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Proton-Scattering on (29)Si in Range Ep = 2.5-3.4 MeV*

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Proton Scattering on ^{29}Si in the Range $E_p = 2.5–3.4$ MeV*

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Elastic and inelastic proton scattering measurements on ^{29}Si have been obtained in the energy range $E_p = 2.5–3.4$ MeV. 30 elastic and 32 inelastic resonances were observed. 14 prominent resonances from elastic scattering were analyzed. Results of the analysis for proton orbital momenta, spin and parity assignments, and proton partial widths are given. The inelastic resonance strengths measured relative to the known strength of the 1302-keV resonance in $^{29}Si(p,\gamma)^{30}P$ are also reported.

INTRODUCTION

Properties of levels in the odd-odd nucleus ^{30}P have been obtained predominately through the $^{29}Si(p,\gamma)^{30}P$ and the $^{29}Si(p,p)^{29}Si$ reactions. Results on the capture reaction have been reported by Harris, Hyder, Jr., and Walinga[1] and Kostin *et al.*[2] The $^{29}Si(p,p)^{29}Si$ reaction has been studied extensively by Storizhko and Popov,[3] L'vov *et al*,[4] and with higher-energy resolution by Poirier *et al.*[5]

The present work was undertaken to extend the high-resolution measurements of Poirier *et al.*[5] to the incident proton energy range $2.5 \leq E_p \leq 3.4$ MeV. The results of these measurements and the analysis of elastic proton scattering on ^{29}Si are reported here. The elastic scattering data as well as the $(p,p'\gamma)$ yield to the first excited state in ^{29}Si are shown in Fig. 1. 30 elastic scattering resonances were observed, 15 of which were previously unreported. 32 inelastic resonances were observed. Two elastic proton resonances were found to have no corresponding measurable inelastic yield.

14 prominent elastic scattering resonances were analyzed for spin and parity assignments and for energy parameters. A survey of all known proton scattering resonances in the energy region $2.5 \leq E_p \leq 3.4$ MeV is given in Table I.

EXPERIMENTAL PROCEDURE

The experiment was performed with the proton beam from the Aerospace Research Laboratories' 8-MeV insulating core transformer (ICT) tandem accelerator. The target preparation and data acquisition systems were similar to those outlined in Ref. 5.

The measurements were performed with a 0.5–1.0-μA beam, collimated and focused to approximately a 2-mm–diam spot at the target position. The energy resolution of the beam was approximately 200 eV.

The target was prepared by evaporating SiO_2, 95% enriched[6] in ^{29}Si onto a 10-μg/cm^2-thick carbon foil. The thickness of the evaporated layer and the energy spread of the beam together determine the total experimental energy resolution. This energy resolution, measured by finding the width of two very narrow $^{29}Si(p,\gamma)^{30}P$ resonances, was found to be 0.8 ± 0.1 keV at 2.5 MeV.

The elastic scattering measurements were made in an ORTEC 17-in. scattering chamber with four surface-barrier detectors placed at laboratory angles of 90, 130, 140, and 150° with respect to the beam direction and at a distance of about 10 cm from the target.

Rutherford scattering of protons from a gold foil was used to determine the relative solid angle subtended by each of the detectors. Aluminum scrapers were placed around the detectors to protect them from background scattering. The energy resolution of the detectors was about 25 keV. A 4.5-cm-diam by 5.1-cm-long NaI(Tl) detector was placed inside the scattering chamber at an angle of 90° to the beam direction and about $1\frac{1}{2}$ cm from the target for (p,p',γ) and (p,γ) measurements simultaneously with the elastic scattering measurements.

The yield of inelastically scattered protons from ^{29}Si for the lowest three excited states was obtained by measuring the yields of the 1.27-, 2.03-, and 2.43-MeV γ rays. The yield pertaining to the third excited state was negligible with respect to the yields of the lowest two excited states. In order to obtain the resonance strengths reported here (Table I), the areas under the inelastic resonances at 2.492, 2.510, and 2.525 MeV were compared and normalized to similar yields as reported in Ref. 5. These in turn, were referred to an absolute measurement of the (p,γ) resonance strength at 416 keV.

The strength function is defined by the equation

$$S_{pp'} = \frac{(2J+1)\Gamma_p\Gamma_{p'}}{\Gamma}$$

which yields double values for both Γ_p and $\Gamma_{p'}$ at each resonance. Both sets of values were tried as possible parameters in the theoretical fit. At three resonances the higher values of $\Gamma_{p'}$ (corresponding to a smaller elastic yield) were found to provide better fits.

The elastic and inelastic measurements were made in the energy region 2.480 to 3.360 MeV with energy steps varying from several keV down to 130 eV, depending on the local structure of the resonance yield. The incident proton energy had been previously calibrated by use of the $E_p = 991.90 \pm 0.04$ keV resonance in the $^{27}Al(p, \gamma)^{28}Si$ reaction as the reference point.

ANALYSIS

With the ground-state spin of $\frac{1}{2}$ for ^{29}Si, the two possible channel spins are $s=0$ and $s=1$. Only if $s=1$ can there be a mixture of l values for the incoming protons. For $s=0$ or when channel-spin mixing occurs, the l value must be unique. Channel-spin mixing was characterized by

$$\zeta = \frac{\text{Probability of formation with } s=1}{\text{Total probability of formation}} = \frac{\Gamma_{s=1,l}}{\Gamma_{s=0,l} + \Gamma_{s=1,l}},$$

so that ζ varies from 0 for pure $s=0$ to 1 for pure $s=1$. The orbital angular momentum mixing for the $s=1$ spin channel involves l and $l+2$. The mixing amplitude[7] is defined by

$$\epsilon = \pm\left(\frac{\text{Probability of formation with } l+2}{\text{Probability of formation with } l}\right)^{1/2} = \pm\left(\frac{\Gamma_{s=1,l+2}}{\Gamma_{s=1,l}}\right)^{1/2}.$$

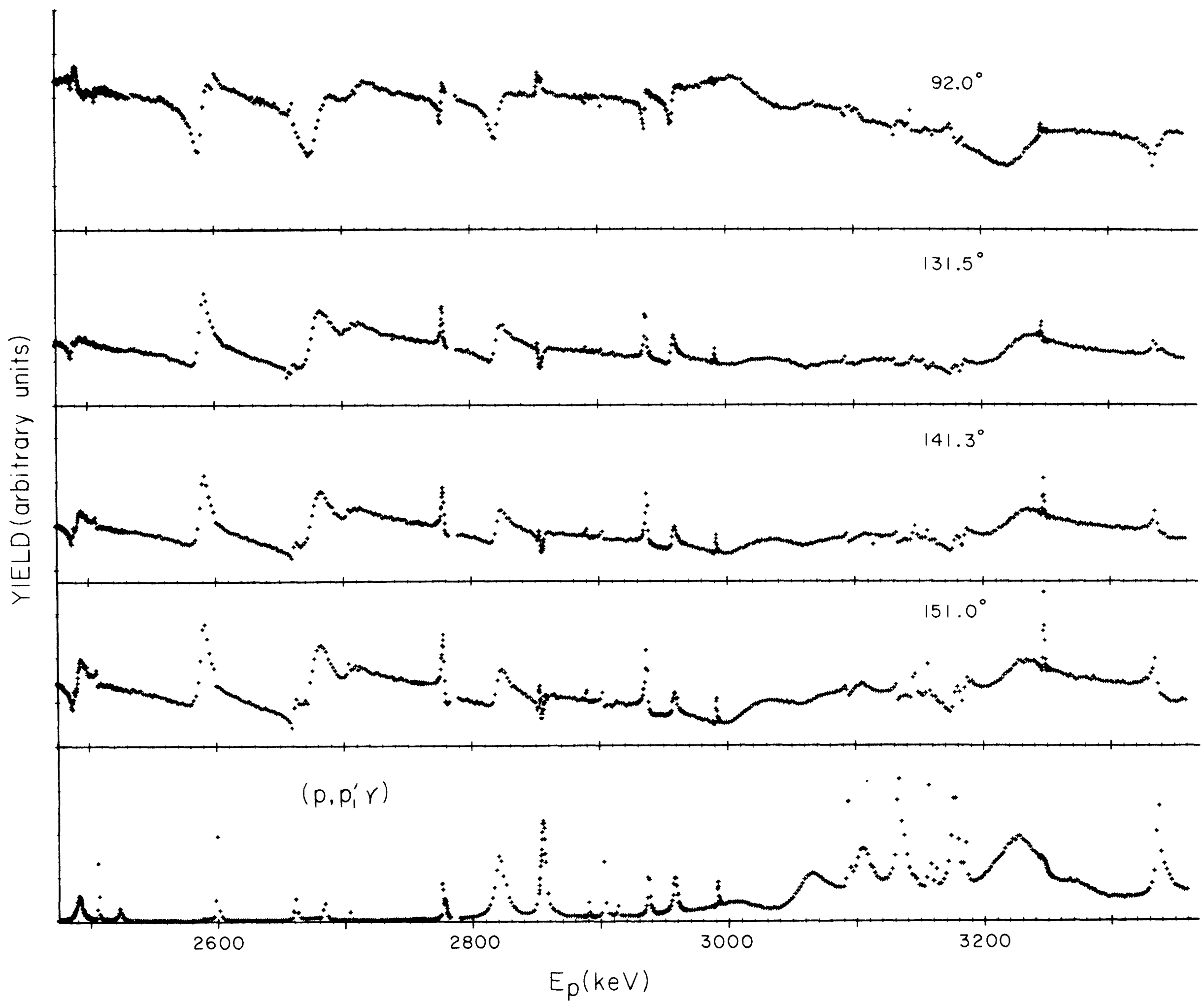

FIG. 1. Experimental elastic scattering yield at $\theta_{c.m.} = 92.0$, 131.5, 141.3, and 151.0°. The lowest curve is the simultaneous yield of $(p, p'\gamma)$ to the first excited state of ^{29}Si at $\theta_{lab} = 90°$.

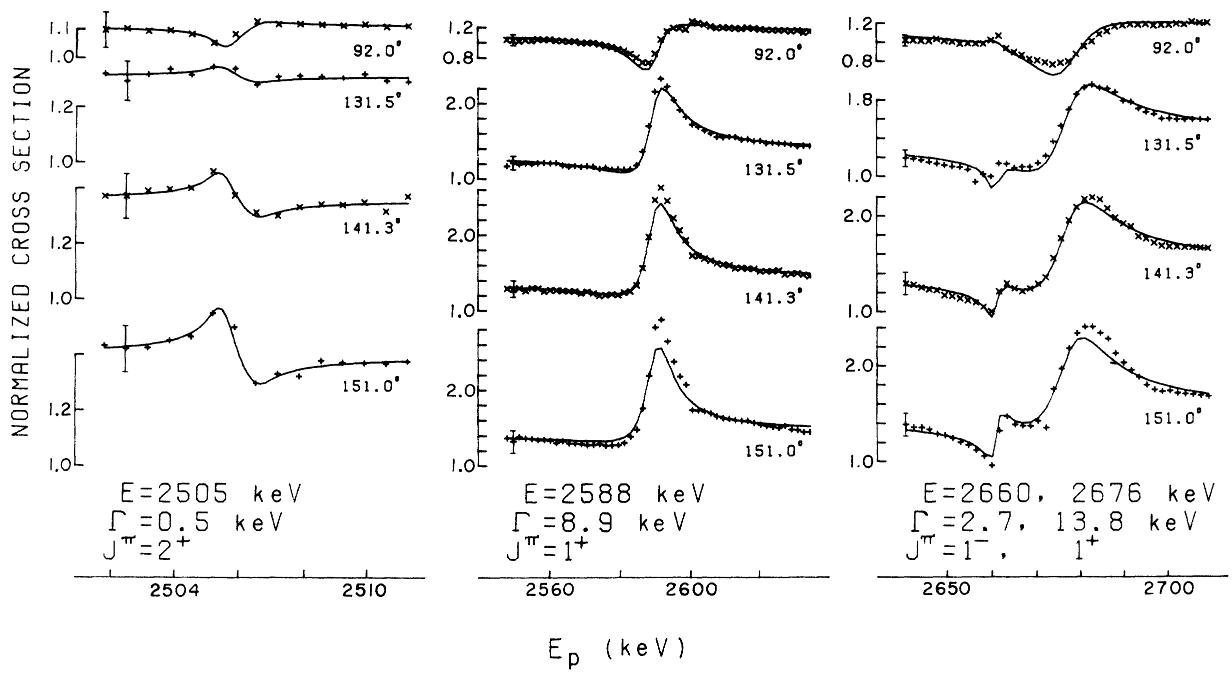

FIG. 2. The differential cross sections at four angles for elastic proton scattering on ^{29}Si in units of the Rutherford contribution at the E_p = 2505-, 2588-, 2660-, and 2676-keV resonances. The solid curves are the theoretical fits for the parameters given.

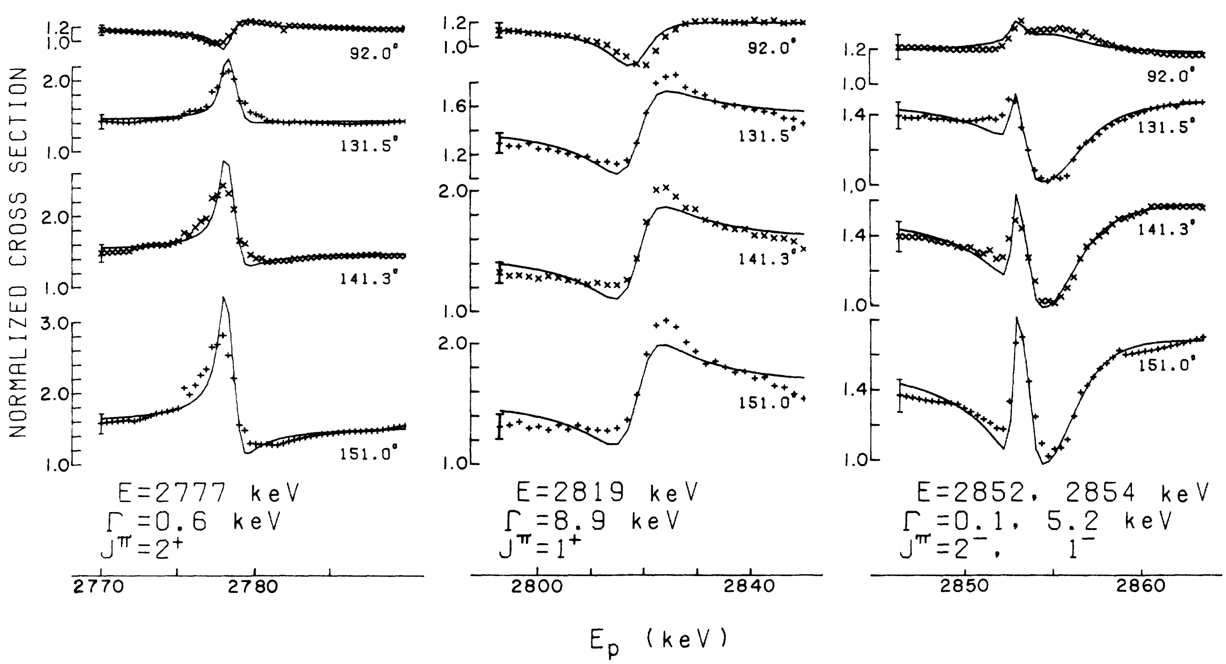

FIG. 3. The differential cross sections at four angles for elastic proton scattering on ^{29}Si in units of the Rutherford contribution at the E_p = 2777-, 2819-, 2852-, and 2854-keV resonances. The solid curves are the theoretical fits for the parameters given. Evidence of the weak 2774-keV resonance can be seen on the left side of the 2777-keV peak.

ϵ goes from 0 for pure l formation to $+\infty$ or $-\infty$ for pure $l+2$ formation. The analysis considered values for $J \leq 4$ and orbital angular momentum contributions up to g waves.

The analysis of the elastic scattering data generally followed the method described by Walinga, Van Rinsvelt, and Endt.[8] Theoretical differential cross sections were calculated by the method of Blatt and Biedenharn.[9] The theoretical calculations and experimental cross-section measurements were each normalized to the Rutherford cross section. An asymmetric triangular function was found to be a good approximation to the experimental energy resolution. This resolution function was folded into the theoretical calculations.

For each resonance with particular trial values of l and J, the values of the resonance energy E_0, the total width Γ, the partial proton width Γ_p, and the channel-spin-mixing parameter ζ or the l-mixing parameter ϵ were varied to minimize the goodness-of-fit parameter χ^2. The selection of the appropriate parameters to characterize each resonance was made on the basis of the shape of the theoretical and experimental differential cross sections and on the relative values of χ^2.

RESULTS

Of the 16 elastic scattering resonances not analyzed, 8 have very weak yields, while the other 8 cluster within a 100-keV region between 3090 and 3190 keV (Fig. 1).

The results of the analysis of the other 14 resonances are shown in Figs. 2 through 5. In each figure the proton yield at four angles is plotted versus the proton energy. The yield has been normalized to the Rutherford contribution after the Rutherford and background have been subtracted. The solid curve at each angle is the theoretical fit to the data. The results of the inelastic strength $S_{pp'}$ are given in Table I. A summary of the elastic scattering results are given in Table II. The partial widths Γ_γ were found to be small enough to have no significant effect on the data analysis.

A resonance was observed at 2505 keV which is weak for elastic scattering but stronger for inelastic scattering. The width observed was less than the experimental resolution of 0.8 keV; a good theoretical fit to the data was obtained for $\Gamma \simeq 0.5$ keV. The data are shown in Fig. 2 with the theoretical curve for $J^\pi = 2^+$, $l=2$ with a channel-spin parameter, $\zeta = 0.0$. Acceptable fits to the data were also found for $l=2$ with other values of J and ζ. The resonance may be $J^\pi = 1^+$ with $\zeta = 1.0$, $J^\pi = 3^+$ with $\zeta = 1.0$, or $J^\pi = 2^+$ with any value of ζ from 0 to 1. The fit in Fig. 2 is slightly better than the others.

There is a strong elastic scattering resonance at 2588 keV with a negligible inelastic yield. This overlaps a resonance at 2600 keV which is strong for inelastic scattering but which is too weak compared to the 2588-keV resonance for any analysis of its elastic scattering. The effect of the 2600-keV resonance elastic scattering is most noticeable at 90 and 150°. The data for these resonances are shown in Fig. 2. The solid curve is the theoretical fit for $J^\pi = 1^+$, $\Gamma = 8.9$ keV and no inelastic width. The orbital angular momentum is a mixture of $l=0$ and $l=2$ with a mixing parameter $\epsilon = 0.85$. This leads to elastic reduced widths of $\theta_p^2 = 0.0062$ for the $l=0(s_{1/2})$ contribution and $\theta_p^2 = 0.047$ for the $l=2(d_{3/2})$ contribution.

Overlapping levels, which were observed at

TABLE I. Resonances in ^{29}Si proton scattering.

$(p, p'\gamma)$ (keV) L'vov *et al.*	$(p, p'\gamma)$ (keV) Present data	$S_{pp'}$ (keV)	(p, p) (keV) L'vov *et al.*	(p, p) (keV) Present data
	2499 ± 2	0.04 ± 0.02		2499
2506	2506 ± 2	0.5 ± 0.1	2506	2505
2524	2523 ± 2	0.37 ± 0.08		
2591	2591 ± 2	0.08 ± 0.03	2591	2588
2600	2600 ± 2	1.9 ± 0.4	2600	2600
2636			2636	
2662	2661 ± 2	0.5 ± 0.1	2662	2660
	2677 ± 3	0.6 ± 0.2	2675	2676
2684	2682 ± 2	0.4 ± 0.1		
2705	2704 ± 2	0.16 ± 0.06	2705	2704
			2710	2712
2740				
	2775 ± 2	0.49 ± 0.15		2774
2778	2778 ± 2	0.4 ± 0.1	2778	2777
2823	2821 ± 2	5.6 ± 1.1	2823	2819
				2852
2855	2854 ± 2	4.9 ± 1.1	2855	2854
2891	2890 ± 2	0.15 ± 0.04		2890
2904	2903 ± 2	1.2 ± 0.3	2904	2903
2914	2913 ± 2	0.33 ± 0.07		
2938	2937 ± 2	1.4 ± 0.3	2938	2937
2958	2957 ± 2	1.6 ± 0.3	2958	2957
2991	2991 ± 2	0.33 ± 0.07	2991	2990
3009	3006 ± 3	7 ± 2	3009	3006
3065	3064 ± 3	11 ± 3	3065	
3092	3093 ± 2	2.0 ± 0.5		3093
3103	3104 ± 3	16 ± 6		3104
	3132 ± 2	12 ± 4		3132
	3145 ± 3	0.20 ± 0.06		3145
	3156 ± 2	6 ± 2		3156
	3162 ± 2	3 ± 1		3162
	3176 ± 2	14 ± 4		3176
	3185 ± 2	1.5 ± 0.4		3185
	3226 ± 3	37 ± 14		3224
	3247 ± 4	0.33 ± 0.18		3246
	3334 ± 2	7.5 ± 2.4		3333

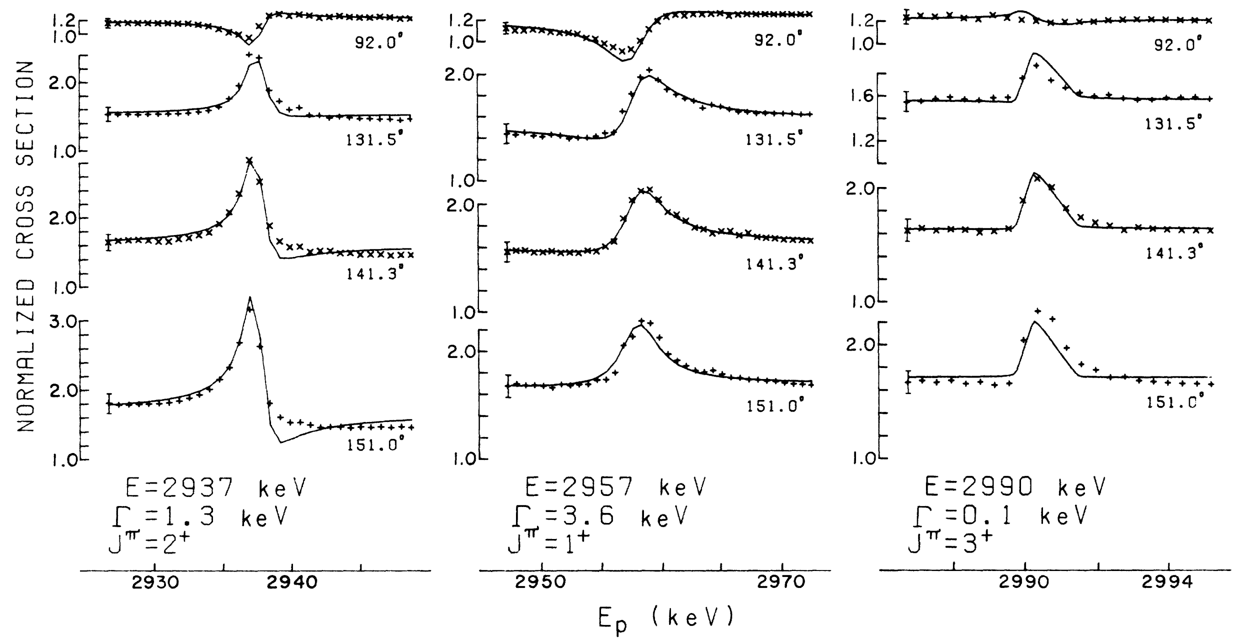

FIG. 4. The differential cross sections at four angles for elastic proton scattering on ^{28}Si in units of the Rutherford contribution at the $E_p = 2937$-, 2957-, and 2990-keV resonances. The solid curves are the theoretical fits for the parameters given.

2660 and 2676 keV, were fitted simultaneously (Fig. 2). The resonance at 2660 keV was found to have $J^\pi = 1^-$ and $l = 1$ with a channel-spin-mixing parameter $\zeta = 0.15$. The elastic reduced width for this state is $\theta_p^2 = 0.0055$ and the inelastic reduced width is $\theta_{p'}^2 = 0.025$. The resonance at 2676 keV has $J^\pi = 1^+$ and the orbital angular momentum is a mixture of $l = 0$ and $l = 2$ with a mixing parameter $\epsilon = -0.7$. The best fit for these resonances was obtained by using widths which lead to a value of the inelastic strength function for the 2676-keV resonance much larger (almost 20 times larger) than the experimentally determined value. It has not been possible to resolve the discrepancy from

TABLE II. Results of the elastic scattering analysis. Numbers in parentheses are the errors in the last digit(s). The values listed for ζ, Γ_p, Γ, θ_p^2, and $\theta_{p'}^2$ correspond to the theoretical fit for the first J value given.

E_p (keV)	E_x [a] (keV)	l	J^π	ζ	ϵ	Γ_p (keV)	Γ (keV)	$10^2\,\theta_p^2$	$10^2\,\theta_{p'}^2$
2505 (2)	8019	2	$2^+, 1^+, 3^+$	1.0		0.10 (5)	0.5 (2)		
2588 (2)	8099	0, 2	1^+		0.85 (10)	8.9 (4)	8.9 (4)	0.6, 5 [b]	
2660 (2)	8168	1	1^-	0.15 (3)		2.3 (2)	2.7 (2)	0.5	2.5 [c]
2676 (3)	8184	0, 2	1^+		−0.7 (1)	10 (2)	14 (2)	0.8, 0.8 [b]	
2777 (2)	8281	2	$2^+(1^+, 3^+)$	0.8 (1)		0.51 (5)	0.59 (5)		
2819 (2)	8322	0	$1^+, 0^+$	1.0		2.9 (3)	8.9 (5)	0.3	7.0 [c]
2852 (2)	8354	3	2^-	1.0			0.1		
2854 (2)	8356	1	$1^-, 0^-, 2^-$	1.0		3.3 (2)	5.1 (2)	0.6	5.0 [c]
2937 (2)	8436	2	$2^+, 1^+, 3^+$	0.6 (1)		0.85 (4)	1.30 (4)	0.95	
2957 (2)	8455	0, 2	$1^+(0^+)$		1.1 (1)	2.5 (2)	3.6 (2)	0.09, 1.0 [b]	0.8 [c]
2990 (2)	8487	4	3^+	1.0			0.1		
3224 (3)	8714	0, 2	1^+		0.5 (1)	16 (5)	38 (8)	0.8, 1.6 [b]	
3246 (2)	8735	3	$3^-, 4^-$	1.0			0.35 (10)		
3333 (2)	8819	2	$1^+, 3^+, 2^+$	1.0		2.2 (1)	4.4 (2)	1.1	8.1 [c]

[a] Using $Q = 5.597 \pm 0.003$ MeV from G. I. Harris and A. K. Hyder, Jr., Phys. Rev. 157, 958 (1967).

[b] For $l = 0$ and $l = 2$ contributions, respectively.

[c] The values for $\theta_{p'}^2$ are calculated by assuming that the lowest allowed l value of the outgoing proton predominates.

our data, although it could be due to complications arising from a narrow resonance at 2682 keV which exhibits resonance activity in the inelastic yield but not in the elastic data.

A strong elastic scattering resonance was observed at 2777 keV with a slight "bump" on the low-energy side that is most evident at the backward angles. The "bump" corresponds to a strong inelastic resonance at 2774 keV to the first excited state. The strength of the 2774-keV inelastic resonance is approximately twice the strength of the 2777-keV inelastic resonance. Since the elastic yield due to the 2774-keV resonance was too weak to be analyzed, the yield at this region was treated as a single resonance at 2777 keV. Good fits occur for $l=2$ and $J^\pi=1^+$, 2^+, or 3^+. The fit for $l=2$, $J^\pi=2^+$ is shown in Fig. 3 for reasons given below.

Strong inelastic scattering was associated with the resonance at 2819 keV. The data can be fitted satisfactorily with $l=0$ for either $J^\pi=0^+$ or $J^\pi=1^+$. The $J=0$ fit produces a smaller value of χ^2 but the $J=1$ fit (Fig. 3) leads to a value for the inelastic strength function which is in much better agreement with the inelastic yield. Thus, $J^\pi=1^+$ is the favored assignment but an assignment of $J^\pi=0^+$ cannot be ruled out.

Two closely spaced levels were observed at 2852 and 2854 keV. The resonance at 2852 keV is much narrower than the experimental energy resolution and has no identifiable inelastic yield. This resonance is best fitted with $J^\pi=2^-$, $l=3$. At 2854 keV, resonances were observed in both elastic and inelastic scattering. The resonance can be adequately fitted with $l=1$ for $J^\pi=0^-$, 1^-, or 2^-. The fit is best for $J^\pi=1^-$ and the resulting inelastic strength function also agrees best with the inelastic yield for this choice. The fit for the two resonances with the choice of $J^\pi=1^-$ for the 2854-keV level is shown in Fig. 3.

An elastic resonance was observed at 2937 keV. The best theoretical fit was for $J^\pi=2^+$, $l=2$, $\zeta=0.6$ (see Fig. 4) but $l=2$, $J^\pi=1^+$, 3^+ or 2^+ with different values for the mixing parameter ζ cannot be excluded.

Both elastic and inelastic scattering data exhibit resonance structure at 2957 keV. This resonance is shown in Fig. 4 with the theoretical fit for $J^\pi=1^+$ and a mixture of $l=0$ and $l=2$ with a mixing parameter $\epsilon=1.1$. The total width for the resonance is 3.6 keV. This leads to an elastic reduced width of $\theta_p^2=0.00091$ for the $l=0(s_{1/2})$ contribution and $\theta_p^2=0.0097$ for the $l=2(d_{3/2})$ contribution. Although the theoretical fit for $J^\pi=0^+$, $l=0$ is significantly poorer, it cannot be ruled out completely.

A resonance at 2990 keV was observed also in both elastic and inelastic scattering yield. This resonance is much narrower than our experimental resolution so that we cannot determine its

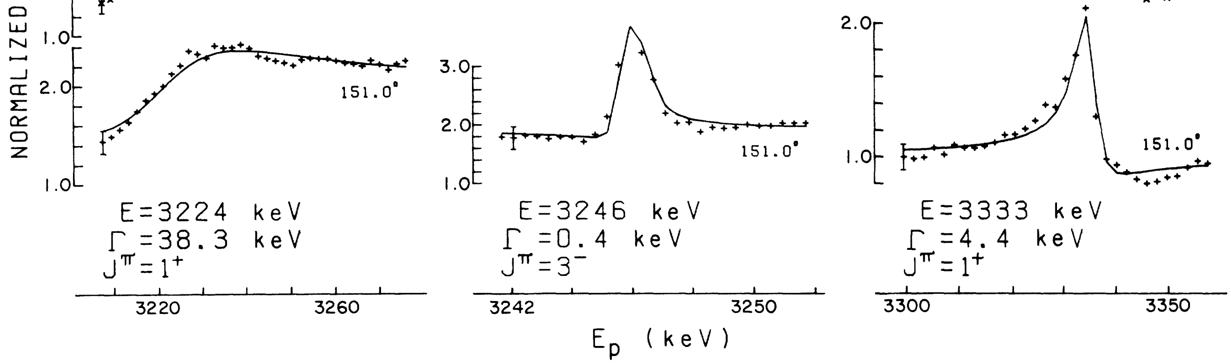

FIG. 5. The differential cross sections at four angles for elastic proton scattering on ^{29}Si in units of the Rutherford contribution at the $E_p=3224$-, 3246-, and 3333-keV resonances. The solid curves are the theoretical fits for the parameters given.

total width. We are able to determine clearly that the resonance has $J^\pi = 3^+$ and that it is primarily $l = 4$ although there may be a small $l = 2$ contribution. The data and the theoretical fit for pure $l = 4$ are shown in Fig. 4. The shape observed in the figure is basically determined by the energy resolution profile.

There is a very narrow resonance at 3246 keV superimposed on a very broad resonance centered at 3224 keV ($\Gamma \simeq 40$ keV). Both resonances showed up in the inelastic data also. Since no interference effect was expected, and none was exhibited in the data, the two resonances were analyzed separately.

Figure 5 shows the broad resonance at 3224 keV where the best theoretical fit corresponds to $J^\pi = 1^+$ and a mixture of $l = 0$ and $l = 2$ with the angular momentum mixing parameter $\epsilon \simeq 0.5$. The reduced widths indicate that the d wave is predominant. The resonance could not be fitted below 3210 keV due to interference from other resonances.

For the narrow resonance at 3246 keV, good theoretical fits occur for $l = 3$, $J^\pi = 4^-$ or 3^-. The width observed was of the order of 0.4 keV, much less than the experimental resolution. Figure 5 shows the fit for $J^\pi = 3^-$, $l = 3$.

The resonance observed at 3333 keV was strong in both elastic and inelastic scattering. Figure 5 shows the data and the theoretical fit for $l = 2$ and $J^\pi = 1^+$. Adequate fits to the data were also obtained for $J^\pi = 2^+$ and 3^+; the differences are not sufficient to allow for a clear choice.

DISCUSSION

The inelastic strengths listed in Table I are calculated from the areas of the inelastic yield curves. The results for the elastic scattering analysis are listed in Table II. The strengths from the inelastic yield curve were compared with the inelastic strengths calculated from the fitted partial widths, Γ_p and $\Gamma_{p'}$. This comparison provided one of the criteria used to select the proper parameters to describe the resonances. Where multiple values of J^π are listed in Table II, they are given in the order of decreasing preference. Values listed in parentheses are for distinctly poorer fits.

The elastic reduced widths, θ_p^2, and the inelastic reduced widths, $\theta_{p'}^2$, were calculated from the partial widths, Γ_p and $\Gamma_{p'}$, using the penetrabilities and level-shift functions based upon an assumed channel radius $R = 1.2F(A^{1/3} + 1)$. The inelastic reduced widths were computed on the assumption that the resonance state decayed with the lowest possible proton orbital angular momentum.

Several resonances in this investigation are of interest because they are possible analogs of states in ^{30}Si. The sharp resonance at 3246 keV has the right energy to be the expected analog of the 8093-keV, $J^\pi = 3^-$ state[10] in ^{30}Si.

The 2937-keV resonance was also seen in the $(p, p'\gamma)$ and (p, γ) reactions.[4,2]. The (p, γ) data yielded assignments $J^\pi = 2^+$, $T = 1$ which is consistent with the measured angular distribution coefficients from the $(p, p'\gamma)$ experiment.[11] A 2^+ assignment for this resonance, then, seems most reasonable and confirms its analog status to the 7899-keV level[10] in ^{30}Si.

Bromley *et al.*[12] reported a $J^\pi = 3^-$ state at 2.80 MeV which may be an analog state to the 7613-keV level[10] in ^{30}Si. The shape of the inelastic scattering data indicated that the 2.80-MeV resonance observed by Bromley *et al.* corresponds to the close doublet seen at 2774 and 2777 keV in the present work. The data for the 2774-keV resonance was too weak to be analyzed while the resonance at 2777 keV was determined to be a positive-parity state with $l = 2$.

This seems to have ruled out the correspondence of the $J^\pi = 3^-$ state to the 2777-keV resonance. However, the $J^\pi = 3^-$ assignment was obtained by Bromley *et al.*,[12] using the $(p, p'\gamma)$ data to the second excited state in ^{29}Si and the present work showed that only the 2777-keV resonance decays to the second excited state. The apparent discrepancy can be resolved if one allows incident channel-spin mixing in the analysis of the $(p, p'\gamma)$ data. Calculations by Harris,[11] using the data of Bromley *et al.*,[12] yielded a $J^\pi = 2^+$ assignment. In fact, further calculations by Harris revealed that the $J^\pi = 2^+$ assignment is also in agreement with the combined results of the inelastic scattering to the first excited state by Bromley *et al.* and L'vov *et al.* It is still possible that the weak elastic resonance at 2774 may correspond to the $J^\pi = 3^-$ analog state. Attempts to conduct a two-level fit for both 2774- and 2777-keV resonances indicated that assignment of $J^\pi = 3^-$ for the 2774-keV resonance gives a reasonable fit to the present data. High energy-resolution data on $(p, p'\gamma)$ to the first excited state are needed to yield more definitive information about the 2774-keV resonance.

A few of the resonances exhibit an inelastic reduced width which is significantly larger than the elastic reduced width. This could be an indication that the ground state of ^{29}Si may be a simple $s_{1/2}$ state while the first excited state has rather complex configurations. Thus, for complex resonance states in ^{30}P, their wave functions could have a greater overlap with that of the first excited state $(\frac{3}{2}^+)$ in ^{29}Si than with the ground state ($\frac{1}{2}^+$).

Finally, the number of isolated resonances found by proton scattering on ^{29}Si seems to exceed normal expectation for this energy range. This suggests that useful information may still be obtained at higher bombarding energies.

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[7]This differs by a square root from the definition used in Ref. 5. This is apparently due to a publication error in that paper.

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