Differential Cross Sections for Neutron Resonance Scattering from Na^{23}†

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The differential scattering cross section for neutrons on sodium has been measured with an energy spread of ~25 kev for neutron energies between 200 kev and 800 kev. The data are presented in the form of Legendre polynomial coefficients.

MEASUREMENTS of differential scattering cross sections for neutrons on sodium from 50 kev to 1400 kev (lab) have been reported by Langsdorf, Lane, and Monahan[1] as part of a survey experiment. The resolution was approximately 60–80 kev so that most of the structure apparent in the total cross-section measurements of Stelson and Preston[2] was smoothed out. In order to obtain more detailed information on the differential scattering cross section in the vicinity of resonances, measurements similar to those of the survey experiment were made with improved resolution. Although an attempt[3,4] was made by the authors to interpret the scattering near some of the resonances in terms of resonance parameters, the proximity of interfering levels so complicated the angular distributions that no definitive results were obtained. However, the experimental data are of current interest and are reported here.

The differential scattering cross sections for Na^{23} were obtained at five angles by a method described previously.[1] A lithium target bombarded by protons from the Argonne 4-Mev electrostatic accelerator served as the neutron source. The energy spread of the neutron beam was approximately 25 kev. The average total count observed at any one angle and energy was in the neighborhood of 2500 with a background of 15–20%. Scattering samples consisted of metallic sodium cast in sections to form a slab 10 in.×20 in. ×½ in. thick. This sample was sealed in a vacuum-tight can whose walls were made of 0.005-in. steel. Approximately half of the background mentioned above was due to the empty can, and the other half was due to scattering by the air column illuminated by the neutron beam.

The differential scattering cross section $\sigma_s(\mu)$ is represented by a Legendre polynomial expansion in the form

$$4\pi\sigma_s(\mu)/\sigma_s=\sum_{l=0}^{4}\omega_l P_l(\mu),\quad \omega_0=1, \tag{1}$$

where σ_s is the scattering cross section integrated over the angles of scatter, μ is the cosine of the scattering angle in the laboratory system, and $P_l(\mu)$ is the conventional Legendre polynomial of degree l normalized such that

$$\int_{-1}^{1} d\mu\, P_l(\mu)P_m(\mu)=2\delta_{lm}/(2l+1).$$

The values of σ_s and ω_l, obtained by fitting Eq. (1) to the measured values of $\sigma_s(\mu)$, are shown as functions of incident neutron energy in Fig. 1. For the angles at which these measurements were made, namely, 24.0°, 55.4°, 91.2°, 112.8°, and 143.7°, an evaluation of Eq. (1) will give the measured value of the cross section.

The errors associated with the values of σ_s are estimated to be less than 10%. The errors in the coefficients in the Legendre expansion increase with l from approximately ±0.05 for ω_1 to ±0.10 for ω_4. The present results for σ_s and ω_l agree with the corresponding results obtained in the earlier survey experiment[1] when corrections are made for the difference in energy spread used in the two experiments. Also the curve for σ_s in Fig. 1 is consistent with the total-cross-section data obtained by Stelson and Preston[2] when the latter are averaged over the energy spread of the present experiment.

The small energy dependence of the detector sensitivity was negligible in this experiment. Also the scattering cross section was not corrected for the contribution from the second group of neutrons from the Li(p,n) source. The yield of this second group of neutrons ranges from zero when the energy of the main group is below 650 kev to less than 3% of the main group when the energy of this group is 800 kev. The errors quoted above include the uncertainties introduced by not explicitly correcting for these effects. Earlier calculations of multiple scattering for the broad-resolution experiment[1] indicate that both ω_1 and ω_2 should be corrected upward by amounts ranging from 0.02 at the lower energies to as much as 0.1 at the higher energies. Thus the values of ω_1 and ω_2 shown in Fig. 1 probably are systematically too small by an amount of the order of the estimated errors. The effect of multiple scattering is negligible for the remaining expansion coefficients.

For the range of neutron energies of interest here,

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[1] A. Langsdorf, Jr., R. O. Lane, and J. E. Monahan, Phys. Rev. **107**, 1077 (1957).
[2] P. H. Stelson and W. M. Preston, Phys. Rev. **88**, 1354 (1952).
[3] R. O. Lane and J. E. Monahan, Argonne National Laboratory Report ANL-5554, August, 1956 (unpublished), p. 22.
[4] R. O. Lane and J. E. Monahan, Bull. Am. Phys. Soc. **1**, 187 (1956).

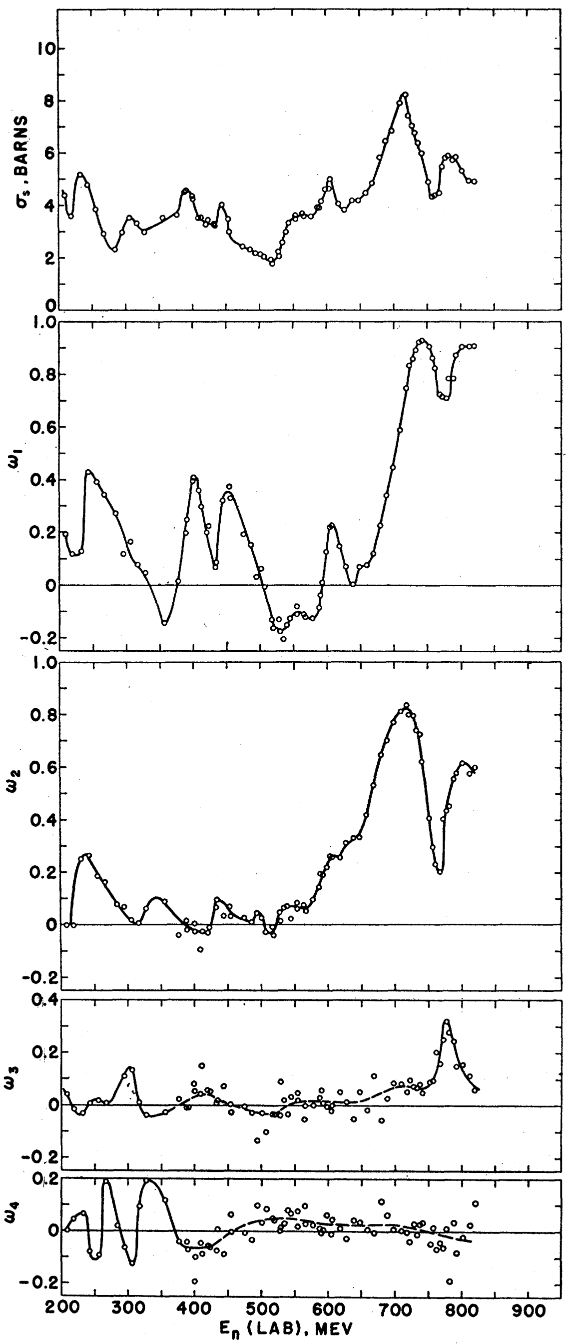

FIG. 1. Total scattering cross section σ_s and the coefficients ω_l in the expansion [Eq. (1)] for the differential scattering cross section for neutrons on Na^{23}. The ω_l are in the laboratory system. The curves through points are drawn to indicate the trend of the data, and are shown dashed in regions where only a very general behavior of the data can be inferred.

the only processes which can contribute to the scattering cross section are elastic and inelastic scattering. Since the neutron detectors used in this experiment do not discriminate with respect to energy,[1] all neutrons emerging from the scatterer are counted with practically the same efficiency. Thus the differential scattering cross section measured at any angle is simply the sum of the differential elastic and inelastic cross sections evaluated at that angle. Let us denote by W_l and W_l' the coefficients in expansions similar to Eq. (1) for the ratio of the differential to the total elastic-scattering cross section [i.e., $4\pi\sigma_n(\mu)/\sigma_n$], and for the ratio of the differential to the total inelastic-scattering cross section [i.e., $4\pi\sigma_{n'}(\mu)/\sigma_{n'}$], respectively. The relation among these expansion coefficients is

$$W_l=(\sigma_s\omega_l-\sigma_{n'}W_l')/\sigma_n. \quad (2)$$

Hausman et al.[5] have measured the inelastic scattering cross section for Na^{23} by comparing the yield at 90° of the 440-kev γ rays from $Na^{23}(n,n')$ with that of the 478-kev γ rays from $B^{10}(n,\alpha)Li^{7*}$. Their results are shown in Fig. 2. The maximum anisotropy in the γ-ray yield at 44° and 88° from the $Na^{23}(n,n')$ reaction was found[5,6] to be approximately 25%. Thus, for our purposes, we can interpret the results shown in Fig. 2 as a measure of the quantity $\sigma_{n'}/4\pi$. The threshold for inelastic scattering is in the vicinity of 460 kev; but the ratio $\sigma_{n'}/\sigma_n$ is less than 0.03 up to approximately 550 kev. In fact, over the entire range of neutron energies for which these measurements were carried out, this ratio is less than 0.05. If we assume that the inelastic scattering cross section is not radically anisotropic, or more explicitly that $W_l'\lesssim\omega_l$, then the differential elastic-scattering coefficients may be evaluated approximately by neglecting the term in $\sigma_{n'}/\sigma_n$ in Eq. (2) for $l>0$. These experiments, of course, yield no direct information concerning the inelastic-scattering coefficients W_l'.

Recently Hibdon[7] has measured the total cross section for the $Na(n,n)$ reaction over the energy range

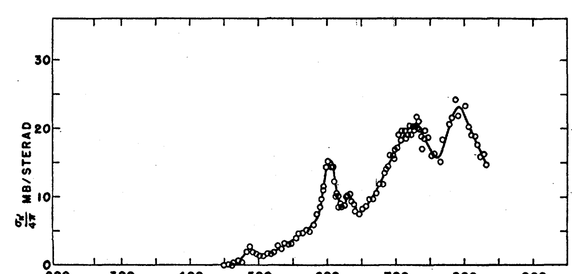

FIG. 2. Inelastic scattering cross section for neutrons on Na^{23} as determined by Hausman et al.[5] from the γ-ray yield at 90° for $Na^{23}(n,n')Na^{23*}$.

[5] N. Hausman, J. E. Monahan, F. P. Mooring, and S. Raboy, Bull. Am. Phys. Soc. 1, 56 (1956). [The present authors wish to express appreciation for the use of the data of this reference prior to publication.]

[6] F. P. Mooring, (private communication).

[7] C. T. Hibdon, Argonne National Laboratory Reports ANL-5915, October, 1958 (unpublished), pp. 17–20; ANL-5955, January, 1959 (unpublished), pp. 28–30; ANL-5978, April, 1959 (unpublished), pp. 14–18; ANL-6038, August, 1959 (unpublished), pp. 3–14; ANL-6052, September, 1959 (unpublished), pp. 34-47; preceding paper [Phys. Rev. **118**, 514 (1960)].

covered in these experiments with an energy spread of $\sim$0.5 kev to 1.0 kev. These measurements indicate the presence of some 127 resonances in the interval from $\sim$1 kev to 500 kev. This is more than ten times the number which was observed previously. In view of these results, it is obvious that many interfering levels must be included in any meaningful fitting of the present data with resonance parameters.

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Photoneutron Cross Sections of Li, N, and A†

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Using a Halpern-type photoneutron detection system, the photoneutron yields from Li, N^{14}, and A^{40} have been measured as a function of the maximum bremsstrahlung energy from threshold to approximately 50 Mev. The method of Penfold and Leiss was used to extract from the yield curves the total neutron cross section; $\sigma_T=\sigma(\gamma,n)+\sigma(\gamma,pn)+2\sigma(\gamma,2n)+\cdots$. The results are compared with previous findings of other laboratories. No gross structure was detected in the lithium cross section in the giant resonance region. The data indicate that lithium has a high-energy tail on the cross section of considerable magnitude.

INTRODUCTION

THE preponderance of accumulated data on the systematics of (γ,n) cross sections is, in general, confined to the giant resonance region. The principal tool for investigation of these cross sections has been the betatron, many of which are limited to a peak energy near 25 Mev. In many cases, existing cross sections in the giant resonance region for the partial reactions $\sigma(\gamma,n)$, $\sigma(\gamma,p)$, $\sigma(\gamma,np)$, etc.; fail to exhaust the dipole sum rule when compounded together to give the total absorption cross section.

With this in mind, three elements have been selected for study in the energy region from threshold to approximately 50 Mev. Using a Halpern-type neutron detection system, excitation curves for the total photoneutron cross section have been obtained experimentally for Li, N^{14}, and A^{40}.

The giant resonance shape of the lithium photoneutron cross section has recently been a subject of considerable disagreement. Several laboratories[1,2] have reported the existence of gross structure in the resonance, while other laboratories[3] have searched for structure, but have found none. For this reason, the giant resonance of lithium has been carefully examined in an effort to locate any gross structure which might exist.

The two gases, N^{14} and A^{40}, were examined particularly as to the width of their giant resonances; the previously reported width of N^{14} being anomalously small.[4]

† Supported by Air Force Office of Scientific Research.
[1] T. A. Romanowski and V. H. Voelker, Phys. Rev. **113**, 886–890 (1959).
[2] F. Heinrich and R. Rubin, Helv. Phys. Acta **28**, 185–192 (1955).
[3] T. W. Rykba and L. Katz, Phys. Rev. **110**, 1123–1126 (1958).
[4] G. A. Ferguson, J. Halpern, R. Nathans, and P. Yergin, Phys. Rev. **95**, 776–780 (1954).

EXPERIMENTAL PROCEDURE

Bremsstrahlung from the University of Virginia electron synchrotron was used to disintegrate the target nuclei. The electron energy can be continuously varied from 6 to 70 Mev by changing the length of the radio-frequency envelope. After acceleration to the desired energy, the electrons are allowed to impinge on a 0.030-inch tungsten target mounted on the inner wall of the vacuum tube.

The electron energy is monitored by integrating the magnetic flux passing through a turn around the magnet polepiece. The integrator circuit is similar to one used by the National Bureau of Standards Betatron Section and has proved extremely stable during two years of continuous operation. Energy calibration for the circuit was accomplished by observing the $C^{12}(\gamma,n)C^{11}$ threshold at 18.7 Mev. The energy calibration is good to about 1%.

Figure 1 is a schematic diagram of the synchrotron area. The x-ray beam is collimated to a diameter of approximately one inch at the center of the neutron house by a half-inch aperture in the lead collimator located 80 cm from the x-ray target. A thick-walled parallel plate ionization chamber is used to monitor the photon flux.

The photoneutrons are thermalized and detected by BF_3 counters in a geometry based on the setup described by Halpern.[5] Nine BF_3 counters (N. Wood Counter Laboratory, 96% B^{10}, 12-in. effective length, 1-in. diameter) are held in thin-walled aluminum tubes spaced symmetrically on a circle of 13.5-cm radius within a two foot paraffin cube. A Lucite tube with a $1\frac{1}{2}$ in. inside diameter runs through the center of the

[5] J. Halpern, A. Mann, and R. Nathans, Rev. Sci. Instr. **23**, 678–680 (1952).