POLARIZATION OF PROTONS ELASTICALLY SCATTERED FROM Si^{28} *NUCLEI*

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The degree of polarization of protons scattered through angles of 60, 90, 125 and 150° in the center-of-mass system in the energy interval 1.6 to 2.2 Mev has been calculated on the basis of a phase-shift analysis of elastic scattering data. The polarization was measured at 60 and 90° with He^4 as the analyzer. The calculated and measured results are in agreement within the experimental accuracy.

INTRODUCTION

OLNESS, Haeberli, and Lewis point out in a short communication[1] the existence of resonances in the cross section for p-Si^{28} scattering at E_p = 1.65 and 2.09 Mev with widths of 60 and 25 kev respectively, as well as a broad resonance at 2.9 Mev apparently due to a number of levels.

The results of measurements of the p-Si^{28} elastic scattering cross section for 1.5 to 3.1 Mev protons and their phase shift analysis are contained in the work of Val'ter et al.[2] The information on the levels of the P^{29} nucleus, corresponding to the 1.65 and 2.08 Mev resonances, obtained from this analysis is given in Table I.

The experimental values for level widths determined in reference 2 differ significantly from the corresponding quantities as given in reference 1. However the results of Val'ter et al.[2] are in good agreement with the data on the width of the corresponding levels obtained in the study of the $Si^{28}(p\gamma)$ reaction.[3] The information on the spin and parity of the 4.31-Mev level given in this review[3] is in agreement with the results obtained in reference 2.

The great width of the 4.31-Mev level and the $3/2^-$ spin value lead one to believe that the scattered proton beam will be polarized to a significant extent in a large energy interval.

It follows from reference 2 that the experimental results can be satisfactorily reproduced theoretically using the characteristics of the levels given in Table I. Therefore these characteristics apparently form a hopeful basis for the calculation of proton polarization.

In this note we report results of calculations and of an experimental study of the energy dependence of proton polarization at various angles for p-Si^{28} scattering.

COMPUTATION OF THE POLARIZATION

The polarization resulting from proton scattering is described by the vector

$$\mathbf{P} = P(\theta, E)\,\mathbf{n},$$

where $\mathbf{n} = (\mathbf{k} \times \mathbf{k}_0)/|\mathbf{k} \times \mathbf{k}_0|$ is a unit vector perpendicular to the scattering plane.

The function $P(\theta, E)$, in the case of elastic scattering by a spin 0 nucleus (in particular p-Si^{28} scattering), can be expressed as follows[4] in terms of the phase shifts $\delta_l^{\pm}$ corresponding to scattering in a state of total angular momentum $l + \frac{1}{2}$ and $l - \frac{1}{2}$:

$$P(\theta, E) = \frac{AB^* + BA^*}{|A|^2 + |B|^2}, \tag{1}$$

TABLE I

E_p, Mev	Level energy, Mev	Level width Γ, kev, c.m.s.	Level spin and parity	Reduced width γ_λ^2, Mev cm	The ratio* $\gamma_\lambda^2 / \frac{3}{2}\frac{\hbar^2}{ma}$
1.65	4.31	48	$3/2^-$	$2.23\cdot10^{-13}$	0.2
2.08	4.73	13	$1/2^+$	$0.13\cdot10^{-13}$	0.01

*a = 5.86×10^{-13} cm

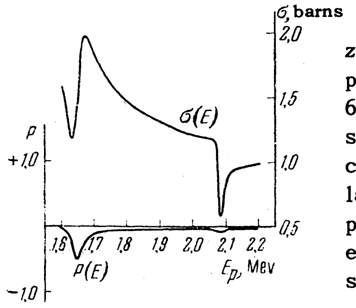

FIG. 1. The proton polarization P(E) resulting from $p-Si^{28}$ elastic scattering at 60° in the center-of-mass system and the corresponding cross section $\sigma(E)$, calculated on the basis of the phase-shift analysis of the experimental data on the scattering cross section.

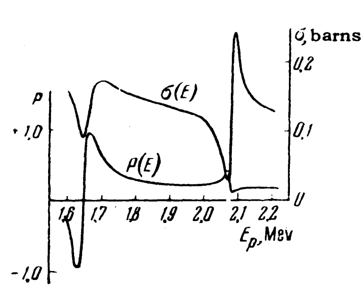

FIG. 3. Same as Fig. 1 but at 125°.

where

$$A(\theta) = -\frac{\eta}{2k}\operatorname{cosec}^2\frac{\theta}{2}\exp\left(i\eta\ln\operatorname{cosec}^2\frac{\theta}{2}\right) + \frac{1}{k}\sum_{l=0}^{\infty}\left[(l+1)e^{i\delta_l^+}\sin\delta_l^+ + le^{i\delta_l^-}\sin\delta_l^-\right]e^{i\alpha_l}P_l(\cos\theta);$$

$$B(\theta) = \frac{i}{k}\frac{d}{d\theta}\sum_{l=1}^{\infty}\left(e^{i\delta_l^+}\sin\delta_l^+ - e^{i\delta_l^-}\sin\delta_l^-\right)e^{i\alpha_l}P_l(\cos\theta), \quad (2)$$

where $\eta = (Ze^2)/(\hbar v)$; $k = \mu v/\hbar$; $\alpha_l = 2\sum_{S=1}^{l}\tan^{-1}\frac{\eta}{S}$ is the Coulomb phase shift. The phase shifts $\delta_l^\pm$ necessary for the computation were obtained from the expression:[5]

$$\delta_l^\pm = \left[-\tan^{-1}\frac{F_l}{G_l} + \tan^{-1}\frac{k\gamma_\lambda^2/A_l^2}{E_\lambda + \Delta_\lambda - E}\right]_{r=a};$$

$$\Delta_\lambda = \left[-\frac{k\gamma_\lambda^2}{\rho}\left(\frac{\rho}{A_l}\frac{dA_l}{d\rho} + l\right)\right]_{\rho=ka}; \quad (3)$$

$$A_l^2 = F_l^2 + G_l^2.$$

Here F_l and G_l are Coulomb wave functions, while E_λ and γ_λ^2 are the characteristic energy and reduced level width of the compound nucleus and $\rho = kr$.

The values of γ_λ^2 were taken from Table I. The calculations were carried out for scattering through angles of 60, 90, 125 and 150° in the center-of-mass system for protons with energies in the interval from 1.6 to 2.2 Mev. The results are shown in Figs. 1 to 4 together with the corresponding curves for the scattering cross section $\sigma(E) = (|A|^2 + |B|^2)k^2$.

MEASUREMENT OF THE POLARIZATION P(E)

For elastic scattering of spin $\frac{1}{2}$ particles by spin zero nuclei the polarization is more sensitive than the cross section to the choice of the characteristics of the levels. Therefore even comparatively crude measurements of the polarization yield valuable information for checking results obtained from an analysis of scattering cross section data. For this reason we performed experiments to determine the proton polarization.

The proton polarization was determined from double scattering experiments. Si^{28} was used as the first, and He^4 as the second scatterer. The apparatus and experimental procedure have previously been described in detail.[6,7] A free film was used as the first target, obtained by evaporating silicon of natural isotopic composition 1 mg/cm^2 thick in vacuum. The experiments were performed with the electrostatic generator of the Physico-Technical Institute of the Academy of Sciences, Ukrainian S.S.R. The results are shown in Table II. Column 1 gives the scattering angle at which the polarization P(E) was measured, column 2 gives the energy of the incident protons, and column 3 gives the value of the asymmetry R in the secondary scattering from He^4. Column four gives the polarization determined from the expression

$$P_{\text{exp}} = \frac{1-R}{P_{\text{eff}}(1+R)},$$

where P_{eff} is the effective polarization of the

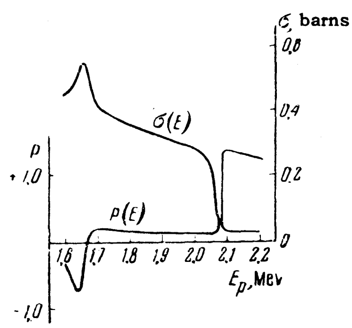

FIG. 2. Same as Fig. 1 but at 90°.

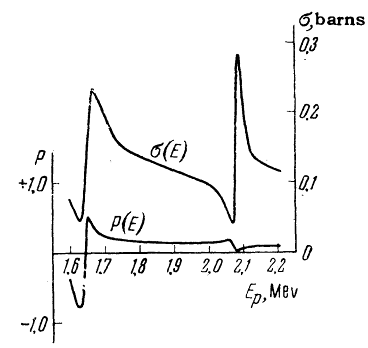

FIG. 4. Same as Fig. 1 but at 150°.

TABLE II

θ, c.m.s.	E_p, Mev	R	P_{exp}	P_{calc}
	1.7	0.86±0.04	−0.34±0.08	−0.26
	1.75	0.90±0.04	−0.18±0.05	−0.19
	1.8	0.90±0.04	−0.14±0.05	−0.07
60°	1.85	0.96±0.04	−0.05±0.04	−0.03
	2.0	0.96±0.04	−0.04±0.04	−0.02
	2.05	0.97±0.04	−0.02±0.03	−0.03
	2.10	0.97±0.04	−0.02±0.03	−0.04
90°	2.15	1.28±0.05	+0.16±0.03	+0.15

helium analyzer determined from the calibration curve published previously.[6,7]

Since a target of considerable thickness was used the values P_{exp} correspond to an average over the energy interval resulting from the energy losses in the target. Therefore, to compare experimental and calculated results, the latter were averaged over energy according to the formula

$$P_{calc} = \int\limits_{E}^{E-\Delta E} P(E)\,\sigma(E)\,dE \Bigg/ \int\limits_{E}^{E-\Delta E} \sigma(E)\,dE,$$

where ΔE is the energy loss of the protons in the silicon target; $P(E)$, $\sigma(E)$ are shown in Figs. 1 and 2. It was assumed that the stopping power dE/dx is constant in the interval ΔE and that the distribution of the protons as they traverse the foil is energy independent.

The integration was performed graphically. No errors were included in the determination of P_{calc} since they are much smaller than the experimental errors in P_{exp}. The results of the calculation, P_{calc}, are given in the last column of Table II.

DISCUSSION OF RESULTS

It can be seen from Table II that the experimental and calculated values for the polarization are in agreement within the experimental accuracy. Since the errors in the determination of P_{exp} are rather large we cannot discuss this agreement quantitatively. However it is possible, on the basis of the results obtained, to draw definite conclusions about the spin and parity of the levels near which the polarization was measured.

It follows from Eqs. (1) and (2) that the near vanishing of the polarization for 2.08-Mev protons is a convincing proof that the spin and parity of the 4.73-Mev level of P^{29} is $\frac{1}{2}^{+}$. If one assumes that the spin of the 4.31-Mev level is $\frac{1}{2}$, then the value of the function $B(\theta)$ in Eq. (2) would have the opposite sign to that which it has for spin $3/2$, and the polarization would, correspondingly, have the opposite sign to what is experimentally observed. (It follows uniquely from a qualitative analysis of the experimental data on the p-Si^{28} scattering cross section[2] that the 4.31-Mev level is due to the capture of an $l = 1$ proton and has odd parity.)

Thus the present investigation provides new confirmation of the validity of the phase shift analysis of the experimental data on the scattering cross section.[2] The results indicate that p-Si^{28} elastic scattering at energies close to 1.65 Mev can be used for manufacturing proton beams of a given polarization, as well as for analyzing of polarized protons, in addition to the presently known (pp) processes on He^4 and C^{12}.

[1] Olness, Haeberli and Lewis, Bull. Amer. Phys. Soc. **2**, 34 (1957).

[2] Val'ter, Malakhov, Sorokin, and Taranov, Report at All-Union Conference on Nuclear Spectroscopy 1958; Izv. Akad. Nauk SSSR, Ser. Fiz. **22**, 871 (1958).

[3] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

[4] J. V. Lepore, Phys. Rev. **79**, 137 (1950).

[5] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).

[6] Sorokin, Val'ter and Taranov, Тр. Харьковского гос. ун-та (Reports, Khar'kov State University) **7**, 119 (1958).

[7] P. V. Sorokin and A. Ia. Taranov, Dokl. Akad. Nauk SSSR **111**, 82 (1956), Soviet Phys. "Doklady" **1**, 637 (1956).

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