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Neutron Nonelastic Cross Sections at 21.0, 25.5, and 29.2 Mev*

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Neutron nonelastic collision cross sections for eleven elements have been measured in the energy range 21–29 Mev. Corrections were applied to the data by means of a UNIVAC calculation. Since no experimental neutron angular distributions are available in this energy region, optical-model calculations were used for the correction problem. In general the cross sections at 25 Mev are 10% to 20% lower than at 14 Mev.

INTRODUCTION

THE Livermore variable-energy cyclotron can produce monoenergetic neutron beams in the energy range 7–29 Mev when used with the $D(d,n)He^3$ and $T(d,n)He^4$ reactions. Previous papers by the present authors have covered nonelastic collision cross-section measurements at 14 Mev[1] and in the range 7–14 Mev.[2] The present paper extends these results to the higher energies available at the cyclotron. The cyclotron energy can be extended below 7 Mev by means of the $T(p,n)He^3$ reaction, but this energy range has been well covered by the very accurate measurements of Beyster and co-workers.[3] Although the sphere transmissions were measured as accurately in the present work as at the lower energies,[1,2] the uncertainties in the final cross-section values quoted here are somewhat larger due to the fact that angular distributions, which are necessary in order to apply corrections to the data, have not been measured in this energy region. In lieu of experimental data, optical-model calculations of the angular distributions were used. Since the optical model, which is that of Bjorklund and Fernbach,[4] gave values for both total and total nonelastic cross sections that were accurate to within about 10%, it is felt that the angular distribution calculations were good enough to permit detailed corrections to the data. Total cross sections were obtained from the measurements of Peterson and co-workers.[5]

Plots of the neutron nonelastic collision cross section against energy in the 0–30 Mev range show that after the initial rise at threshold, the cross sections are flat in the 7–14 Mev region and then fall off gradually at the higher energies. Tin and lead show indications of a slight increase in cross section with energy in the 21–29 Mev region.

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1 MacGregor, Ball, and Booth, Phys. Rev. **108**, 726 (1957). This work was carried out at the Livermore Cockcroft-Walton accelerator.
2 Ball, MacGregor, and Booth, Phys. Rev. **110**, 1392 (1958).
3 Beyster, Henkel, Nobles, and Kister, Phys. Rev. **98**, 1216 (1955); Beyster, Walt, and Salmi, Phys. Rev. **104**, 1319 (1956).
4 We are indebted to F. Bjorklund and S. Fernbach for these calculations.
5 Bratenahl, Peterson, and Stoering have measured total cross sections at 25 and 29 Mev (private communication). We are grateful for the use of their data before publication.

EXPERIMENTAL

The equipment used for the present measurements has been well described in previous papers.[1,2] A $\frac{3}{4}$-in. diameter plastic-scintillator neutron detector was used which limited gamma-ray pulse heights to a neutron equivalent of about 10 Mev. The scattering sphere was positioned and removed automatically, and data were taken at ten detector biases simultaneously. A scintillation counter biased to match the detector was used to monitor the neutron beam. The beam energy was determined by making range measurements on the deuteron beam and using the kinematics of the $T(d,n)He^4$ reaction. All electronic equipment including the scintillation detector was temperature-stabilized,[6] and a precision pulser was used to set the detector biases initially and to check periodically the stability of the system. The pulser was calibrated by means of the detector neutron spectrum displayed on a 256-channel pulse-height analyzer. Calibration of the detector efficiency as a function of neutron energy was accomplished with the aid of a proportional counter telescope monitor.

CORRECTION FACTORS

The theory of neutron sphere transmission measurements, as applied to the present work, has been discussed in considerable detail in references 1 and 2. Corrections must be applied for (1) energy loss of the elastically scattered neutrons; (2) multiple-scattering; (3) finite detector size; (4) finite source-detector

TABLE I. Neutron nonelastic collision cross sections (in barns) at 21.0, 25.5, and 29.2 Mev.

Element	σ_{nx} 21.0	25.5	29.2
Be		0.38±0.05	
C	0.49±0.04	0.44±0.04	0.45±0.04
Mg	0.78±0.05	0.78±0.05	0.76±0.05
Al		0.81±0.05	
Ti		1.08±0.06	
Fe		1.21±0.07	
Cu	1.39±0.07	1.33±0.07	1.30±0.07
Zr		1.58±0.08	
Sn	1.72±0.08	1.77±0.08	1.83±0.10
Pb	2.44±0.10	2.56±0.10	2.60±0.10
Bi		2.43±0.10	

6 Ball, Booth, and MacGregor, Nuclear Instr. **1**, 71 (1957).

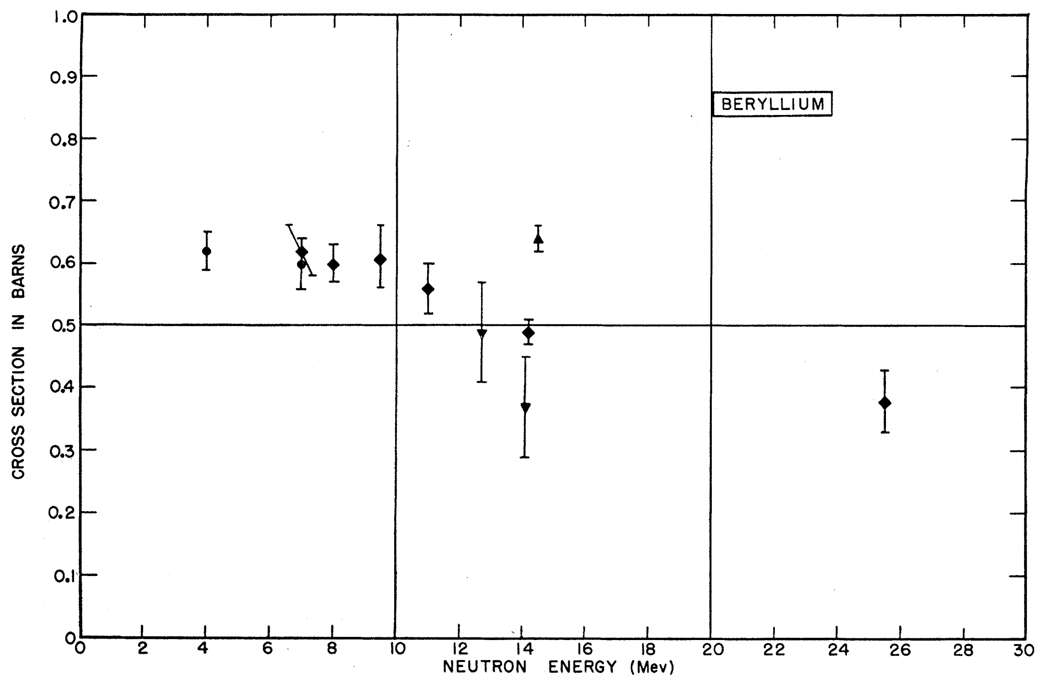

Fig. 1. Neutron nonelastic collision cross-section measurements on beryllium. The data for Figs. 1–11 are from the following sources: ● Beyster and co-workers (reference 3); × E. R. Graves and R. W. Davis, Phys. Rev. **97**, 1205 (1955); ▲ N. N. Flerov and V. M. Talyzin, Soviet J. Atomic Energy (U.S.S.R.) (English Translation) No. 4, 617 (1956); ▼ Taylor, Lonsjo, and Bonner, Phys. Rev. **100**, 174 (1955); ♦ MacGregor, Ball, and Booth (present work and references 1 and 2). The low values at 12.7 and 14.1 Mev (▼) are due to the fact that the data were overcorrected (see reference 1). The high value at 14.5 Mev (▲) is because no corrections were applied (see reference 1).

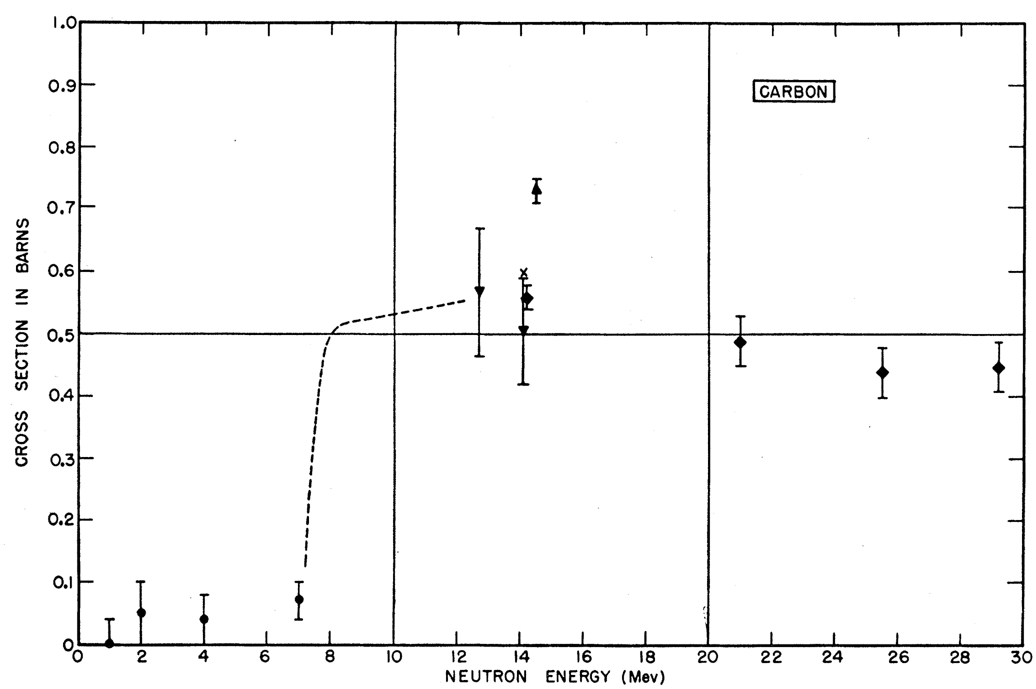

Fig. 2. Neutron nonelastic collision cross-section measurements on carbon. The low (▼) and high (▲) values at 14 Mev are for the same reasons as discussed for beryllium in Fig. 1. Graves (×) estimated a correction of 0.05 barn at 14 Mev, which would would put this measurement into agreement with the Livermore measurement (♦). The dotted line represents preliminary measurements by the present authors.

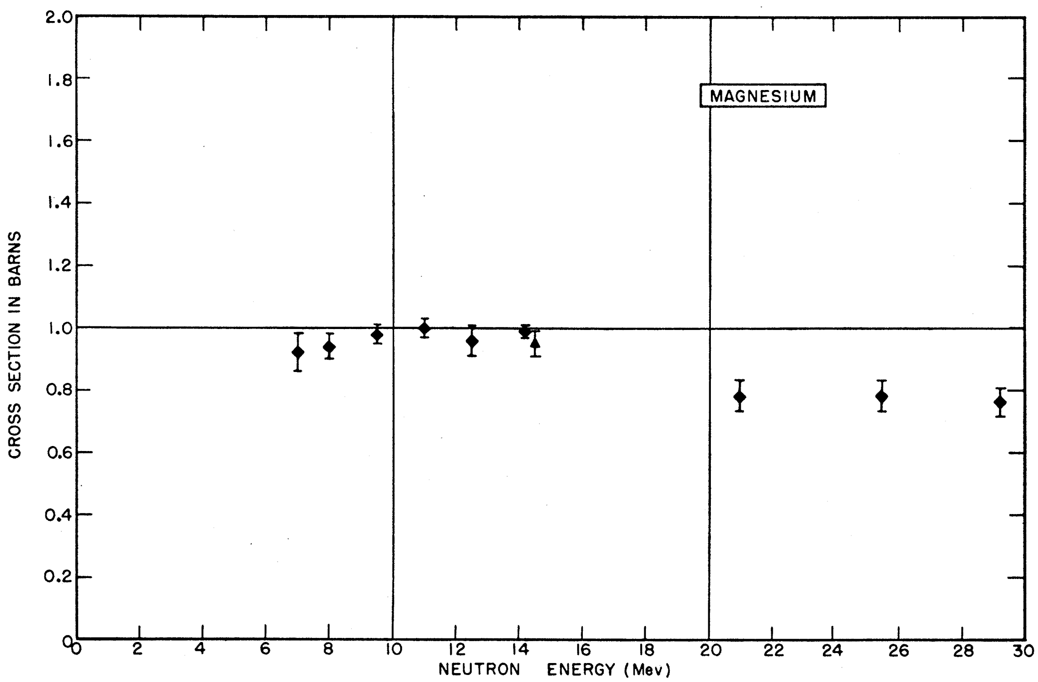

FIG. 3. Neutron nonelastic collision cross-section measurements on magnesium.

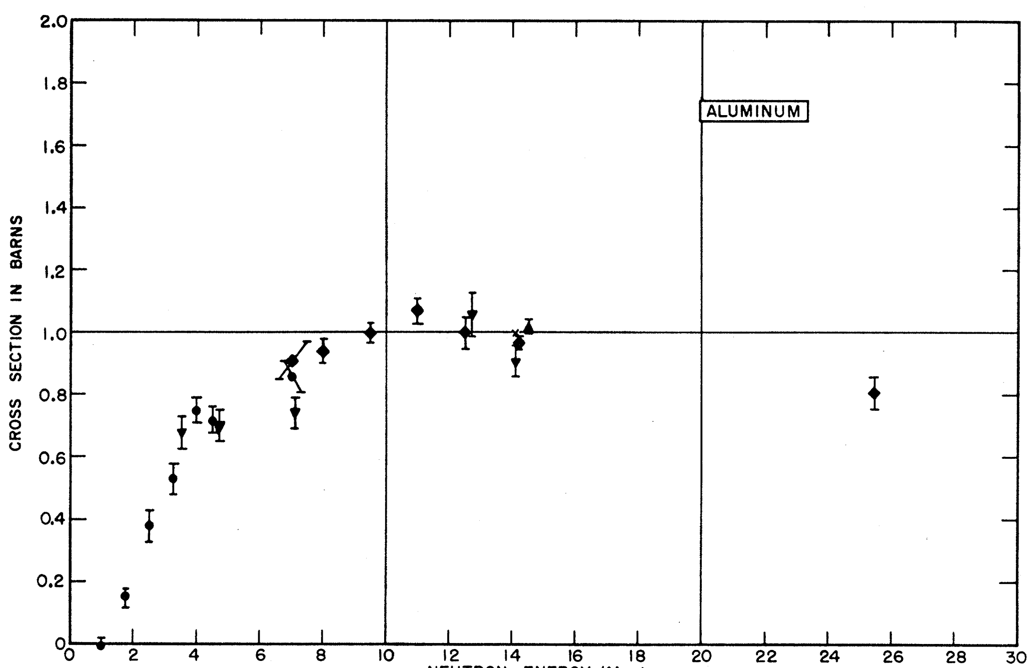

FIG. 4. Neutron nonelastic collision cross-section measurements on aluminum. The low (▼) and high (▲) values at 14 Mev are for the same reasons as discussed for beryllium in Fig. 1. although since aluminum is a heavier element the effect (correction 1) is less pronounced.

spacing; and (5) variation of the neutron beam in energy and intensity as a function of the angle to the deuteron beam. In order to compute these corrections, it is necessary to have accurate information on total cross sections and differential elastic-scattering cross sections. Correction 1 was applied to the data by means of a Monte Carlo calculation run on the Livermore UNIVAC. The detector efficiency as a function of

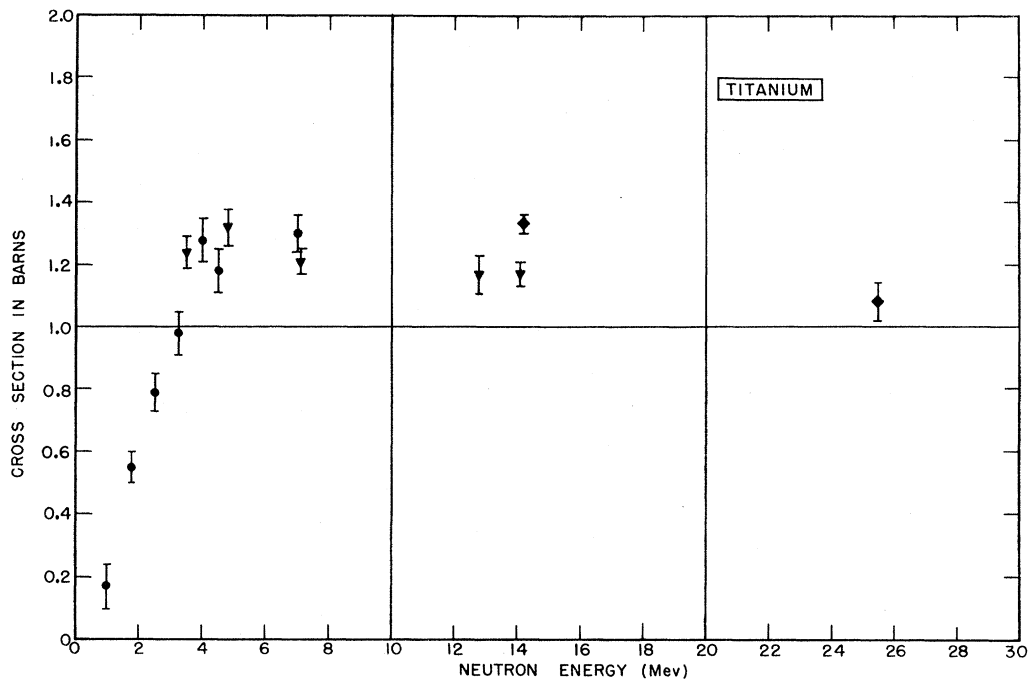

FIG. 5. Neutron nonelastic collision cross-section measurements on titanium. For elements with $Z>18$ the correction factors are small, and errors due to failure to make corrections and to use a high enough detector bias tend to compensate (see discussion in reference 1). Hence experimental results in Figs. 5–11 show no systematic variations.

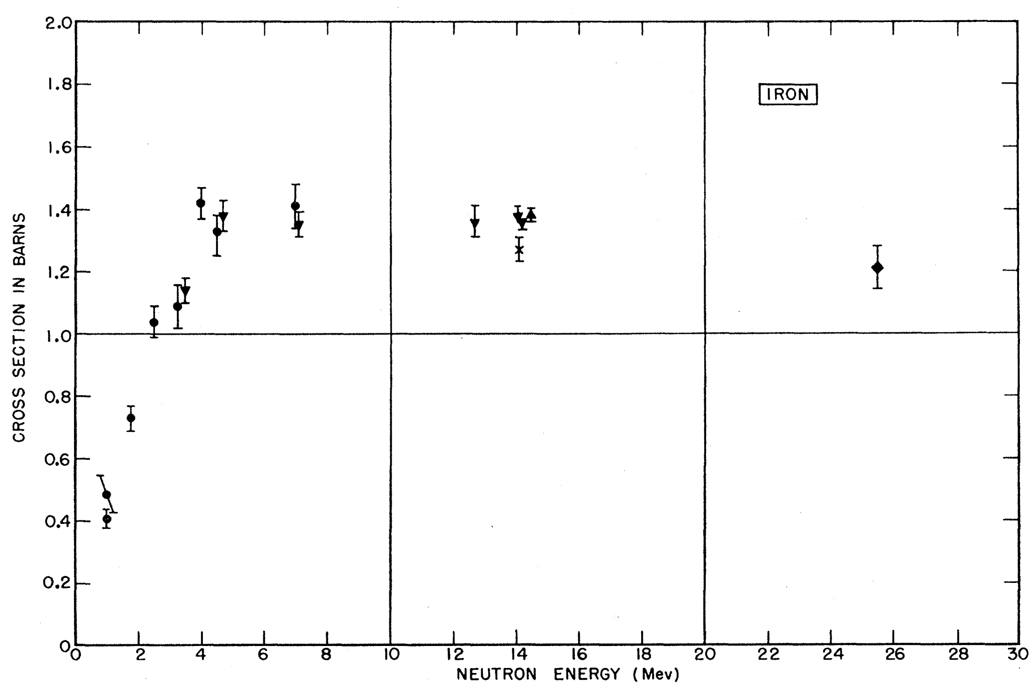

FIG. 6. Neutron nonelastic collision cross-section measurements on iron.

neutron energy, which is necessary for this correction, was determined experimentally for each of the ten biases. Corrections 2–5 were done analytically by means of another UNIVAC problem. The variation in detector efficiency as a function of the angle to the incident deuteron beam, which is necessary for correction 5, was determined experimentally.[7] In the present meas-

[7] Details of the analytical equations used can be found in Bethe, Beyster, and Carter, Los Alamos Report LA-1429, 1955, (unpublished).

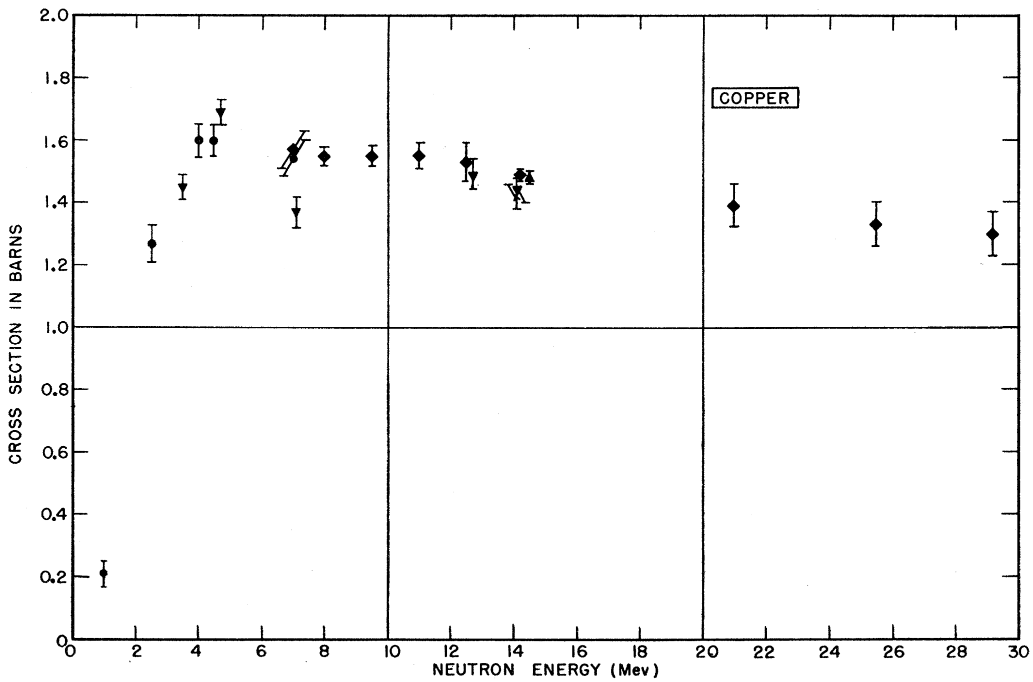

FIG. 7. Neutron nonelastic collision cross-section measurements on copper.

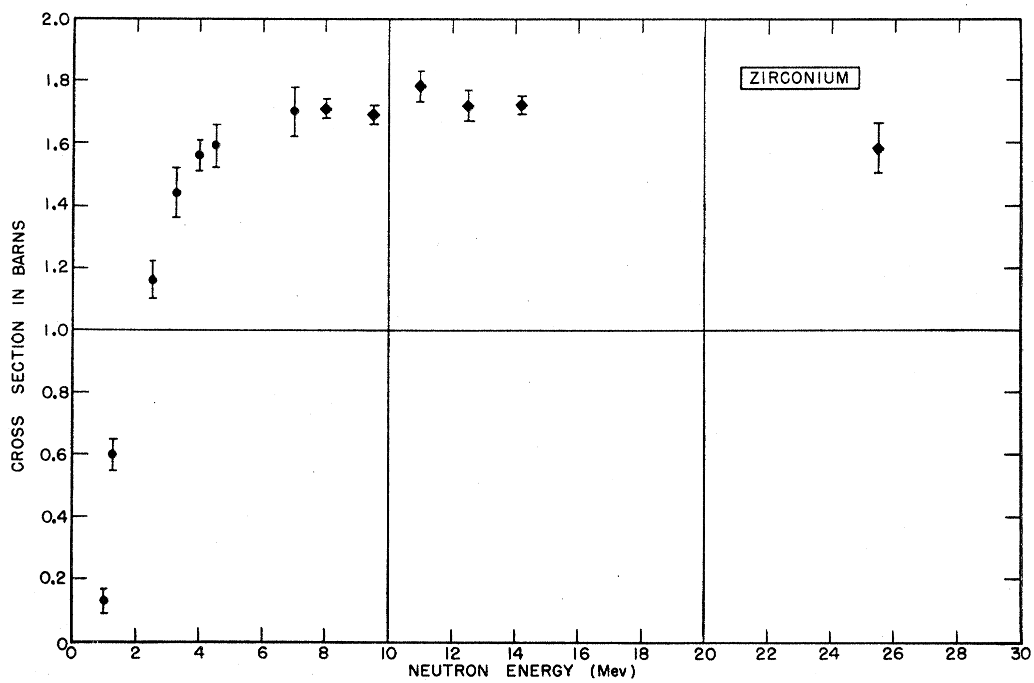

FIG. 8. Neutron nonelastic collision cross-section measurements on zirconium.

urements the neutron detector was placed at an angle of 0° to the deuteron beam. For light elements correction 1 is by far the most important. This correction, unfortunately, is the one most sensitive to the shape of the angular distribution. Corrections 2–5, which for the sphere thicknesses used in the present work—$\frac{1}{4}$ to $\frac{1}{8}$ of an inelastic mean free path—amount to about 5% in cross section for all elements, are rather insensitive to changes in the total or differential elastic-scattering cross sections. For elements with $Z>18$, correction 1 is less important than the other corrections.

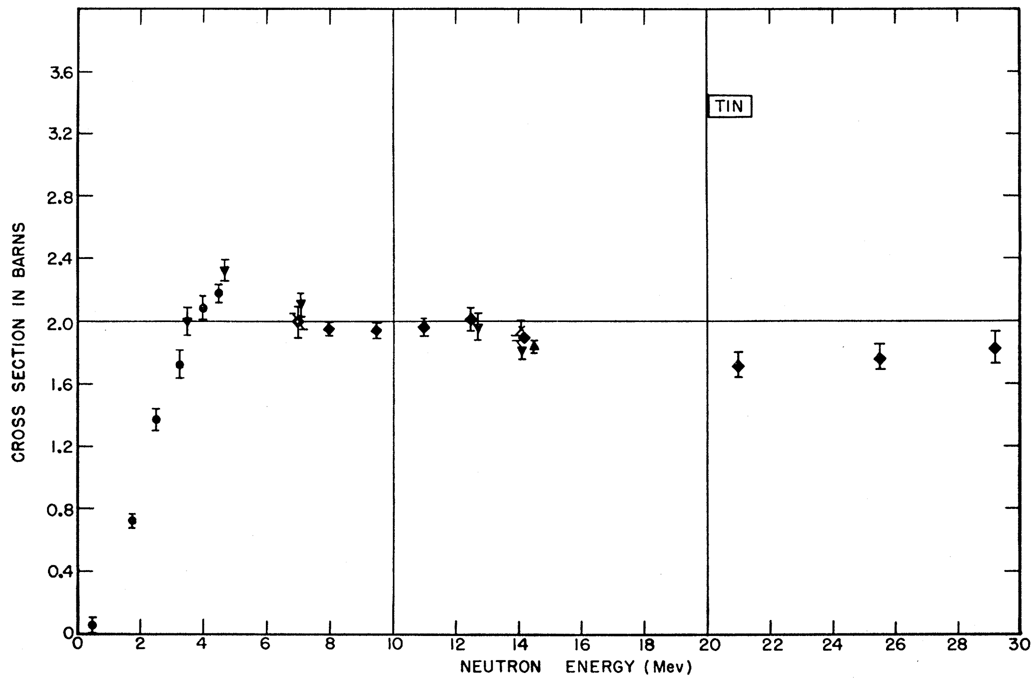

Fig. 9. Neutron nonelastic collision cross-section measurements on tin. The measurements indicate a slight rise from 21 to 29 Mev, although the total cross section is decreasing in the same region.

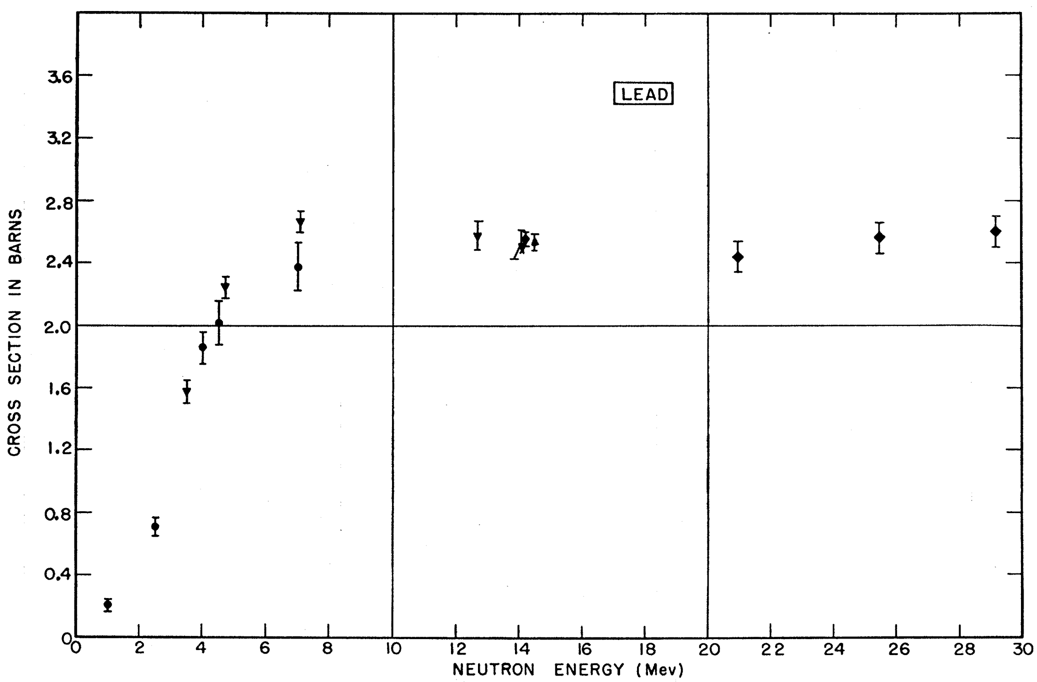

Fig. 10. Neutron nonelastic collision cross-section measurements on lead. This is the only case measured where the cross-section value at 25 Mev is as high as the value at 14 Mev.

RESULTS

Transmission data were taken at ten different biases simultaneously. After corrections had been applied, the top few biases gave the same cross-section values, showing that the biases were high enough to exclude inelastically-scattered neutrons and gamma-ray effects. The flatness of the high-energy plateaus also indicated that the corrections to the data were accurate. The

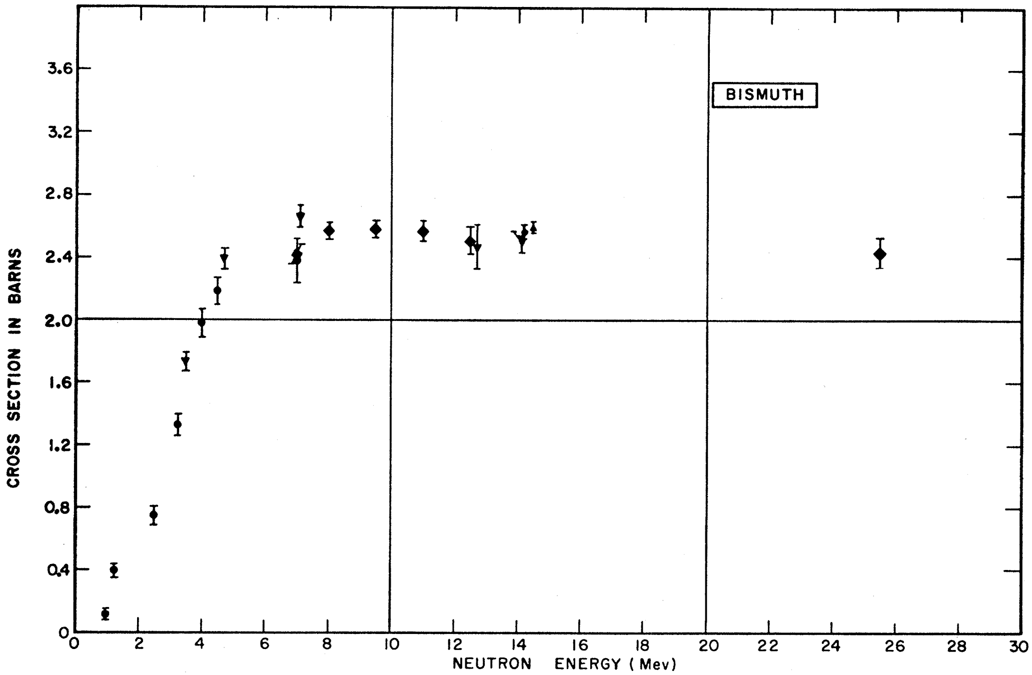

FIG. 11. Neutron nonelastic collision cross-section measurements on bismuth.

neutron nonelastic cross sections obtained from the present measurements are listed in Table I. The major uncertainty in the results is due to the lack of experimental measurements of differential elastic scattering cross sections in this energy region. Angular distributions for the correction problems were obtained by optical-model calculations, using the model of Fernbach and Bjorklund.[4,8] This optical model gives a good fit to neutron total, nonelastic, and differential cross sections in the 7–14 Mev energy region. Good agreement is also obtained with proton data at 17 Mev.[9] A study of the variation of the optical-model parameters with energy shows that the most significant change occurs in the depth of the real potential. The optical model potential[8] is of the form

$$V=V_{CR}\rho(r)+iV_{CI}q(r)+V_{SR}\left(\frac{\hbar}{\mu c}\right)^2\frac{1}{r}\frac{d\rho(r)}{dr}\boldsymbol{\sigma}\cdot\mathbf{l},$$

where

$$\rho(r)=[1+e^{(r-r_0)/a}]^{-1}$$

and

$$q(r)=\exp(-[(r-r_0)/b]^2).$$

At 21, 25, and 29 Mev, V_{CR} was chosen to be 40 Mev, 37.5 Mev, and 35 Mev, respectively. The other parameters were kept fixed at the following values.

$$V_{CI}=11.0\text{ Mev},\quad V_{SR}=8.3\text{ Mev},\quad r_0=1.25A^{\frac{1}{3}},$$
$$a=0.65\times10^{-13}\text{ cm},\quad b=0.98\times10^{-13}\text{ cm}.$$

With these parameters, the optical-model calculation gave total cross sections that were within 10% of experimental values in every case, and it gave nonelastic collision cross sections that were within 10% of experimental values in every case except for beryllium and carbon. Hence the angular distributions that were predicted should be reasonably accurate.

A summary of the neutron nonelastic collision cross

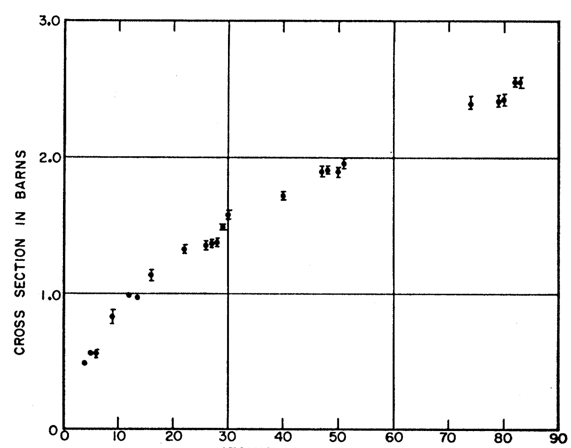

FIG. 12. Neutron nonelastic collision cross-section measurements for 23 elements at 14.2 Mev. Data from reference 1.

[8] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).
[9] S. Fernbach (private communication).

sections over the 1–30 Mev energy range for the elements listed in Table I is given in Figs. 1–11. As an aid in interpolating between these results, Fig. 12 summarizes the neutron nonelastic collision cross-section measurements on some 23 elements at a single energy, 14 Mev.[1]

ACKNOWLEDGMENTS

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Search for Delayed Neutrons from the Photon Bombardment of Lithium*

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A search has been made for delayed neutrons resulting from the reaction $Li^7(\gamma,2p)H^5$ in an effort to decide whether or not H^5 exists. Delayed neutrons were detected in a moderated counter assembly and scaled in nine delay channels which were variable in width and initial delay. A small signal observed after background subtraction showed no decay within statistics over a period of 0.45 sec. The first 0.05-sec counting period has been analyzed for the presence of a decay of 0.01-sec half-life and compared with a predicted yield of the reaction $Li^7(\gamma,2p)$ obtained by extrapolation of the measured yields of the reactions $B^{11}(\gamma,2p)$ and $F^{19}(\gamma,2p)$. The conclusion is that less than one percent of the expected $Li^7(\gamma,2p)$ yield can result in a particle stable final state.

I. INTRODUCTION

THE known delayed-neutron emitters among the light nuclei, Li^9 and N^{17}, belong to the nuclear species of the form $Z=2N-1$, $A=4N+1$. Of the other members of this series, B^{13} has recently been shown to exist[1] but no neutrons have been observed from its decay, and delayed-neutron emission from F^{21} is known to be energetically forbidden.[2] Searches have been made without success for other members of the series or for other unknown delayed-neutron emitters formed as a result of spallations induced by high-energy particles[3] and photons.[4] Attention has recently been drawn to the first member of the series described above by the suggestion[5] that H^5 might be particle stable. If so, H^5 would decay by energetic β^- emission ($\sim$19 Mev) to He^5, all states of which are unstable against neutron emission. The transition would be first-forbidden since the ground level of H^5 would be $(\frac{1}{2},+)$, while the ground level and first excited level of He^5 are odd. With outside limits on the mass and the ft value, one finds a minimum possible half-life of 0.01 sec.

Analysis of the previous searches in this region,[3,4] indicate that because of the targets chosen or the detection-sensitivity employed, detectable quantities of H^5, if particle stable, would probably not have been formed.

In this paper we present the results of a search for the delayed neutrons which would accompany the decay of H^5 formed by the reaction $Li^7(\gamma,2p)H^5$ if H^5 were particle stable.

II. EXPERIMENTAL PROCEDURE

The apparatus used was identical to that employed to measure the delayed-neutron yield from the photoproduction of Li^9 and has already been described in detail.[6] Neutrons are detected in a moderated array of enriched BF_3 proportional counters and scaled in nine delay channels following the photon burst from the Purdue University Synchrotron. The absolute neutron detection efficiency was determined with the aid of the Argonne National Laboratory standard Ra-Be working source.[7] Bremsstrahlung of peak energy 320 Mev bombarded a lithium target which was of natural isotopic abundance and 22.9 g/cm² thick. The beam was monitored with a "Cornell-type" thick-walled ionization chamber. The background was measured by replacing the lithium target with a copper absorber of the same thickness in radiation lengths.

The result of a first series of runs was a large delayed-neutron signal which varied linearly with target thickness and which had a half-life of 170 milliseconds. This signal was initially believed to be due to Li^9 formed from a contaminant in the target but the amount of contamination required to explain the observed yield was

* Supported in part by the U. S. Atomic Energy Commission.
[1] E. Norbeck, Jr., Phys. Rev. **105**, 204 (1957).
[2] Nelson Jarmie, Phys. Rev. **104**, 1683 (1956).
[3] Hubbard, Ruby, and Stebbins, Phys. Rev. **92**, 1494 (1953).
[4] R. K. Sheline, Phys. Rev. **87**, 557 (1952).
[5] C. H. Blanchard and R. G. Winter, Phys. Rev. **107**, 774 (1957).
[6] G. W. Tautfest, Phys. Rev. **110**, 708 (1958).
[7] We are indebted to Dr. E. W. Phelan of the Argonne National Laboratory for his assistance in arranging for the loan of this source and some of the BF_2 counter used in this experiment.