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Elastic Scattering of 8-Mev Polarized Protons*

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The angular dependence of the polarization produced in the elastic scattering of 8-Mev protons by complex nuclei has been measured for 23 elements. The polarization exhibits a smooth dependence on mass number and scattering angle for most of the elements studied. The systematics in the angular distributions are reproduced by an optical model calculation in which only the radius is permitted to vary.

A SYSTEMATIC study has been carried out of the angular dependence of the left-right asymmetry resulting from the elastic scattering of 8-Mev polarized protons by complex nuclei. The present experiments represent an extension of our previous work at 10 Mev.[1]

The method of generating the polarized protons, performing the measurements, and analyzing the results is identical to that described in our previous publication. One comment about our previous paper is, however, in order. We inadvertently omitted an

Table I. Angular dependence of the polarization of protons elastically scattered by various elements. The mean energy of the incident proton is listed in parentheses.

He^4 (8.5 Mev)		Be (8.5 Mev)		C (8.6 Mev)		N (7.8 Mev)		O (7.9 Mev)		Ne (8.0 Mev)	
θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)
40	-29 ± 7	33	-16 ± 5	32.5	-10 ± 6	32.5	-50 ± 6	32	-24 ± 5	34	-12 ± 6
51.5	-41 ± 5	44	-18 ± 5	43	$+4\pm6$	43.5	-52 ± 5	42	-29 ± 5	43.5	-6 ± 6
62	-57 ± 5	57	-29 ± 5	56	$+16\pm7$	54	-54 ± 5	53	-29 ± 7	53	$+12\pm7$
75.5	-74 ± 4	65.5	-32 ± 6	64	$+55\pm7$	66	-7 ± 7	63	-5 ± 7	65	$+43\pm7$
87	-74 ± 5	76	-8 ± 8	74.5	$+96\pm4$	77	$+49\pm7$	75.5	$+40\pm8$	75.5	$+28\pm6$
97	-65 ± 4	88.5	$+42\pm7$	87	$+71\pm5$	88	$+10\pm7$	85.5	$+3\pm7$	86.5	0 ± 7
107.5	-12 ± 7	96.5	$+25\pm10$	95	$+45\pm7$	97	-20 ± 7	96	-14 ± 8	96	-27 ± 7
118	$+69\pm6$	101.5	$+21\pm9$	101	$+38\pm7$	108	-47 ± 7	105.5	-37 ± 8	106.5	-32 ± 9
127	$+92\pm6$	106.5	$+6\pm9$	108.5	$+11\pm7$	117	-60 ± 7	115	-31 ± 10	116	-42 ± 9
129.5	$+100{+0 \atop -4}$	116	-4 ± 7	114.5	$+3\pm7$	124	-44 ± 7	128	$+4\pm7$	123	-28 ± 10
133.0	$+96\pm5$	135	$+10\pm8$	121.5	-9 ± 7	134.5	-27 ± 7	137	$+52\pm7$	134.5	-5 ± 12
143.0	$+70\pm9$			126	-15 ± 7	143.5	$+25\pm8$	147	$+56\pm7$		
150.5	$+52\pm12$			133.5	-33 ± 7						
				143	-38 ± 10						
				152.5	-41 ± 16						

Table II. Angular dependence of the polarization of protons elastically scattered by various elements. The mean energy of the incident proton is listed in parentheses.

Mg (8.5 Mev)		Al (7.6 Mev)		Ar (7.6 Mev)		Ca (8.6 Mev)		Ti (8.5 Mev)		V (8.3 Mev)	
θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)
31	-10 ± 5	31	$+9\pm6$	33.5	$+2\pm5$	30.5	$+8\pm5$	30.5	$+2\pm6$	30.5	$+8\pm4$
41.5	-3 ± 6	41.5	$+12\pm6$	42.5	$+2\pm5$	41	$+11\pm6$	41.5	0 ± 5	40.5	0 ± 5
54	$+13\pm7$	53.5	$+15\pm6$	52	0 ± 5	53	$+10\pm6$	53	-6 ± 5	53	-9 ± 5
62	$+39\pm6$	62	$+10\pm5$	64	-6 ± 5	61.5	$+2\pm6$	61	-9 ± 6	61	-13 ± 5
72	$+28\pm7$	72	$+7\pm7$	74	-23 ± 6	71.5	-1 ± 7	71	-8 ± 5	71	-31 ± 7
84.5	$+12\pm6$	84	-11 ± 6	85	-45 ± 8	83.5	-13 ± 7	83	-5 ± 6	83	$+2\pm8$
92.5	-10 ± 7	92	-9 ± 7	94.5	-12 ± 11	91.5	-18 ± 7	91	$+18\pm7$	91	$+32\pm7$
102.5	-14 ± 9	98	-18 ± 8	104.5	$+19\pm15$	101.5	$+28\pm10$	97	$+38\pm7$	101	$+25\pm7$
112	-3 ± 8	102	-6 ± 9	133.5	$+16\pm21$	111.5	$+62\pm9$	105	$+47\pm7$	111	$+17\pm9$
118	0 ± 8	112	$+2\pm7$			118.5	$+29\pm9$	111	$+37\pm7$	118	-8 ± 8
124	$+11\pm8$	119	$+28\pm9$			123	$+22\pm9$	118	$+12\pm9$	123	$+7\pm8$
132	$+25\pm9$	124	$+52\pm9$			131	-13 ± 9	123	-1 ± 10	131	-36 ± 10
141.5	$+38\pm14$	131.5	$+41\pm9$			141	-31 ± 10	131	-15 ± 11	140.5	-28 ± 12
		141.5	$+61\pm8$			150.5	-36 ± 10	141	-43 ± 14		

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] L. Rosen, J. E. Brolley, Jr., and L. Stewart, Phys. Rev. **121**, 1423 (1961).

TABLE III. Angular dependence of the polarization of protons elastically scattered by various elements. The mean energy of the incident proton is listed in parentheses.

Mn (8.1 Mev)		Fe (8.5 Mev)		Co (8.4 Mev)		Ni (8.2 Mev)		Cu (8.5 Mev)		Zn (8.6 Mev)	
θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)
30.5	−5±5	30.5	0±5	30.5	−2±5	30.5	+6±5	30.5	−8±5	30.5	+3±5
40.5	−11±5	40.5	+5±5	40.5	+2±5	40.5	−1±4	40.5	−6±5	40.5	+6±5
53	−14±5	53	−5±5	53	−9±5	53	−3±5	52.5	−17±5	52.5	−8±5
61	−12±5	61	−3±6	61	−14±6	61	−5±5	61	−10±5	61	−10±5
71	−20±7	72	−9±6	71	−7±7	71	−7±6	71	0±6	71	+7±7
83	−1±7	83	+4±8	83	+17±6	83	−13±6	83	+28±5	83	+22±6
91	+22±8	91	+25±7	91	+26±7	91	+12±7	91	+19±7	91	+20±9
101	+32±8	96	+27±7	97	+20±9	96	+25±7	101	+5±7	101	+3±7
111	+28±9	101	+29±7	105	+10±7	105	+21±8	111	−1±8	111	−2±8
118	−3±8	111	0±10	111	+6±7	111	+11±7	118	−8±7	118	−10±10
123	+1±8	117	−16±9	118	+4±10	118	−6±7	123	−20±9	123	−21±10
131	−32±9	123	−3±10	123	−9±10	123	+7±8	130.5	−13±10	130.5	−16±14
140.5	−42±13	131	+6±10	131	−7±12	131	+11±10	140.5	+15±13		
		140.5	+7±15	140.5	−17±19	140.5	−8±11				
						150.5	+9±18				

TABLE IV. Angular dependence of the polarization of protons elastically scattered by various elements. The mean energy of the incident proton is listed in parentheses.

Nb (8.4 Mev)		Mo (8.2 Mev)		Rh (8.8 Mev)		Pd (8.7 Mev)		Ag (8.3 Mev)	
θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)	θ (deg)	P_2 (percent)
30.5	−6±5	30.5	−1±5	30.5	−5±5	30.5	−5±5	30.5	−2±5
40.5	−8±5	40.5	+3±5	40.5	+2±5	40.5	+2±5	40.5	+1±5
52.5	−1±5	52.5	+2±5	52.5	−2±5	52.5	0±5	52.5	+4±5
60.5	+2±5	60.5	−3±5	60.5	+1±5	60.5	0±5	60.5	+3±5
70.5	+10±5	70.5	+4±5	70.5	−6±5	70.5	+3±5	70.5	+4±5
82.5	+2±7	82.5	+7±5	82.5	+4±5	82.5	−5±5	82.5	−8±6
90.5	−20±8	90.5	−5±7	90.5	−10±7	90.5	−10±7	90.5	−8±7
100.5	−27±9	100.5	−1±7	100.5	−12±7	100.5	−2±7	100.5	0±8
110.5	−4±7	110.5	−9±7	110.5	+2±7	110.5	−8±7	110.5	+20±8
116.5	−11±8	117.5	−9±9	117.5	−2±9	117.5	+29±8	117	+5±7
122.5	+2±10	122.5	−17±10	122.5	−6±9	122.5	+3±9	122.5	+1±8
130.5	−1±10	130.5	−24±11	130.5	−1±10	130.5	+1±10	130.5	−2±9
140.5	+11±12	140.5	+5±12	140.5	+5±15	140.5	−4±11	140.5	−4±11

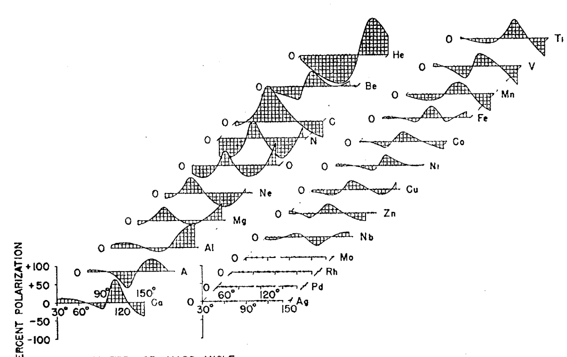

FIG. 1. Angular dependence of the polarization of protons elastically scattered by various elements. The smooth curves were drawn to illustrate the trends of the experimental points.

important reference (under reference 18) to the work of Adair, *et al.*[2] Not only does their paper describe some of the earliest low-energy neutron polarization experiments carried out at Wisconsin, but it also documents the first attempt to explain the observed neutron polarization by the addition of a spin-orbit term to the optical model potential.[3]

As in the previous paper,[1] the results of the present experiments are given in terms of the degree of polarization imparted to an unpolarized proton beam when it is elastically scattered by a given target through a specified angle. All targets were of normal isotopic

[2] R. K. Adair, S. E. Darden, and R. E. Fields, Phys. Rev. **96**, 503 (1954).

[3] One of the authors (L.R.) is indebted to Dr. R. K. Adair for bringing this omission to his attention.

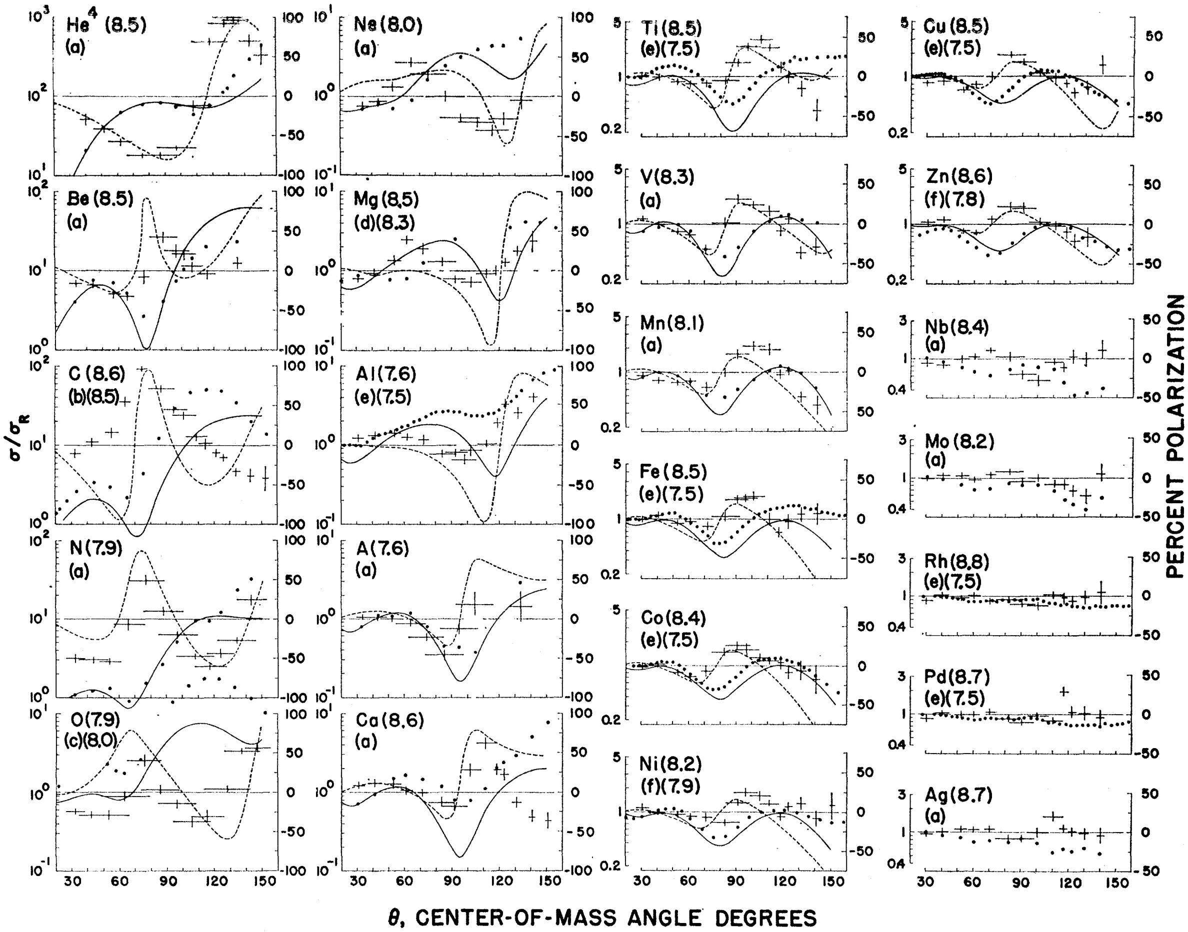

FIG. 2. Angular dependence of the polarization (+) and ratio of elastic to Rutherford scattering (·) of protons elastically scattered by various elements. The polarized proton beam energy, in Mev, is listed in parentheses after each element. On the lower line the letter references the elastic scattering data and the number is the corresponding proton energy. The dashed and solid curves represent, respectively, the optical model predictions for the polarization and σ/σ_R at the appropriate energies. The elastic scattering data were reproduced from the following references: (a) Relative elastic scattering distribution calculated from the yield of the polarization data. He^4 through Mn normalized to theoretical σ/σ_R at smallest angle. Nb through Ag normalized to $\sigma/\sigma_R=1$ at smallest angle. (b) J. Benveniste, R. Booth, A. Mitchell, C. Schrader, and J. Zenger, Lawrence Radiation Laboratory, Livermore (private communication). (c) Shinsaku Kobayashi, J. Phys. Soc. Japan **15**, 1158 (1960). (d) N. Yamamuro, S. Kobayashi, K. Matsuda, Y. Oda, and Y. Nagahara, Tokyo University Institute for Nuclear Study, Report INSJ-29, 1960 (unpublished). (e) W. F. Waldorf and N. S. Wall, Phys. Rev. **107**, 1602 (1957). (f) C. Hu, K. Kikuchi, S. Kobayashi, K. Matsuda, Y. Nagahara, Y. Oda, N. Takano, M. Takeda, and T. Yamazaki, J. Phys. Soc. Japan **14**, 861 (1959) and Tokyo University Institute for Nuclear Study Report INSJ-20, 1959 (unpublished).

abundance. The sign of the polarization is taken to be positive when in the direction $\mathbf{k}_i\times\mathbf{k}_f$. The data are presented in Tables I–IV. The energy spread for all exposures, resulting from the thickness of both the primary and secondary targets, was approximately 1 Mev full width at half maximum.

Only in the case of C,[4,5] Al,[5] and Mg,[5,6] can comparisons be made between the present results and other data near 8 Mev.

In the case of C and Mg the agreement is good. In the case of Al there is little similarity between the two sets of data. However, this may be due to the fact that the incident energies differ by 1.5 Mev and that, for aluminum, we are in the region where the polarization is a sensitive function of proton energy.

The 8-Mev data are quite similar to those at 10 Mev in that they show the same kind of regular variation with scattering angle and with mass number. This regularity is demonstrated by Fig. 1. The polarizations are, however, rather smaller than at 10 Mev and go to zero faster as the atomic number of the target is increased. The 8-Mev data also exhibit somewhat larger fluctuations from one element to the next. The first two effects can be attributed to the enhanced influence of the Coulomb barrier as the incident energy is lowered. The last effect is probably due to the increased importance of compound elastic scattering, since at the lower energy there are fewer open channels

[4] S. J. Moss, R. I. Brown, D. G. McDonald, and W. Haeberli, Bull. Am. Phys. Soc. **6**, 226 (1961).

[5] G. W. Greenlees and A. B. Robbins, Proceedings of the International Symposium on Polarization Phenomena of Nucleons Helv. Phys. Acta, Suppl. VI, p. 325 (1961).

[6] A. B. Robbins and G. W. Greenlees, Phys. Rev. **118**, 803 (1960).

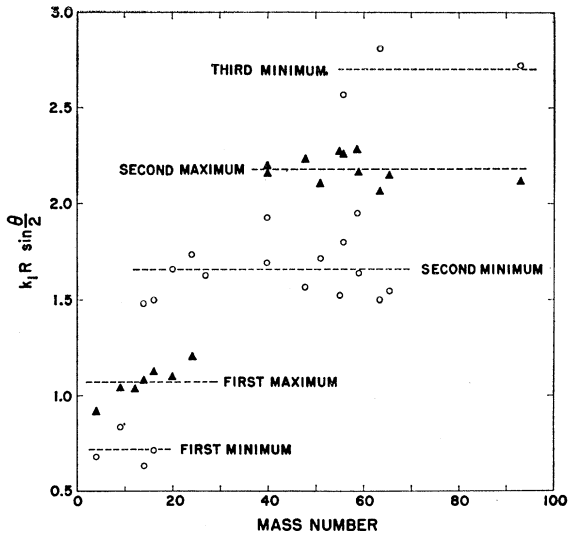

FIG. 3. $k_1R\sin(\theta/2)$ versus A for positions of corresponding maxima and minima in the polarization curves.

through which a compound nucleus, once formed, can decay. This supposition is given credence by the observation that, below 8 Mev, polarization data[7] exhibit fluctuations from one angle to the next for the same element and at the same angle for neighboring elements.

Figure 2 displays the angular dependence of the polarizations and elastic scattering cross sections along with optical model fits to both. Wherever elastic scattering data were available from single-scattering experiments, these were used. Otherwise, the less accurate elastic scattering data which are a by-product of the present polarization measurements are plotted. The dashed and solid curves are theoretical fits to the polarization and elastic scattering data, respectively, using the potential

$$V(r)=(V+iW)\rho(r)+\frac{\gamma V}{2}\left(\frac{\hbar}{mc}\right)^2\frac{1}{r}\frac{d\rho}{dr}\mathbf{l}\cdot\mathbf{s}$$

and the set of parameters[8]

$$R=1.25A^{\frac{1}{3}}\,\text{f};$$
$$V=-55\text{ Mev},\quad W=-6\text{ Mev};$$
$$\gamma=-23,\qquad a=0.50\text{ f}$$

where

$$\rho(r)=\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}.$$

The above parameters are the same as those used to describe the 10-Mev data except that the constant in the radius parameter has been increased by 4%. Again, no attempt was made to carry out a systematic parameter search for a best fit to the data.

As in the case of the higher energy data, extrema in the polarization distributions occur for constant values of the product of target radius and momentum transfer, as predicted by simple diffraction theory. This is shown in Fig. 3. However, the average value of $[k_1R\sin(\theta/2)]$ corresponding to a given extremum point is not the same for the two energies, being as much as 19% lower for the lower energy, if the same radius is used at both energies.

ACKNOWLEDGMENTS

It is desired to acknowledge the large amount of help rendered us by the cyclotron group in providing beams of appropriate energy and intensity. We are also indebted to all of the personnel of the microscopy laboratory for performing the plate analysis work involved in these experiments, and especially to Mrs. May Bergstresser for supervising much of the analysis work and data compilation.

[7] R. E. Warner and W. P. Alford, Phys. Rev. 114, 1338 (1959).

[8] In the paper previously published, reference 1, γ should be negative instead of positive.

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Momentum and Angular Distribution of Recoil Electrons in Triplet Production*

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Ilford G-5 emulsion was bombarded by a hardened bremsstrahlung spectrum of maximum energy of 90 Mev. In 54 433 fields of view of the microscopes 1935 triplets were observed, out of which 1872 triplets were measured in the energy interval of 2 to 90 Mev. Recoil momentum distributions of the low-energy partner of the triplets have been compared with the theory of Suh and Bethe. In addition, the angular distribution of recoil electrons has been presented.

INTRODUCTION

THE cross section for triplet production has been studied[1–3] by absorption method within $10\leq E_\gamma\leq 300$ Mev photon energy range. The absorption technique, however, does not permit such detailed studies as momentum and angular distribution of recoil electrons. Recent theoretical calculations on the momentum

* This work was supported by the Atomic Energy Commission.

[1] John D. Anderson, Robert W. Kenney, and Charles A. McDoland, Phys. Rev. 102, 1626 and 1632 (1956).

[2] J. Moffatt, J. J. Thresher, G. C. Weeks, and R. Wilson, Proc. Roy. Soc. (London) A244, 245 (1958); J. Moffatt and G. C. Weeks, Proc. Phys. Soc. (London) 73, 114 (1959).

[3] E. Malamud, Phys. Rev. 115, 687 (1959).