot\mathbf{S}\mathbf{N}\cdot\mathbf{S}]\}. \end{aligned}$$

The symbols have previously been defined. At the end one averages over the directions of **n** (this is equivalent to averaging over the orbital magnetic quantum number in the initial P state). The final results are

$$\begin{aligned} R&=\tfrac{1}{12}\{5|d_1|^2+3(|d_2|^2+|d_3|^2+|d_4|^2+|d_5|^2)+|d_6|^2\}, \\ \alpha&=\alpha_1+\alpha_2, \\ \alpha_1&=\tfrac{1}{8}(2|d_1|^2-\sqrt{2}\,\mathrm{Re}d_2{}^*d_3), \\ \alpha_2&=(1/24)\,\mathrm{Re}\{d_1{}^*(2d_2+3\sqrt{2}d_3+2\sqrt{2}d_4+6d_5) \\ &\qquad +d_2{}^*(3d_5+4d_6)+2d_4{}^*(3d_3-\sqrt{2}d_6)\}, \qquad (9) \\ \beta&=\beta_1+\beta_2, \\ \beta_1&=\tfrac{1}{8}(-|d_1|^2+|d_2|^2+\sqrt{2}\,\mathrm{Re}d_2{}^*d_3), \\ \beta_2&=(1/24)\,\mathrm{Re}\{d_1{}^*(-d_2+\sqrt{2}d_3+4\sqrt{2}d_4+2d_5) \\ &\qquad -d_2{}^*(6\sqrt{2}d_4+4d_6)-d_3{}^*(6d_4+4\sqrt{2}d_6)+4d_5{}^*d_6)\}. \end{aligned}$$

The conditions for incoherence are the same as discussed in the previous paragraph. If they are met, then

$$\alpha_2=\beta_2=0.$$

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Emission of Secondary Neutrons from Nuclei Bombarded by High-Energy Neutrons*

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The mean number of secondary neutrons emitted in a single act of absorption of 120- and 380-Mev neutrons by Be, C, Al, Fe, Cu, Sn, and Pb nuclei has been determined for secondary neutron energies up to ~15–20 Mev; the neutrons are predominantly emitted as a result of evaporation which occurs after an intranuclear nucleon cascade. The mean number of secondary neutrons was found to increase monotonically from carbon ($\nu=1$–1.8) to lead ($\nu=6.6$–9.9) and was almost constant when the primary neutron energy was varied from 120 to 380 Mev. The experimental results are compared with those obtained by studying star formation in nuclear emulsions and also fission of heavy nuclei and the production of neutrons by cosmic rays.

I. INTRODUCTION

DURING the years following the advent of the first relativistic heavy-particle accelerators a number of investigations were carried out on star formation induced by high-energy nucleons. Two stages of interaction between high-energy nucleons and nuclei were invoked to explain star formation, namely, an internal nucleon cascade in the nucleus and a subsequent process of evaporation of nucleons from the heated, excited nucleus.

Agreement between the theoretical predictions and experimental results pertaining to the main properties of cascade nucleons indicated that the intranuclear nucleon cascade model proposed by Goldberger[1] and developed by Bernardini[2] satisfactorily described the first stage of interaction between nuclei and high-energy nucleons. The second step of this interaction was theoretically studied in great detail by Le Couteur[3] on the basis of the particle evaporation concept proposed by Weisskopf.[4] It has been the object of a large number of investigations to check experimentally the theory of particle evaporation which is assumed to occur in the nuclear interaction of high-energy nucleons. However the results of these studies were not completely convincing since, as a rule, only nuclear emulsions or cloud chambers were employed.

Despite the merits of these methods they possess some serious shortcomings which become apparent when one uses them to study the dependence of star formation on mass number of the bombarding nuclei or, to an even greater extent, when they are employed in neutron emission studies. In general no systematic study of neutron emission in the interaction between

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* This work was presented by V. I. Gol'danskii at the Gordon Research Conference on Nuclear Chemistry, June, 1957.

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[1] M. Goldberger, Phys. Rev. **74**, 1269 (1948).

[2] Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 826 (1952); **88**, 1017 (1952).

[3] K. J. Le Couteur, Proc. Phys. Soc. (London) **A63**, 259, 498 (1950).

[4] V. Weisskopf, Phys. Rev. **52**, 295 (1937).

nuclei and high-energy nucleons has been carried out up to the present time. However, in order to obtain a better idea of the nature of high-energy nuclear reactions it would undoubtedly be of interest to study the emission of secondary neutrons from various nuclei. We consequently carried out in 1950–1951 some investigations of this type with the synchrocyclotron which belongs now to the Joint Institute for Nuclear Research.

II. EXPERIMENTAL METHOD

We investigated the emission of secondary neutrons from Be, C, Al, Fe, Cu, Sn, and Pb nuclei induced by high-energy neutron bombardment.

The neutrons used in the 1950 experiments were obtained by stripping 280-Mev deuterons in a 16-mm copper target. The average energy of the neutrons thus obtained was 120 Mev. In the 1951 experiments the neutrons were obtained by charge exchange of 480-Mev protons in a 25-mm beryllium target. The peak of the neutron spectrum was located at about 380 Mev.[5] The neutron beam employed to bombard the investigated samples was collimated by a pipe of square cross section (10×10 cm^2) situated in a concrete shield whose thickness in various experiments varied from 2 to 5 m.

In order to measure the mean number of secondary neutrons produced per absorbed primary neutron, the following quantities had to be determined: (1) the flux of primary neutrons striking the investigated sample; (2) the fraction of the flux absorbed in the sample; (3) the yield of secondary neutrons.

Carbon, activated in the reaction $C^{12}(n,2n)C^{11}$, was used to determine the primary neutron flux. The cross section of this reaction for 120-Mev neutrons was assumed to equal 22 millibarns.[6] Independent experiments were performed to determine this cross section for 380-Mev neutrons; in this case *np* scattering data were used and a value of 21 millibarns was obtained.[7]

The counting efficiency of the graphite detectors and the magnitude of the effective operating mass depends on the self-absorption of the positrons from C^{11} and the geometrical conditions during the activity measurements. The geometrical counting efficiency was found by measuring the activity of a uranium standard with the aid of a thick-wall mica end-window counter (which counted decay β particles from UX_2). The absorption factor for C^{11} positrons in graphite was established by comparing the counting rate of samples activated under various conditions. For this purpose the thickness of the samples or the thickness of the aluminum layers surrounding them were varied. It was found in this way that the thickness of the effective operating layer was $(1/\mu)(1-e^{-\mu l})$, where l is the total thickness of the detector and $1/\mu=56$ mg/cm^2 for graphite.

In the principal experiments the graphite detectors were placed directly in front of the blocks (secondary neutron sources) and completely covered the irradiated surface of these blocks. To check any possible influence on the detector of scattered or secondary neutrons possessing energies above 20 Mev, we compared the graphite detector activity with the response of a detector possessing a higher threshold, namely, with that of an ionization chamber which recorded fission fragments from bismuth. The comparison was carried out under the actual experimental conditions as well as at large distances from any possible scatterers. The conclusion which could be drawn was that the carbon detectors yielded a correct value (one that was not too high) for the primary neutron flux striking the surface of the investigated samples.

The cross sections for inelastic collisions (σ_a) of 120- and 380-Mev neutrons with C, Al, and Pb nuclei obtained by direct measurement[8] were employed to determine the fraction of incident primary neutrons absorbed in the C, Al, and Pb blocks (secondary neutron sources). For other nuclei this fraction was determined by interpolation or from the total neutron interaction cross sections σ_t for these nuclei, it being assumed that $\sigma_a=\frac{1}{2}\sigma_t$. If the flux striking the surface of the block (S cm^2) is Π (n/cm^2 sec), the number of neutrons absorbed per second will be $\alpha\Pi S$ (n/sec), where $\alpha=1-e^{-h/\lambda_a}$; here $\lambda_a=1/N\sigma_a$ is the absorption length, N the nuclear density of the block in cm^{-3}, and h the thickness of the block in cm. If Q_x secondary neutrons are emitted per second, the average number of secondary neutrons emitted in the absorption of a primary neutron will be $\nu=Q_x/(\alpha\Pi S)$. The yield of secondary neutrons was determined by slowing them down and then activating indium or manganese in the reactions $In^{115}(n,\gamma)In^{116}$ and $Mn^{55}(n,\gamma)Mn^{56}$. A complete diagram of the experiments is shown in Fig. 1 (the dimensions of the secondary neutron moderator are not to scale) and Fig. 2. After traversal of the square collimator (channel in concrete wall) the beam entered a horizontal 12×12 cm channel directed along the beam axis; this channel passed through a cubical tank of 1 meter (or 1.4 meter) edge. The secondary neutron sources made of blocks of the aforementioned substances were placed in front of the tank. The area of the front

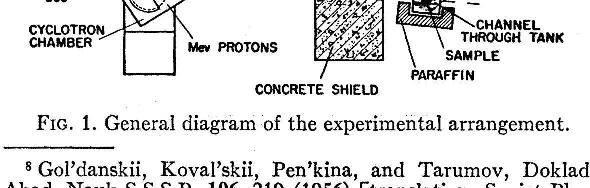

FIG. 1. General diagram of the experimental arrangement.

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[5] V. P. Dzhelepov and Yu. M. Kazarinov, Doklady Akad. Nauk S.S.S.R. **99**, 939 (1954).

[6] E. McMillan and H. York, Phys. Rev. **73**, 262 (1948).

[7] K. O. Oganesyan, Report of Institute for Nuclear Problems, Acad. Sci. USSR (1953).

[8] Gol'danskii, Koval'skii, Pen'kina, and Tarumov, Doklady Akad. Nauk S.S.S.R. **106**, 219 (1956) [translation: Soviet Phys. Doklady **1**, 16 (1957)].

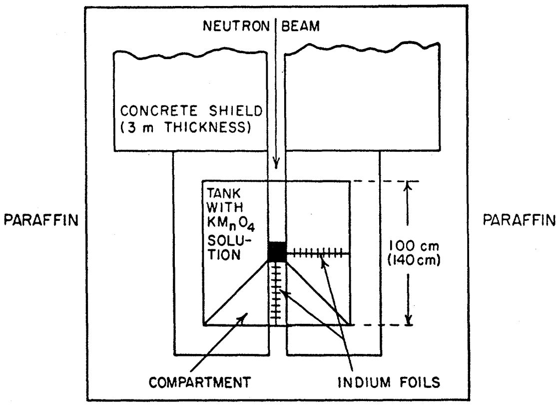

FIG. 2. Arrangement of secondary neutron sources (blocks) and detectors.

wall of the blocks was 100 cm^2 (10×10 cm) and the thickness in most cases was 10 cm. A 20-cm paraffin layer surrounded the tank and stopped scattered neutrons. The tanks were filled with water which was used to slow down the secondary neutrons emerging from the blocks of the investigated substances. The determination of the number of secondary neutrons with the aid of manganese is based on measurement of the total activation. No analysis of distribution of the activity in the moderator body was required in this case. Manganese in the form of potassium permanganate ($KMnO_4$) was dissolved in the tank water, up to a concentration of about 4 g/liter. Radiative capture activation of manganese induced by thermal neutrons ($\sigma = 10.7$ barns) involves a Szilard-Chalmers type of reaction in which the chemical bonds in the $KMnO_4$ molecule are ruptured and free manganese atoms are liberated. These atoms are then rapidly oxidized and insoluble MnO_2 is formed. Thus it was sufficiently easy to filter out samples of the solution which were taken from the tank after irradiation and careful mixing of the moderator; in this way practically all the Mn^{56} activity ($T_{\frac{1}{2}} = 2.59$ hr) could be retained on the filter. Special experiments showed that only about 1% of the activity was in the filtrate. There was no need to determine the absolute efficiency of the activity measurements since all data on manganese and indium activation were compared with the results obtained under identical geometrical conditions by replacing the blocks (secondary neutron sources) with a Ra-Be source [1.479g(Ra+MsTh)] enclosed in a lead cube of 10-cm edge. The strength of this source ($Q_0 = 1.2 \times 10^7$ n/sec) was specially determined by A. M. Kucher under definite standard conditions and was subsequently checked with an international calibrated source. Obviously the desired quantity equals $Q_x = Q_0(A_x/A_0)$, where A_0 and A_x are activities of identical samples of a potassium permanganate solution irradiated under identical geometrical conditions with a Ra-Be source (enclosed in a 10×10×10 cm lead cube situated at the center of the tank) and by secondary neutrons produced in the investigated blocks.

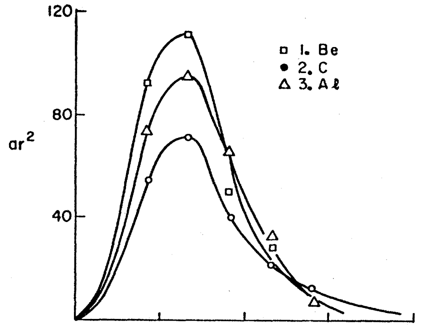

FIG. 3. Slowing-down curves of secondary neutrons from beryllium, carbon, and aluminum ($E_n{}^0 = 380$ Mev).

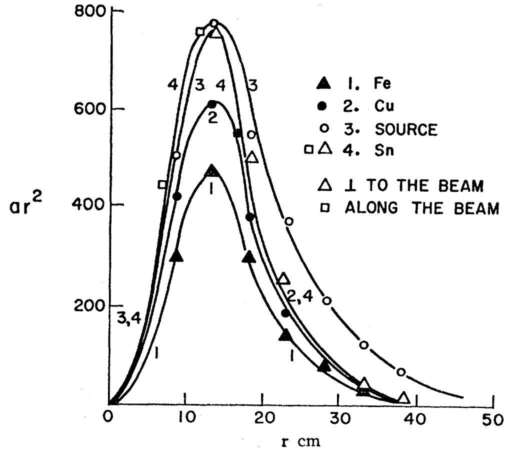

FIG. 4. Slowing-down curves of secondary neutrons from iron, copper, tin, and Ra-Be source ($E_n{}^0 = 380$ Mev).

In most measurements of the number of secondary neutron performed by activating indium, from 8 to 15 indium plates of 15 cm^2 area and approximately 0.1 mm in thickness were used. These plates were wrapped in cadmium foils so that the indium was activated by 1.44-ev resonance neutrons. The activity of the isomer In^{116*} was recorded (half-life 54 min, peak β-particle energy 0.85 Mev). The indium detectors were arranged perpendicularly to the primary neutron beam above the block and at distances of 3–5 cm from each other. After irradiation, measurement of activities of the various detectors, A, and reduction to the standard value $A_\infty{}^0$ (min^{-1}) (corresponding to infinite irradiation), slowing-down curves of the form $ar^2 = f(r)$ were plotted, where a (cm^{-2} sec^{-1}) denotes the standardized activity of a unit of the detector surface situated at a distance r cm from the center of the neutron source (Figs. 3–5). Evidently the integral of the slowing-down curve, $\int_0^\infty ar^2 dr$, is proportional to the strength of the neutron source, and hence

$$Q_x=Q_0\int_0^\infty a_x r^2 dr \Big/ \int_0^\infty a_0 r^2 dr;$$

that is, one can determine the unknown quantity Q_x from the ratio of the areas under standardized slowing down curves for neutrons from a Ra-Be source, and from the investigated block.[9]

Measurement of the slowing-down curves permits one to determine the age of resonance neutrons activating the indium and thus to estimate roughly the mean energy of the secondary neutrons; in this respect this method is more advantageous than that of determining the average activity in the moderator volume. To determine from the experimental data the age of the resonance neutrons which activate the indium, τ_{res} (cm^2), the following relation may be used:

$$\tau_{\text{res}}=\tfrac{1}{6}\langle r^2\rangle_{\text{Av}}=\tfrac{1}{6}\int_0^\infty a r^4 dr \Big/ \int_0^\infty a r^2 dr.$$

For estimation of the mean energy of the investigated secondary neutrons, the quantity $(\tau_{\text{res}})_x$ should be compared with $(\tau_{\text{res}})_0$ determined under the same conditions (that is, in the presence of a pipe passing through the tank) for a Ra-Be source. Determination of $(\tau_{\text{res}})_0$ when the latter source was located within a continuous moderator mass, yielded the value 45 cm^2, whereas under the conditions encountered in the experiments $(\tau_{\text{res}})_0$ was found to equal 64 cm^2. Thus, in estimating the mean neutron energy with the aid of the curve in Fig. 6 taken from Marshak's paper,[10] we increased all values of τ_{res} plotted along the ordinate axis by 40%.

In order to avoid recording secondary neutrons produced in the water as a result of interaction of primary neutrons elastically scattered from the blocks with oxygen nuclei, a compartment having the form of a truncated pyramid was made in the front part of the tank (with respect to the direction of the beam) and in part of the experiment this compartment was not filled with water. Comparison of the results obtained with empty compartments and with the compartments filled with water showed that the effect due to secondary neutron formation in the water itself was (within the accuracy of the experiments) negligible. This permitted us to carry out a few experiments in which the indium detectors were arranged not only at angle of 90° above the blocks but also in the direction of the primary beam; in the latter case the detectors were placed in a box filled with water and the box was closely mounted next to the source which was located in side the square pipe running through the tank. The measurements showed (Figs. 4, 5) that the slowing-down curves were identical in both directions and thus confirmed the validity of determining the total secondary neutron yield from slowing-down curves obtained at 90°; however, they cannot be considered as a proof of isotropy of emission of the recorded secondary neutrons (because of smearing out of any possible anisotropy during the slowing-down process).

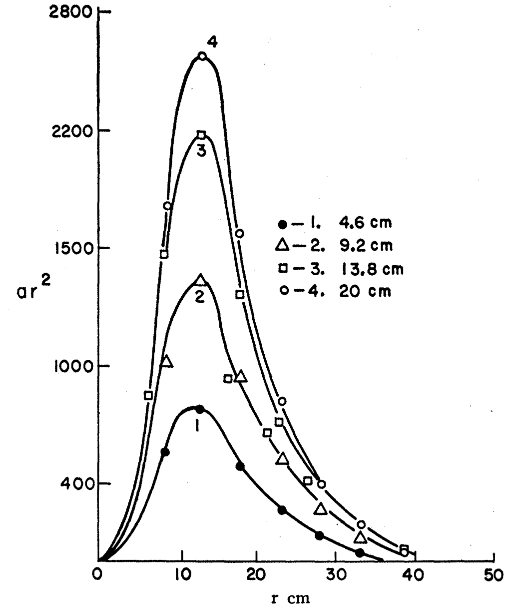

FIG. 5. Slowing down curves of secondary neutrons from lead blocks of various dimensions ($E_n{}^0=380$ Mev).

Besides the main experiments some auxiliary background measurements were carried out in the absence of the blocks (secondary neutron sources). These experiments indicated that background activation of indium due to neutrons scattered from the walls or surroundings and also to incidence of the diverging

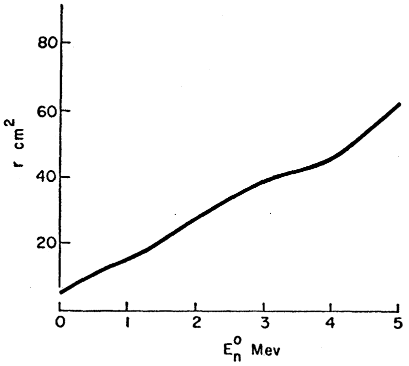

FIG. 6. Dependence of age of thermal neutrons in water on their energy prior to slowing down (after Marshak[10]).

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[9] In the 120-Mev neutron experiments only one In detector was used and its activity was assumed to be proportional to the total secondary neutron yield Q_x. Subsequent experiments with 380-Mev neutrons demonstrated the similarity of the slowing down curves for various nuclei (neutron sources) and thus confirmed the correctness of reduction of the experimental data obtained with a single detector in the first series of experiments.

[10] R. E. Marshak, Revs. Modern Phys. 19, 185 (1947).

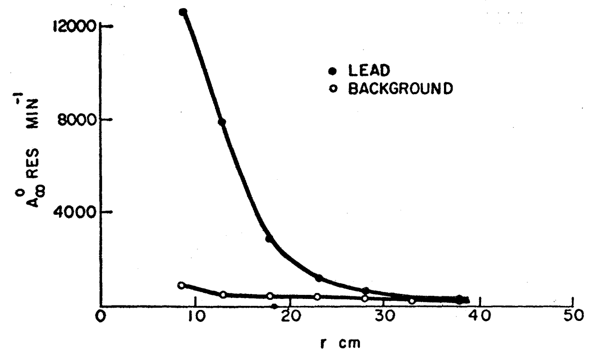

FIG. 7. Activation of indium detectors at various distances from beam axis as determined in background and principal experiments.

primary neutron beam on the edges of the pipe or on the tank water, was commensurate with the main effect only for distances of 25–35 cm from the beam (see, for example, Fig. 7). At such distances the product ar^2 is sufficiently small but ar^4 is only 1.5–2 times smaller than its maximal value. The background therefore did not considerably affect the accuracy of the neutron yield determinations but appreciably lowered the accuracy of the age determinations.

In the maganese experiments, in which the results were averaged over the moderator volume, the effect due to the background was naturally larger; for this reason these experiments (which require shielding of the tank with paraffin) could be carried out only by using lead blocks (secondary neutron sources) which were equivalent to a Ra-Be neutron source strength of several curies when the incident neutron flux was $\Pi = 10^5$ n/cm^2 sec. Even in these experiments the background activation was about half as large as that obtained in the presence of the blocks. However, in experiments with lighter nuclei, when the strength of the secondary neutron sources was 0.1–1 curie (10^6–10^7 n/sec), the background activation of manganese was too large. The duration of the experiments involving irradiation of indium or manganese was 30–80 minutes. Absolute values of the activity of the indium detectors can be deduced from the ordinates in Fig. 7. The absolute activities per liter of $KMnO_4$ solution were 2000–4000 disintegrations/min ($A_\infty^0 = 17\,000$–$35\,000$ disintegrations/min) in the experiments with Pb blocks. Since the slowing-down curves are valid only for water thicknesses of not more than 25–35 cm, it may be considered that in our experiments neutrons with energies not exceeding ~15–20 Mev were effectively slowed down and recorded. These neutrons are similar to the protons responsible for the "black" tracks observed in photographic emulsions; that is, they are mostly evaporation and not cascade neutrons.

TABLE I. Emission of secondary neutrons from various nuclei bombarded by 120-Mev neutrons.

Element	Block thickness (cm)	ν	Neutron binding energy (Mev)	Neutron kinetic energy (Mev)	Total excitation energy spent in neutron evaporation (Mev)
C	10	1.8±1	25	4	30±17
Al	10	1.5±0.8	17	3	20±10
Fe	10	1.5±0.8	12	3	15± 8
Cu	10	1.8±0.9	15	4	20±10
Sn	10	4.5±2	35	9	45±20
Pb	9.2	9 ±3	65	20	85±28
Pb (from Mn)	9.2	9.9±3.3	...	...	...

As a matter of fact, the range of 20-Mev neutrons in water is 12.6 cm, whereas the collision range for hydrogen in water is 38.6 cm. Thus these neutrons emerge from the tank with a sufficiently high probability after a few collisions. Statistical errors and the background are the main factors which affect the accuracy of determination of the relative mean number of secondary neutrons emitted from various nuclei (ν_{rel}) (referred to the value ν of a certain nucleus such as that of lead). For the 380-Mev experiments we estimate a precision of ±10–20%. The accuracy of determination of the absolute values of ν also depends on the error in determination of the cross section for the $C^{12}(n,2n)C^{11}$ reactions and of the strength of the source. The error these factors introduce is estimated to be ±35–50%.

III. RESULTS

A summary of the results is presented in Tables I and II.

All neutron yield data presented in Tables I and II (except those which are specially denoted) were obtained in experiments with indium detectors. In accord with Skyrme and Williams,[11] the kinetic energy of the neutrons estimated from their age was assumed to lie between 2 and 2.5 Mev. All evaporation energy values presented in the tables have been rounded off. Since the mean energy of evaporated neutrons is proportional to the temperature T, it may be concluded that in the neutron evaporation stage the temperatures of light and heavy nuclei are approximately the same. This corresponds, however, to higher excitation energies (U) of heavy nuclei since, according to the Fermi gas model, the coefficient a in the relation $U = aT^2$ increases with mass number; on changing from carbon to lead it increases by approximately a factor of five.

When the primary neutron energy is changed from 120 to 380 Mev, a decrease of the number of secondary neutrons possessing energies up to 15–20 Mev and of the energy expended in neutron evaporation is observed which apparently does not signify a general decrease of the neutron yield; the reason for this is[8] that the yield of secondary high-energy neutrons increases and it is these neutrons that are responsible for the transition effects observed in neutron absorption measurements performed with bismuth fission chamber and

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[11] D. M. Skyrme and W. S. C. Williams, Phil. Mag. 42, 1187 (1951).

TABLE II. Emission of secondary neutrons from various nuclei bombarded by 380-Mev neutrons.

Element	Block thickness (cm)	ν	Age (cm^2) τ_{res}	Neutron binding energy (Mev)	Neutron kinetic energy (Mev)	Mean excitation energy Spent in neutron evaporation (exper.)	Mean excitation energy Total for $E_n{}^0=400$ Mev (calc^{a})
Ra-Be source	...		64				
Be	10	1.6±0.8	38	12	3	15± 7	
C	10	1 ±0.6	42	18	2	20±12	
Al	10	1.6±1.1	39	15	3	18±12	35
Fe	10	2.3±1.2	37	20	5	25±13	
Cu	10	2.8±1	39	24	6	30±11	
Br	...						52
Ag							52
Sn	10	4.4±1.8	41	35	10	45±20	
Pb	4.6	6.5±2.4	45	50	15	65±24	94
Pb (from Mn)	9.2	7.4±2.5					
Pb	9.2	7.1±2.4	49				
Pb	13.8	7.7±2.6	49				
Pb	20	7.8±2.6	50				

[a] McManus, Sharp, and Gellman, Phys. Rev. **93**, 924 (1954).

graphite detectors. Rough estimates made on the basis of the results obtained previously[8] and on the assumption that high-energy neutrons are emitted at an angle of 0° lead to the conclusion that absorption of 380-Mev neutrons by lead or uranium nuclei involves the emission of a single secondary neutron whose energy lies above the threshold of the reaction $C^{12}(n,2n)C^{11}$ (i.e., $E_n>20$ Mev). About half of such neutrons lead to efficient fission of bismuth ($E_n>50$–60 Mev) (it has been assumed in the calculations that for neutrons inducing fission in bismuth $\sigma_{a\text{ sec.}}=\sigma_{a\text{ prim.}}$ and $\sigma_{f\text{ sec.}}=\frac{1}{2}\sigma_{f\text{ prim.}}$, and for neutrons activating carbon $\sigma_{a\text{ sec.}}=1.5\sigma_{a\text{ prim.}}$ and $\sigma_{n,2n\text{ sec.}}=\sigma_{n,2n\text{ prim.}}$). Here the subscripts a, f, and n,$2n$ refer to inelastic interaction, fission, and $(n,2n)$ reactions, and prim. and sec. to primary and secondary neutrons.

The effect due to fast secondary neutrons is manifest in Table II by the slight (20%) increase of ν with increase of the lead block thickness. It should be kept in mind that it is the errors in the absolute values of ν which are presented in Table II and as has been previously mentioned, these errors are much higher than those of the relative secondary neutron yields shown in Fig. 8 [dependence $\nu/\nu_{\mathrm{Pb}}=f(A)$]. Thus the 20% increase of ν due to increase of the lead block thickness exceeds the experimental errors. It should also be mentioned that under the described geometrical conditions it is certain that not all high-energy secondary neutrons could produce new "neutron stars" or $(n,2n)$ reactions in the lead blocks.

IV. DISCUSSION OF RESULTS

We shall compare the measured values of ν with the predictions of the statistical model based on the concept of particle "evaporation" from excited nuclei.

The "evaporation" mechanism at high excitation energies has been considered most thoroughly by Le Couteur.[3] The results of his calculations were found to be in good agreement with experimental results on star formation in photographic emulsions.[12–16] Therefore, instead of directly comparing our results with theory, we shall compare the experimental data on neutron emission and the data on emission of charged particles. On the basis of his investigation of the relative probabilities for proton and neutron emission Le Couteur predicted the following peculiarities of the evaporation process. There should be a small neutron deficiency in the final nucleus, the magnitude of this deficiency being independent of the initial excitation energy. Owing to the small magnitude of the excitation

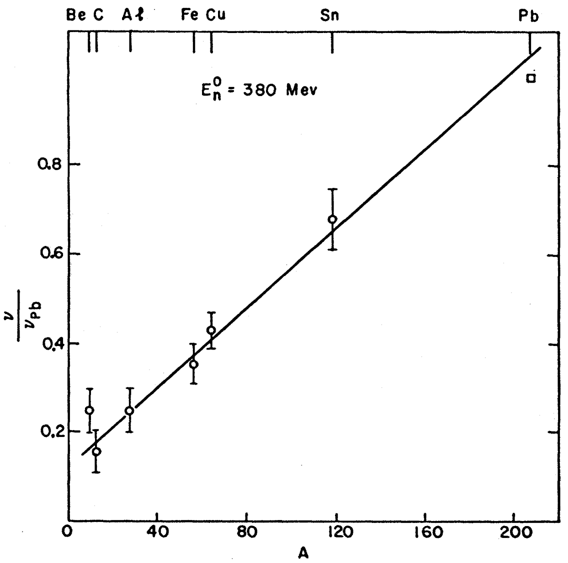

FIG. 8. Dependence of the relative average number of secondary neutrons (assuming that $\nu=1$ for lead) on mass number of nuclei for $E_n{}^0=380$ Mev.

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[12] Meschcheryakov, Grigoriev, Bogachev, and Soroko, Report of Institute for Nuclear Problems, Acad. Sci. USSR (1950).

[13] Y. B. Harding, Phil. Mag. **42**, 63 (1951).

[14] N. Page, Proc. Phys. Soc. (London) **A63**, 260 (1950).

[15] P. E. Hodgson, Phil. Mag. **42**, 82 (1951).

[16] I. G. Barbour, Phys. Rev. **93**, 534 (1954).

TABLE III. Comparison of the experimental data on neutron emission with calculations based on experiments performed with nuclear emulsions.

	Computed values							
Nucleus	ξ	α/H	Number of particles with $z=1$	$Z_{\text{fin.}}$	$A_{\text{stab.}}$	ν	ν (120 Mev)	ν (380 Mev)
Pb	0.20	0.3	4.6	74	184	10	9.9±3.3	(6.5±2.4)+1
Sn	0.25	0.3	3.8	44	102	7.5	4.5±2	4.4±1.8
Ag	0.27	0.3	3.6	41	93	6		
Br	0.33	0.4	2.9	30	67	5		
Cu	0.40	0.5	2.3	24	53	3	1.8±0.9	2.8±1

energy the final nucleus should become stable by γ-ray emission, β decay, or K capture. It should also be mentioned that investigations performed with electron-sensitive plates[12] show that most star products are not β active and that they are either stable nuclei or nuclei decaying via electron capture. This is the basis of Pontecorvo's[17] method of estimating the number of evaporation neutrons by computing the mass number of the final nucleus and assuming that the number of neutrons corresponds to maximal stability ($A_{\text{stab.}}$). In this case the most probable value of the mass number $A_{\text{fin.}}$ of a final nucleus possessing a charge $Z_{\text{fin.}}$ is close to $A_{\text{stab.}}$, where $A_{\text{stab.}}=2Z_{\text{fin.}}[1+(1/131)A_{\text{stab.}}^{\frac{3}{2}}]$ and $Z_{\text{fin.}}$ can be found by analyzing the star data presented in references 13–16.

From these data one may derive the approximate form of the star prong distribution curve, $Q(n)=\text{const}\times e^{-\xi n}$, where ξ is a constant, and also information relating to the ratio α/H between the number of prongs of doubly-charged particles (mostly alphas) and singly charged particles (p, d, t). Evidently for an exponential prong distribution curve the mean number of prongs per star will be $\bar{n}=1+1/\xi$. Knowing ξ and α/H and assuming that the mean mass of singly charged particles is 1.3 (as d and t are also emitted), it is easy to estimate the sum of the charges and masses of all charged particles in the stars, that is, to find $Z_{\text{fin.}}$ and $A_{\text{fin.}}$ (taking account of neutrons) and hence $\nu=A_{\text{fin.}}-A_{\text{stab.}}$. The results of such rough calculations are presented in Table III.

As can be seen from Table III, the experimental results agree satisfactorily with the computations based on Le Couteur's work.[3] Experimental data from references 13–16, which also agree satisfactorily with Le Couteur's theory, were used in these calculations. The conclusion that may be drawn is that our results agree with the theory of evaporation of nuclear particles at high excitation energies and that the theory is confirmed not only for charged particles but for neutral particles as well. It should be noted that the energy spent in evaporation of neutrons also agrees reasonably well with the mean excitation energies of various nuclei bombarded by 400-Mev nucleons. The energy values were computed by the Monte Carlo method and are presented in Table II. It can be seen from Table I that in the case of lead almost all of the energy of 120-Mev neutrons is spent in emission of relatively low-energy secondary neutrons. Emission of such a neutron requires the expenditure of about 10–15 Mev, which is three times smaller than the energy expended in the formation of a "black" proton track (which is usually accepted in the literature to equal 35 Mev). If the energy of the incident neutrons is 380 Mev, the residual excitation energy of the nucleus which is responsible for neutron evaporation is relatively small for all types of nuclei, and this signifies that most of the energy is carried away from the nucleus already in the first interaction stage, that is, in the intranuclear nucleon cascade.

It would seem to be of interest to compare the results obtained in the present work with available data on fission of heavy nuclei obtained for excitation energies of the order of tens or hundreds of Mev. Beginning in 1949,[18] many arguments have been presented which indicate that this fission is of the emissive type, that is, that it is preceded by the emission of a large number of neutrons. However, as a rule, the number of neutrons emitted prior to fission (ν_f) has been determined by indirect and quite rough methods such as from the position of the hump in the fission fragment spectrum[18–21] or by analysis of the variation of the fission cross section with decreasing atomic number from uranium to lighter nuclei (down to tungsten[22]) and also from the dependence of the ranges of definite fragments on the energy of the fission-producing particles.[23] Only recently some papers by Harding[24,25] have appeared which contain convincing proof[25] that most of the neutrons are emitted prior to fission. This author

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studied the angular distribution of neutrons relative to the direction of fragment emission and confirmed the finding that fission of uranium nuclei induced by 150-Mev protons is of the emissive type. According to Harding,[24] coincidence measurements between bismuth uranium fission fragments and fission neutrons indicate that in the fission induced by 150-Mev protons the mean number of neutrons per fission act is 10.0±2.7 for bismuth and 13.1±1.6 for uranium (in the latter case 2.5±1 neutrons are emitted by the fission fragments and 10.6±1.9 neutrons are emitted prior to fission).

Our data on the mean number of neutrons emitted in the absorption of 120-Mev neutrons by lead nuclei (see Table I) agree quite well with Harding's results for bismuth fission. By extrapolating the dependence of the mean number of secondary neutrons on the mass number to uranium, we also obtain good agreement with Harding's data for uranium fission.

For a more detailed comparison of neutron emission in the fission of heavy nuclei and in any other processes of inelastic interaction of high-energy nucleons with such nuclei, it would be very desirable to continue direct experiments on the measurement of the average number of neutrons emitted per fission act.

It would be even more interesting to investigate (by employing the coincidence technique described by Diven *et al.*[26] and Hicks *et al.*[27]) the distribution of secondary neutrons emitted in fission and processes of inelastic interaction between high-energy nucleons and various heavy nuclei.

In conclusion we shall compare our results with those of Cocconi and Cocconi-Tongiorgi[28–30] who investigated the production by cosmic rays of secondary neutrons with energies up to 15 Mev in lead and carbon. It was shown in a study of secondary neutron emission coherent with extensive penetrating showers[30] that from 30 to 60 secondary neutrons are emitted per primary nucleon absorbed in a 5-cm lead block. However, if neutrons which were not coherent with extensive showers (and were thus produced by particles of smaller energy) were investigated,[29] the number of secondary neutrons was found to be much smaller, and equaled 8 for lead and 1.6 for carbon. The number of secondary neutrons emitted in this way from lead and carbon was determined by other authors and found to equal 6.5 [31] and 7.5.[32] The mean energy of secondary neutrons emitted from lead and carbon has been estimated to be 3 Mev.[29] Their angular distribution has not been investigated but it has been shown that emission in the forward and backward directions (into each hemisphere) is practically the same.[30] Besides the secondary neutrons with energies below 15 Mev which were recorded in the experiments, it is probable that high-energy neutrons were also emitted. An indication of this is the fact mentioned by Cocconi and Cocconi-Tongiorgi,[30] that with increase of block thickness the mean number of secondary neutrons emitted from lead per primary particle also increases. The data cited above apparently prove that, in contrast with the relatively rare processes of the explosion type which are concurrent with extensive showers, the formation of secondary neutrons which are not coherent with extensive showers is exactly analogous to that observed by us under laboratory conditions. This agreement may be regarded as a proof that the main source of cosmic-ray neutrons are nuclear disintegrations of the usual type produced by nucleons with energies of several hundreds of Mev.

V. CONCLUSIONS

1. The mean number of secondary neutrons with energies up to 15–20 Mev produced by 120- and 380-Mev neutrons in Be, C, Al, Fe, Cu, Sn, and Pb nuclei has been determined. This number increases from 1–1.8 for carbon to 6.5 (380 Mev) or 9–10 (120 Mev) for lead.
2. The mean energy of the observed secondary neutrons determined from age measurements (from the shape of the showing-down curves) is 2–2.5 Mev.
3. The number of secondary neutrons possessing energies above 15–20 Mev increases with increase of the primary neutron energy from 120 Mev to 380 Mev; the number of secondary neutrons with energies up to 15–20 Mev is constant in this case (or even slightly decreases).
4. Comparison of the results of the present investigation with data pertaining to secondary charged particles and hence with the theory of particle evaporation at high excitation energies, yields satisfactory agreement between the theory and experiment.
5. The average number of secondary neutrons emitted by a lead nucleus after absorption of a 120-Mev neutron is equal to the average number of neutrons emitted in fission of bismuth induced by 150-Mev protons.[24]
6. Comparison of our results with results on neutron production in cosmic rays confirms the conclusion that the main neutron-producing component in the cosmic radiation consists of nucleons with energies of hundreds of Mev.

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