tion energies in the compound nucleus P^{29} are also given in Table I. The present experiment has covered the range of excitation energies from 3.8 to 6.4 Mev.

From the large reduced *elastic* scattering widths for the $3/2^-$ level at 4.33 Mev and the $1/2^-$ level at 5.51 Mev, it is suggested that these levels arise primarily as single-particle excitations of a ground-state Si^{28} core plus a proton. In particular, in view of the excitation energies and splittings, it is suggested that these levels correspond to the $2P_{3/2}$ and $2P_{1/2}$ excitations, respectively.

Conversely, the large reduced *inelastic* scattering widths observed for the levels at 5.717 and 6.176 Mev would seem to suggest that these levels arise primarily as single-particle excitations of an excited Si^{28} core plus a proton.

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Differential Elastic Scattering of 14-Mev Neutrons by Zn, Sn, Sb, Pb, and Bi†

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Differential elastic scattering cross sections in the angular interval from 10° to 165° have been measured for Zn, Sn, Sb, Pb, and Bi. The experimental measurements are corrected for multiple scattering and the finite angular resolution by Monte Carlo methods. The corrected cross sections are compared with theoretical values computed by use of a complex potential with a spin-orbit term.

INTRODUCTION

DURING the past few years considerable effort has been expended in measuring differential elastic scattering cross sections at various energies for both neutrons and protons. These measurements have stimulated the development of various complex potential nuclear models[1–6]; and the partial successes obtained with these models have in turn been instrumental in causing more extensive and accurate measurements to be made. Much work has been done with 14-Mev neutrons[7–19] because the $H^3(d,n)He^4$ reaction is a convenient source of neutrons and also because the experimentally measured differential cross sections can be directly compared with theoretical predictions. (The elastic scattering cross section consists of a shape elastic part and a compound elastic part,[2] these being experimentally indistinguishable. However, for 14-Mev neutrons the compound elastic part is expected to be so small that the elastic scattering is essentially all shape elastic.)

The earlier measurements were confined mainly to scattering in the forward direction because of the formidable experimental difficulties encountered in measuring the cross sections at large angles. Many of these difficulties have been circumvented in various ways within the past two years so that reasonably accurate differential cross-section measurements have now become available over most of the angular range for a large number of elements. The measurements in the present paper cover the angular range from 10° to 165° for five elements. Preliminary reports of some of these measurements have been given previously.[15]

EXPERIMENTAL DETAILS

By using the associated-particle technique in conjunction with millimicrosecond electronic circuitry, we reduced the background problems inherent in this type of work to such an extent that cross-section measurements could be made within reasonable counting times. The experimental arrangement is shown in Fig. 1.

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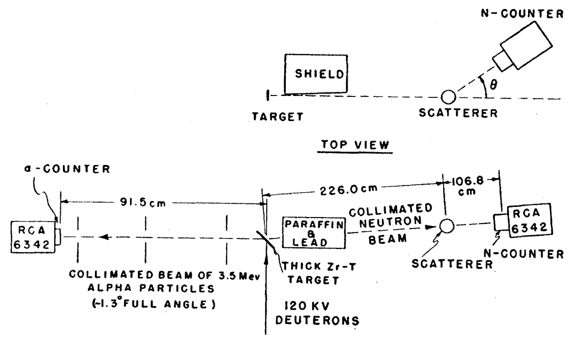

FIG. 1. Experimental arrangement for elastic scattering of 14-Mev neutrons.

Deuterons are accelerated to approximately 120 kev in a Cockcroft-Walton accelerator. When these deuterons strike a thick Zr-T target one obtains 3.5-Mev alpha particles and 14-Mev neutrons by the $H^3(d,n)He^4$ reaction. The alpha particles going off at 90° to the direction of the incoming deuterons are collimated by a system of apertures and then detected with a plastic scintillator, $\frac{1}{16}$ inch thick, mounted on an RCA-6342 photomultiplier tube. In effect, a collimated beam of 14-Mev neutrons will be obtained if one selects only those neutrons that are coincident with the collimated alpha particles. Some of these neutrons are scattered by the scatterer and are then detected in a plastic scintillator 3 inches in diameter by 6 inches long. The paraffin and lead are used to shield the neutron detector from the direct neutron flux.

A block diagram of the electronic circuitry is shown in Fig. 2. A fast and a slow output pulse are taken from each photomultiplier tube. The slow pulses are analyzed in conventional slow pulse-height analyzers. The fast pulses are amplified by Hewlett-Packard 460-*A* distributed amplifiers, limited by EFP-60 limiter circuits,

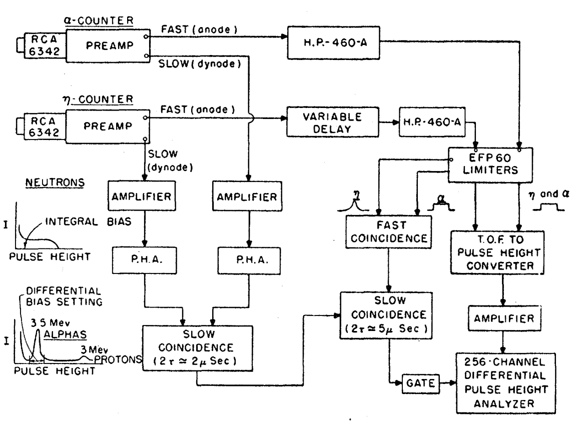

FIG. 2. Electronic circuitry. The limited and shaped alpha-particle pulses are 80 mμsec in duration and 5 volts in amplitude. The limited and shaped neutron pulses going to the time-of-flight-to-pulse-height converter have a duration of 80 mμsec and an amplitude of 5 volts and those going to the fast coincidence circuit have a duration of about 8 mμsec and an amplitude of about 2 volts.

and shaped by delay lines. The conversion from time-of-flight to pulse height is achieved by measuring the amount of overlap of the limited and shaped neutron and alpha-particle pulses. This is accomplished by using a circuit which includes a 6*BN*6 gated-beam tube. This circuit is a modification of one developed by Neilson and James.[20]

The accidental coincidence rate is cut in half by eliminating one of the two possible ways in which the limited and shaped fast pulses may overlap to produce the same pulse-height output. This is done by feeding suitably shaped alpha pulses (width about 80 mμsec) and neutron pulses (width about 8 mμsec) into a fast coincidence circuit. (The coincidence resolving time of this fast circuit was several millimicroseconds.) An output is obtained from this fast coincidence circuit if and only if the alpha pulse precedes the neutron pulse as it

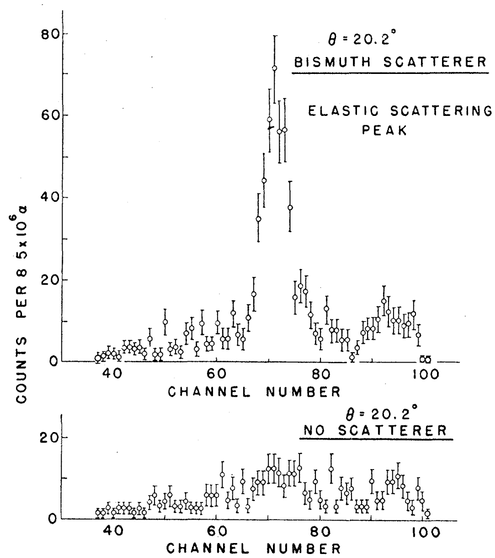

FIG. 3. Elastic scattering of 14-Mev neutrons on Bi at $\theta = 20.2°$.

must when the alpha particle and neutron originate in the same event. The multichannel analyzer is gated "on" when there is a triple coincidence between the pulse-height analyzed neutron and alpha pulses and the output of the fast coincidence circuit. When a triple coincidence occurs, the amplified output of the time-of-flight-to-pulse-height converter is analyzed by the multichannel analyzer.

A typical time-of-flight spectrum, analyzed for pulse height, is shown in Fig. 3. The full width at half-maximum of the elastic scattering peak is 3.3 mμsec and is typical of the resolution used in all of the measurements. Pulses due to coincident gamma rays from the inelastic scattering of neutrons in the scatterer would appear at channel 98 (see Fig. 3) because of their

[20] G. C. Neilson and D. B. James, Rev. Sci. Instr. 26, 1018 (1955).

different flight time from scatterer to neutron detector. It is evident that these gamma rays do not contribute to the elastic scattering peak.

Experimental differential cross sections were computed from the equation

$$\sigma(\theta)=[(C_t-C_b)/C_0N](rR/q)^2,$$

where r is the distance from the neutron source to the center of the scatterer, R is the distance from the center of the scatterer to the center of the neutron detector, q is the distance from the neutron source to the center of the neutron detector when the detector subtends the same solid angle at the neutron source as the scatterer, N is the number of scattering centers in the scatterer, C_t is the counting rate at angle θ with the scatterer in the neutron beam, C_b is the counting rate at angle θ with the scatterer removed, and C_0 is the counting rate

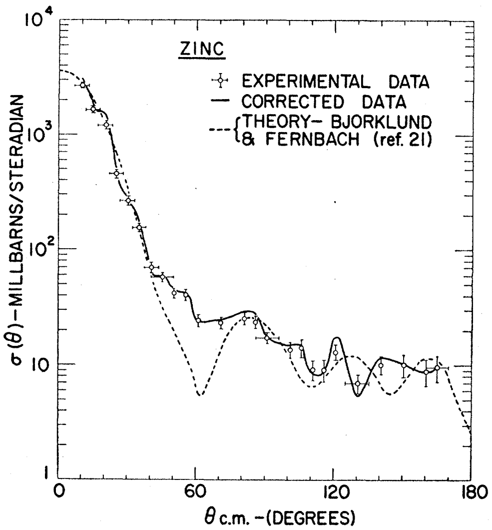

FIG. 4. Angular distribution of elastically scattered 14-Mev neutrons on Zn.

with the neutron detector in the center of the beam of neutrons at a distance q from the neutron source. These experimental cross sections must then be corrected for (a) inelastic scattering, (b) multiple scattering and attentuation of the scattered neutrons in the scatterer, and (c) the finite angular resolution employed in the experiment. The corrected cross sections can then be compared with theoretical predictions.

RESULTS

The experimental measurements and their comparison with the theoretical predictions of Bjorklund and Fernbach[4,5,21] are shown in Figs. 4 through 8. The errors shown for the experimental points are probable errors and include all known contributions.

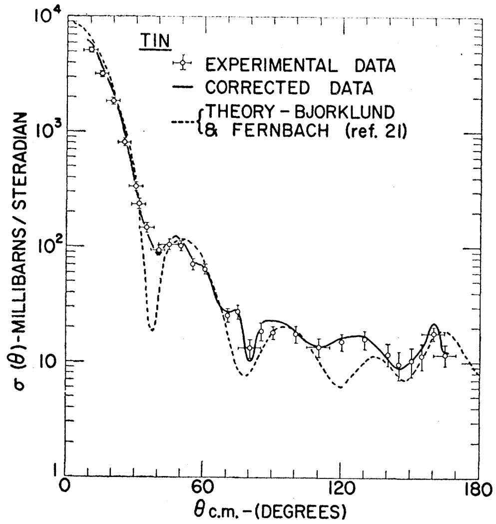

FIG. 5. Angular distribution of elastically scattered 14-Mev neutrons on Sn.

Since time-of-flight-to-pulse-height converter pulses due to neutrons having energies less than about 11 Mev were not used in the calculation of experimental cross sections, the contribution from inelastically scattered neutrons should be small. This is evident from the nonelastic cross-section measurements of MacGregor, Ball, and Booth.[22] (See also reference 18.) This was confirmed in the present experiment in the following way. Two calculations were made of the differential-elastic-scattering cross section for each angular position of the neutron detector for each scatterer. In the first of these, time-of-flight-to-pulse-height converter pulses due to neutrons having energies greater than about 12 Mev

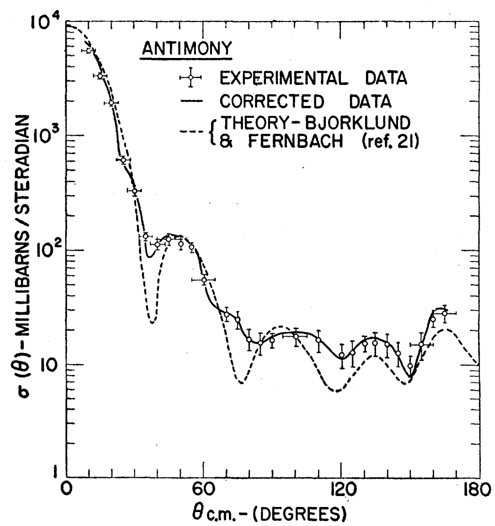

FIG. 6. Angular distribution of elastically scattered 14-Mev neutrons on Sb.

[21] F. Bjorklund and S. Fernbach, University of California Radiation Laboratory Report 4932-*T* (unpublished).

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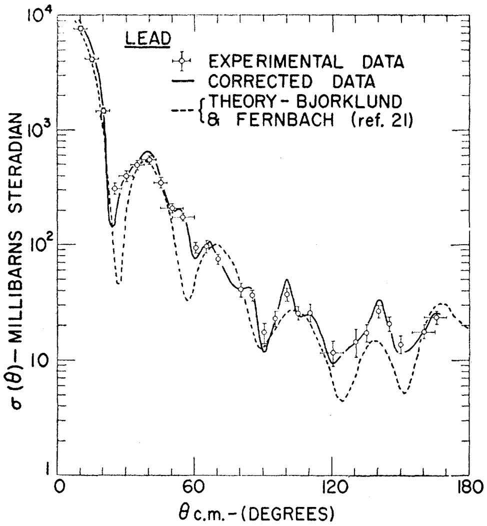

FIG. 7. Angular distribution of elastically scattered 14-Mev neutrons on Pb.

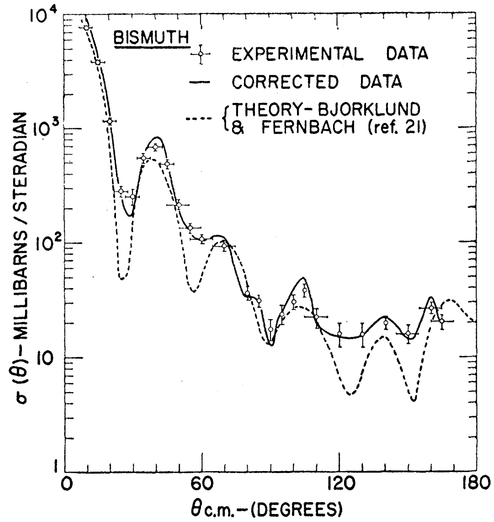

FIG. 8. Angular distribution of elastically scattered 14-Mev neutrons on Bi.

were used and in the second, pulses due to neutrons having energies greater than about 10.5 Mev were used. Since the computed cross sections always agreed well within the experimental error, a negligible contribution from inelastic scattering was indicated.

The corrections for multiple scattering and angular resolution (both corrected for the attenuation of the scattered neutrons in the scatterer) were made by Monte Carlo methods.[23] The multiple scattering correction was a few percent for angles near 90° and much smaller elsewhere.

The data corrected for all of the foregoing effects are shown by the solid curves in Figs. 4–8. Even with the reasonably good angular resolution (±3° for angles less than 50°) used in this experiment, it is evident from the curves for Bi and Pb that the value of the cross section at the first minimum changes drastically when the correction for angular resolution is applied so that this kind of correction is very necessary if the data are to be compared with theoretical predictions. Also shown (as dashed curves) are the theoretical predictions of Bjorklund and Fernbach.[4,5,21] They used a potential having a real central part with a diffuse boundary, a Gaussian imaginary part centered on the nuclear edge, and a real spin-orbit term. The agreement between the corrected experimental data and the theoretical curves is seen to be fairly good.

[23] The necessary analysis for making these corrections was done by L. T. Wos who, with the aid of R. T. Julke, also made the calculations with the computer GEORGE of the Applied Mathematics Division.

The agreement between these data and the data of other experimenters is very good. For Zn the data of Nauta[14] (angular interval from 15° to 90°) are in good agreement although at the larger angles the errors in his values of the cross section are quite large (about a factor of 2). There is also very good agreement between our measurements on Zn and the Los Alamos[9] (5° to 150°) and Livermore[18] (90° to 167°) data for Cu. The elastic scattering for Zn and Cu is expected to be similar since they are neighboring elements with nearly the same total cross section and nonelastic cross section.[22]

The agreement is also very good between our Pb data and the Los Alamos[9] and Livermore[18] data. The data of Nauta[14] for Pb (15° to 125°) is also in reasonable agreement although here again at the larger angles the errors in his values of the cross section are quite large (about a factor of 2). There is also good agreement with the data of Yuasa[19] for Pb (90° to 170°).

The data on Bi agree very well with the measurements of Elliot[13] (5° to 70°) and Yuasa[19] (70° to 170°).

The measurements for Sn are also in very good agreement with the Los Alamos[9] and Livermore[18] data for this element.

No previous measurements exist near this neutron energy for Sb.

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