Neutron Nonelastic Cross Sections from 7 to 14 Mev*

William P. Ball,† Malcolm MacGregor, and Rex Booth
University of California Radiation Laboratory, Livermore, California

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Neutron nonelastic cross sections for seven elements have been measured over the range from 7 to 14 Mev. The cross sections are almost constant in this range, showing that variations in the total cross sections are due primarily to variations in the elastic cross sections.

INTRODUCTION

MEASUREMENTS of the neutron nonelastic cross sections in the 1–7 Mev range have been published,[1–3] as well as measurements at 14 Mev.[2,4–6] In the low-energy region Van de Graaff accelerators were used to produce the $D(d,n)He^3$ reaction, and at 14 Mev both Van de Graaff and Cockcroft-Walton accelerators were used to produce the $T(d,n)He^4$ reaction. In the region from 7 to 14 Mev total cross sections exhibited considerable variations,[7] and it was not clear whether these were due to changes in the total elastic cross section, the nonelastic cross section, or both. The present measurements in this region show that the changes must be attributed almost entirely to changes in the total elastic cross sections.

THEORY

The theoretical treatment of neutron sphere transmission measurements, as applied to the present work, has been discussed in considerable detail in reference 5, hereafter referred to as "I." In brief, a neutron detector operated at a high bias is placed about 2 feet from a monoenergetic neutron source. A spherical shell is alternately placed over the detector and removed, and the change in counting rates is attributed to nonelastic scattering events occurring in the shell, since to a first approximation elastic scattering effects cancel out. Corrections to the data must be made to compensate for the following factors: (1) elastically-scattered-in neutrons suffer an energy loss and are not detected as efficiently as the unscattered beam; (2) part of the elastically-scattered-in neutrons are lost by subsequent inelastic scatterings before they reach the detector; (3) the detector has a finite size, which means that the average path length through the shell for detected neutrons is increased; (4) the source-to-detector distance is not infinite, which causes an apparent increase in source strength with the sphere on; (5) the neutron beam striking the spherical shell is not monoenergetic and not isotropically distributed. For light elements, correction (1) is by far the most important, changing the cross section values by a factor of 2 in extreme cases. For the heavy elements the total correction amounts to only a few percent for spherical shells of the thicknesses used in the present experiment ($\frac{1}{8}$ to $\frac{1}{4}$ of a mean free path for nonelastic events). As the neutron energy is decreased, the correction factors become larger due to the fact that the elastic scattering is less peaked in the forward direction. The correction factors were applied to the data by means of a problem run on the Livermore UNIVAC, which consisted of a Monte Carlo calculation to apply correction (1), followed by an analytical calculation to apply corrections (2)–(5). Corrections (1)–(4) were practically the same for the present cyclotron experiment as for the Cockcroft-Walton (C. W.) experiment discussed in I. However, correction (5) was more important in the present experiment than in I. For C. W. measurements, the detector was placed at an angle of 90° to the incident deuteron beam. In this position the neutron beam was very uniform, and whatever deviations existed tended to cancel out. For the cyclotron measurements, the detector was placed at an angle of 0° to the direct beam. Neutrons from the $D(d,n)He^3$ reaction fall off in both energy and numbers as the angle to the incident beam is increased, so that all parts of the sphere were not evenly "illuminated." The effects of this fall-off were measured by placing the detector at the different positions occupied by the spherical shell. Detection efficiency curves as a function of the angle to the beam were obtained and put into the analytical correction problem. Experimentally this effect was minimized by using small diameter spheres and staying at a considerable distance from the source (i.e., 20–40 inches). For the largest ratio of sphere diameter to source-detector distance used in the present experiment (0.2), correction (5) amounted to 5% at 14 Mev and was less at the lower energies.

EXPERIMENTAL

The equipment used for the present measurements was similar to that described in I. A $\frac{3}{8}$-in. diameter plastic neutron detector was used which limited gamma-

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† Now at Ramo-Wooldridge Corporation, Los Angeles, California.
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TABLE I. Nonelastic cross sections from 7 to 14 Mev (in barns).

	Be Mev	Be σ_{nx}	C Mev	C σ_{nx}	Mg Mev	Mg σ_{nx}	Al Mev	Al σ_{nx}
Los Alamos	7.0	0.60±0.04	7.0	0.17±0.03			7.0	0.86±0.05
Rice Institute							7.1	0.74±0.05
Livermore cyclotron	7.0	0.62±0.04	7.0	0.18±0.03	6.7	0.92±0.06	7.3	0.91±0.06
	8.0	0.60±0.03			8.3	0.94±0.04	8.1	0.94±0.04
	9.6	0.61±0.05			9.6	0.98±0.03	9.5	1.00±0.03
	11.2	0.56±0.04			11.0	1.00±0.03	11.0	1.07±0.04
					12.5	0.96±0.05	12.8	1.00±0.05
			14.2	0.55±0.03				
Livermore C. W.	14.2	0.49±0.02	14.2	0.56±0.02	14.2	0.99±0.02	14.2	0.97±0.02
	Cu Mev	Cu σ_{nx}	Zr Mev	Zr σ_{nx}	Sn Mev	Sn σ_{nx}	Bi Mev	Bi σ_{nx}
Los Alamos	7.0	1.54±0.06	7.0	1.70±0.08	7.0	2.00±0.10	7.0	2.38±0.14
Rice Institute	7.1	1.37±0.05			7.1	2.12±0.06	7.1	2.66±0.07
Livermore cyclotron	7.2	1.57±0.06			7.4	2.01±0.05	7.2	2.42±0.06
	8.3	1.55±0.03	8.4	1.71±0.03	8.3	1.96±0.04	8.4	2.57±0.05
	9.6	1.55±0.03	9.5	1.69±0.03	9.6	1.94±0.04	9.5	2.58±0.05
	11.0	1.55±0.04	11.0	1.78±0.05	11.0	1.97±0.05	11.0	2.57±0.06
	12.5	1.53±0.06	12.8	1.72±0.05	12.6	2.02±0.07	12.8	2.51±0.08
	14.0	1.52±0.03			14.5	1.87±0.07	13.9	2.59±0.05
Livermore C. W.	14.2	1.49±0.02	14.2	1.72±0.03	14.2	1.92±0.03	14.2	2.56±0.04

produced pulse heights to a neutron equivalent of about 4.5 Mev. All electronic equipment, including the scintillation detector, was temperature-stabilized. The sphere was positioned and removed automatically, and data were taken simultaneously at ten different detector biases. A scintillation counter biased to match the detector was used to monitor the beam. The beam energy was determined by making range measurements on the deuteron beam and using the kinematics of the reaction. A precision pulser was used to set the biases initially and to periodically check the stability of the system. Calibration of the detector efficiency as a function of neutron energy was accomplished with the aid of a proportional counter telescope monitor, as described in I.

RESULTS

The nonelastic cross-section measurements in the 7–14 Mev range are summarized in Table I. For purposes of comparison, data at 7 Mev obtained from Los Alamos,[3] and Rice Institute,[2] and Livermore Cockcroft-Walton[5] data at 14 Mev are also included. At 14 Mev, the agreement between cyclotron and C. W. data shows that the correction factors were put into the problem properly. At 7 Mev, the agreement between the Livermore and Los Alamos results is excellent; the agreement is within 5% for the light elements, and within 2% for the heavy elements. The measurements at Rice Institute, on the other hand, differ from the combined Livermore-Los Alamos cross sections by amounts which are, in some cases, well outside the quoted errors.

Since experimental angular distributions are available at[3] 7 Mev and[8] 14 Mev but at no energies in between, angular distributions for the intermediate energies were obtained by interpolation and by optical-model calculations.[9] Detector efficiencies were measured only over the 8–14 Mev range since the neutron energies available did not go low enough to permit a measurement below 7 Mev. However, the shapes of the curves plotted on a relative neutron scale changed very little from 8 to 14 Mev, and the extrapolation to 7 Mev was readily made. It is believed that the quoted uncertainties reflect the validity of the corrections. After corrections were applied, the data taken at the ten biases exhibited a plateau at the high biases, and the quoted cross section is an average over the top half-dozen biases, ranging from 74% to 92% of the incident neutron energy (see I for typical plateaus).

TABLE II. Cross sections for neutron inelastic scattering to the 9–14 Mev energy region, with a neutron bombarding energy of 14 Mev.

Element	Sphere transmission method,[a] mb	$\int_{9}^{14\text{ Mev}}\int_{40^\circ}^{180^\circ}\sigma_{n,n'}(\theta)d\Omega dE$,[b] mb
Fe	102±35	76±30
Cu	119±35	72±30
Sn	136±40	91±30
Pb	161±45	88±30

[a] MacGregor *et al.*, reference 5. Data corrected for detection efficiency of inelastically scattered neutrons.
[b] Reference 11.

[8] The experimental data are those of Coon, Davis, Felthauser, and Nicodemus (Los Alamos); Whitehead, Groseclose, and Berko (University of Virginia); and Wong, Anderson, Gardner, and Nakada (University of California, Livermore). We wish to thank these authors for allowing us to use their data prior to publication of their results.

[9] We are indebted to F. Bjorklund and S. Fernbach for these calculations.

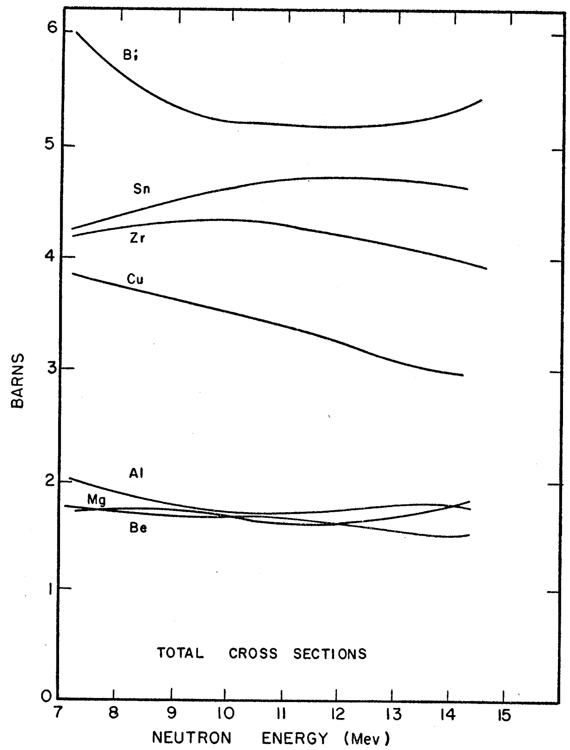

FIG. 1. Neutron total cross sections from 7 to 14 Mev (data from Bratenahl, Peterson, and Stoering[7]).

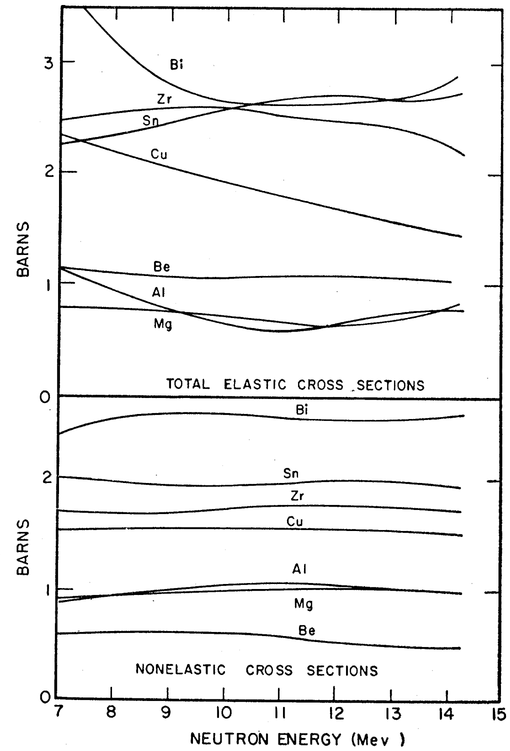

FIG. 2. Neutron total elastic and neutron nonelastic cross sections from 7 to 14 Mev.

DISCUSSION

As Table I shows, nonelastic cross sections in the 7–14 Mev range are notable chiefly for their lack of structure. This is more clearly brought out in Figs. 1 and 2, which show the total cross sections,[7] the nonelastic cross sections, and the total elastic cross sections (obtained by subtraction) for the elements discussed in this paper. The nonelastic cross sections are quite flat and follow a smooth $A^{\frac{2}{3}}$ (geometric) progression. The total elastic cross sections, on the other hand, exhibit considerable variations and do not follow a geometric progression. A plot of these same cross sections *versus* the mass number, A, instead of the energy (Fig. 7 of I), shows that here also the nonelastic cross sections vary geometrically, and the elastic cross sections do not. A three-dimensional graph of the total elastic cross sections plotted against both A and E would show undulations corresponding to the various partial waves as they enter into the scattering. Optical-model calculations give nonelastic cross sections in agreement with experiment.[10]

DIRECT INTERACTION NEUTRONS

Coon and co-workers[11] have recently measured cross sections for inelastically scattering 14-Mev neutrons into the energy band from 9 to 14 Mev. Such high-energy inelastically scattered neutrons are attributed to direct interaction processes.[12] (The 9-Mev cutoff is for experimental convenience and has no particular theoretical significance.) Since the same cross sections can be obtained from sphere measurements, a comparison was made between the results of Coon *et al.*,[11] and the results of Table III in I. Since the data of Coon *et al.* consist of differential cross-section measurements in the angular range from 40° to 180°, the sphere measurements, which represent an integration over the entire angular range, are expected to yield larger cross sections. As Table II shows, this is in fact the case. The difference between the two sets of measurements can be used to infer the shape of the angular distribution of 9–14 Mev neutrons in the 0° to 40° angular range. A subtraction indicates a rather sharp forward peaking, in agreement with predictions of the direct interaction hypothesis,[12] although the magnitude of the errors precludes quantitative comparisons.

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