Proton resonances in ^{28}Si from $E_x = 12.5$ to 13.4 MeV

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The ^{27}Al(p,p) and (p,α_0) differential cross sections were measured in the range $E_p = 0.92$ to 1.85 MeV with an overall resolution of 350 to 400 eV (full width at half maximum.) Resonance parameters were extracted for 31 resonances with a multilevel, multichannel, R-matrix analysis code; these parameters include resonance energy, total angular momentum, partial elastic and inelastic widths, and channel spin and orbital angular momentum mixing ratios. Eleven analog states were identified, and the Coulomb displacement energies and spectroscopic factors were calculated. For the 2^+ resonance at $E_p = 1.37$ MeV the entrance orbital angular momentum mixing ratio was determined. The relevance of this mixing ratio to a previous test of time reversal invariance is discussed.

I. INTRODUCTION

High resolution proton resonance measurements at the Triangle Universities Nuclear Laboratory (TUNL) recently have been extended to odd-mass targets. The first study[1] on ^{29}Si demonstrated the feasibility of resonance analysis for nonzero spin targets. The present results are from an extensive study of ^{27}Al. With a target spin of $\frac{5}{2}$, and with as many as five particle channels contributing significantly, the analysis of the ^{27}Al data involves numerous possible mixings and resonance angular momenta. However, the data were successfully analyzed with relatively little ambiguity remaining. Here we present the results for 31 resonances in the energy range $E_p = 0.92$—1.85 MeV. In this region only the (p,p$_0$) and the (p,α_0) reactions contribute strongly. A subsequent paper[2] will present the (five channel) data up to $E_p = 3.05$ MeV. Preliminary results were reported[3] earlier in connection with the 6^-, $T=1$ stretched state in ^{28}Si which occurs as a resonance at $E_p = 2.875$ MeV.

Although several previous measurements of the (p,γ), (p,α), and (p,p) reactions have provided a large amount of information on states in ^{28}Si in the energy range $E_x = 12.5$—13.4 Mev, for none of these studies was the overall energy resolution comparable to that in the present experiment. The previous work through 1978 is summarized in the review of Endt and Van der Leun.[4] The only previous elastic scattering study for which a detailed analysis was performed is that of Tveter[5] in the energy range $E_p = 1.1$—1.8 MeV. In the present study with an overall resolution of 350 to 400 eV (FWHM), nine new elastic scattering resonances were observed in this energy range. Two of these resonances had not been observed in proton capture studies,[6] while nine resonances seen in proton capture were not observed in the present experiment.

One of the resonances in this energy range ($J^\pi = 2^+$, $E_p = 1.3656$ MeV) has been employed in a test of time reversal invariance through a measurement of detailed balance.[7] The sensitivity of this experiment to a possible violation of time reversal invariance depends upon the mixing of the entrance orbital angular momenta. In the present study this l-mixing ratio has been determined from the (p,α_0) angular distribution and the elastic scattering excitation function.

The experimental equipment and procedures are described in Sec. II. The analysis and spectroscopic results are presented in Secs. III and IV, while the analog states are discussed in Sec. V. Results of the measurement of the entrance channel mixing ratio for the $E_p = 1.3656$ MeV resonance are described in Sec. VI.

II. PROCEDURE

The experiment was performed with the model KN Van de Graaff accelerator and the associated high resolution system at TUNL. This system, which has been described elsewhere,[8,9] has recently been upgraded to allow operation at proton energies up to 4 MeV.

Targets consisted of 0.6 to 1.4 μg/cm^2 Al evaporated onto 2 μg/cm^2 collodion coated C foils or 5 μg/cm^2 C foils. The vacuum evaporation was performed with an open Ta boat and pure Al wire.

The scattered protons and alpha particles were detected by Si surface barrier detectors at laboratory angles of 90°, 105°, 135°, and 160°. Dead time and pulse pileup problems due to the strong ^{12}C(p,p) resonances near $E_p = 1.7$ MeV were minimized by electronically gating the C peak out of the spectra, using very thin C backings, and reducing the incident beam current to about 200 nA. Typical beam currents of 3 to 6 μA with counting times of 40 to 100 s maintained 1.5% counting statistics in the off resonance yield. Data were taken in steps of 100 eV over very small resonances and in steps of 600 eV or less elsewhere. The spectra were monitored on line and also stored on magnet-

ic tape for later analysis.

Absolute energy calibrations were based on the resonances in the ^{27}Al(p,γ) reaction at E_p=991.90±0.04 keV (Ref. 10) and 1799.75±0.09 keV (Ref. 11). Standard relativistic corrections were applied.

III. ANALYSIS

For proton scattering from ^{27}Al at incident energies below 1.7 MeV only the p_0 and α_0 channels exhibit strong decay. The p_1, p_2, and α_1 decay channels account for less than 2% of the total width and thus may be neglected in the elastic scattering analysis. Since the ground state spin-parity of ^{27}Al is $\frac{5}{2}^+$, the elastic scattering channel spins are $s=2$ and 3. Both channel spin and orbital angular momentum mixing may occur. Elastic scattering l values are limited to 4 or less by penetrability considerations; no $l=4$ strength was observed.

The ^{27}Al(p,α_0) ^{24}Mg exit channel spin is 0; there can be no mixing for α_0 decay. Due to the zero spin and positive parity of both the alpha particle and the ^{24}Mg ground state, only natural parity states [$\pi=(-1)^J$] can decay through the α_0 channel. The absence of mixing in the α_0 decay channel and the restrictions imposed on the resonance angular momenta make the α_0 data extremely valuable in determining resonance spins and entrance channel mixing ratios. In addition, strong α_0 decay indicates a resonance isospin $T=0$. The positive Q value[11] of 1.600 MeV for the ^{27}Al reaction leads to relatively large penetrabilities for the emitted alphas; exit l values up to 5 were considered in the analysis.

The elastic scattering channel spin mixing ratio is defined as

$$\xi=\sum_l \Gamma_{p,s=3,l}/\Gamma_p\ , \tag{1}$$

where $\Gamma_{p,s=3,l}$ is the partial proton width for channel spin 3 with orbital angular momentum l, and Γ_p is the total elastic scattering width. The range of ξ is 0—1. The l-mixing ratios are defined as

$$\epsilon_s=\pm(\Gamma_{p,s,l+2}/\Gamma_{p,s,l})^{1/2}\ . \tag{2}$$

For convenience we define the corresponding mixing angles as

$$\tan(\psi_s)=\epsilon_s\ , \tag{3}$$

where the range of ψ is $-90°$ to $+90°$.

These definitions exploit the coherence properties of the scattering of unpolarized beams from unpolarized targets. The cross sections for different values of the channel spin add incoherently, with no dependence upon the relative phases of the reduced width amplitudes. Correspondingly the channel spin mixing ratio is positive or zero and is defined in terms of widths. The reduced width amplitudes for different l values (and the same channel spin) contribute coherently to the differential cross sections. In principle the relative phase of the two reduced width amplitudes can be determined. In practice the observed l-mixing ratios are usually very small and the sign of the mixing ratio is difficult to determine. Mixing of different partial waves with different channel spins is incoherent. With two channel spins and two l values contributing there are a maximum of four elastic scattering partial widths $\Gamma_{p,s,l}$. These widths may be expressed in terms of three mixing ratios and the total elastic scattering width.

The data were fit using an R-matrix[12] based computer program. A best visual fit is obtained by varying the angular momentum, resonance energy, and the magnitudes and phases of the allowed reduced width amplitudes. The fit was multilevel and two-channel in the energy range presented. The energy shift at each resonance was made zero by choosing the boundary condition parameter equal to the shift function. Spins up to 7 were considered in the analysis. Higher spins can be ruled out on the basis of penetrability considerations. The capture process was neglected in the R-matrix analysis. For all resonances observed in elastic scattering the dominant l value was determined by shape analysis.

A catalog showing the variation of the elastic scattering resonance shapes with both channel spin mixing and orbital angular momentum mixing was generated in order to assist in determining the acceptable solutions. Examples of channel spin mixing and of orbital angular momentum mixing have been presented in a previous paper.[1]

The resolution width was determined by fitting resonances with widths less than that of the experimental resolution function. The resolution function employed consisted of a Gaussian function with a low energy Lorentzian tail to reproduce energy straggling effects. The energy resolution varied between 350 and 400 eV FWHM.

The resonance angular momentum for states possessing widths greater than the resolution width usually could be determined from the elastic scattering fits to the data. As an example, the $J=2$ and 3 fits to an $l=0$ resonance with a width of 550 eV are shown in Fig. 1. The presence of α_0 decay and the α_0 angular distributions often made spin assignments possible for resonances with widths smaller than the resolution width. Figure 2 shows the data and R-matrix fit for a small energy region containing a doublet consisting of an $l=0$ (Γ_p=50 eV) resonance and an $l=1$ (Γ_p=2.4 keV) resonance. The dashed line shows the

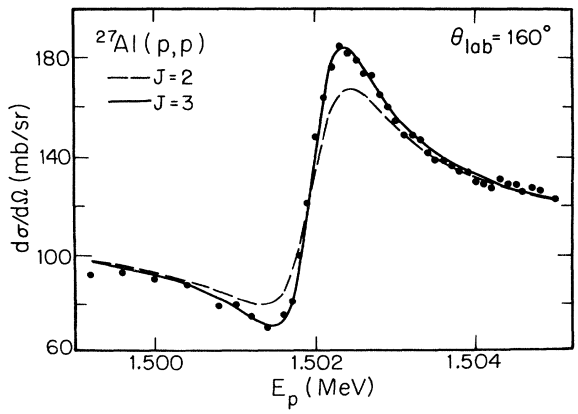

FIG. 1. The 160° data and best R-matrix fits for $J=2$ and 3 to the $l=0$ resonance at E_p=1.503 MeV. The plotted energies are uncorrected laboratory energies. Note the suppressed zero of the ordinate.

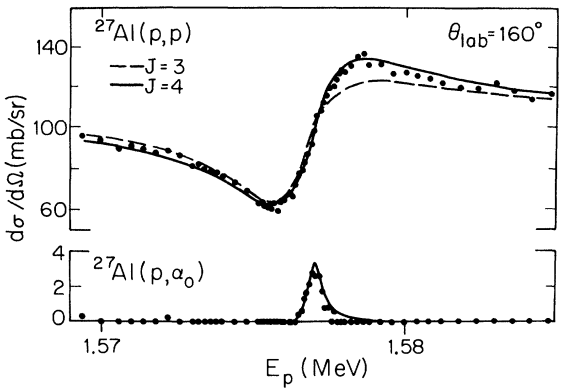

FIG. 2. The 160° data and best R-matrix fits for $J=3$ and 4 to the $l=1$ member of the resonance doublet at $E_p=1.578$ MeV. The channel spin admixture for $J=3$ was adjusted to give the best fit. The $l=0$ member of the doublet is observed predominantly through the α_0 channel. Uncorrected laboratory energies are plotted.

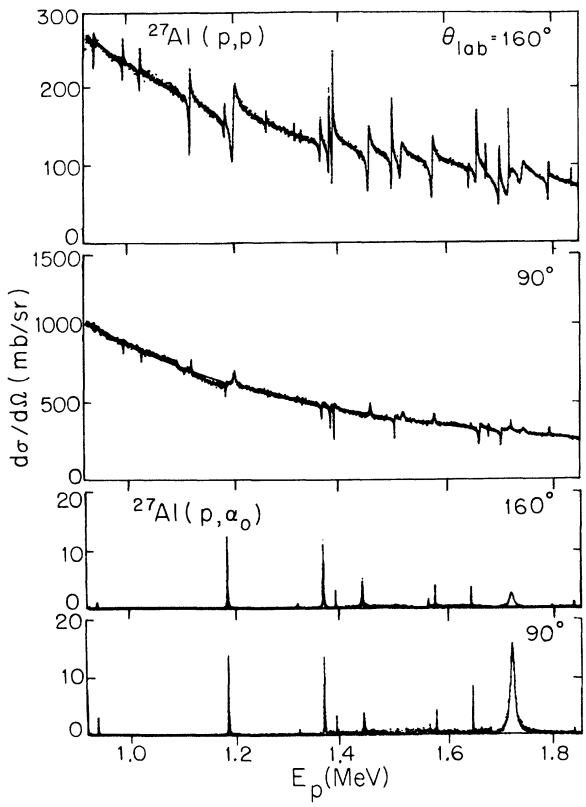

FIG. 3. The ^{27}Al(p,p) and (p,α_0) differential cross sections at two angles in the range $E_p=0.92-1.85$ MeV. The solid line is the R-matrix fit to the data. Background due to pulse pileup is seen in the α_0 excitation functions above $E_p=1.4$ MeV. There are no 160° α_0 data for the resonance near $E_p=1.7$ MeV due to the large contribution of pulse pileup from strong ^{12}C(p,p) resonances. Acceptable data were obtained at the three other angles. Uncorrected laboratory energies are plotted.

theoretical fit for $J=3$ for the $l=1$ resonance; the solid line for $J=4$ is a better fit to the data. The $l=0$ resonance is observed predominantly through the α_0 channel, although some indication is seen in the elastic scattering excitation function (especially at 90° and 105°). Spin assignments and mixing ratios for a few resonances were adopted from other studies when consistent with a solution from the present experiment.

The (p,p) and (p,α_0) data were fit simultaneously. Parameters for all resonances were included in the final fit including parameters for resonances in the higher energy region from 1.85 to 3.0 MeV. The higher energy data will be presented in a separate article.[2]

IV. RESULTS

The 90° and 160° data and fit are presented in Fig. 3, where the solid line is the R-matrix fit to the data. The extracted resonance parameters are listed in Table I. Total reduced widths γ_p^2 are defined as

$$\gamma_p^2=\sum_{s,l}\Gamma_{p,s,l}/2P_l\ , \tag{4}$$

where the Coulomb penetrability, P_l, is calculated from the Coulomb wave functions evaluated at a channel radius $R_c=1.25(1+A^{1/3})$ fm.

Table II lists the resonance energies, angular momenta, and widths from the compilation of Endt,[4] the present work, and that of Tveter.[5] The spin assignments are in good agreement with a few exceptions: (1) One member of the 1.389 MeV doublet has $J=3$, not $J=2$. (2) The 1.457 MeV resonance was best fit with $J=4$, although $J=3$ could not be ruled out entirely. Weak transitions[6] in the gamma decay of this resonance require $J=3$. (3) The doublet at 1.578 MeV (shown in Fig. 2) accounts for the previous $J=3$ assignment. Our best fit gives $J=4$. (4) The 1.841 MeV resonance is definitely $J=4$ from both the elastic scattering fit and from the (p,α_0) angular distribution. The previous $(2^+,3^-)$ assignments are due to weak gamma transitions[6] which probably arise from near-by resonances.

Qualitatively our results are in excellent agreement with those of Tveter. The widths agree well quantitatively except for many of the resonances with α decay and the resonance at $E_p=1.520$ MeV. In the latter case our value for the width is 22% smaller, while for the former cases the most severe disagreement occurs for the $E_p=1.647$ MeV resonance. Our value for the proton width is 2.8 times larger than that of Tveter. The disagreements in the widths of the resonances with α decay may arise from the indirect fitting procedure used by Tveter to account for the α decay. The channel spin mixing ratios and l-mixing ratios are in good agreement with the exception that Tveter often lists slightly larger values for the l-mixing ratio of $J^\pi=2^+$ resonances.

The average absolute energy difference between the present results and 21 precision energies of Maas *et al.*[11] is 700 eV. All of our energies agree within 1.5 keV with those of Maas. Errors in the widths are typically 10% for widths larger than 300 eV and 20% for widths less than this value. The errors in ξ and ψ depend upon the width, l value, and total angular momentum of a resonance. Typical errors in ξ are ±0.15, while typical errors in ψ are $\pm15°$. Individual errors may vary significantly from these

TABLE I. Resonance parameters for ^{27}Al(p,p) and ^{27}Al(p,α_0).

E_p[a] (MeV)	J^{π}[b]	l[c]	ξ	ψ_2[d] (deg)	ψ_3[d] (deg)	Γ_p[e] (keV)	γ_p^2[f] (keV)	l_{α_0}	Γ_{α_0}[e] (keV)	$\gamma_{\alpha_0}^2$[f] (keV)
0.9370	3^-	1	0.80	0	0	0.10	28.	3	0.008	17.
0.9919	$(2)^+$	0	0.0	0		0.10	5.0			
	$(3)^+$	0	1.0		0	0.070	3.5			
1.0253	2^+	0	0.0	0		0.11	4.5			
1.1189	4^-	1	1.0		0	0.70	62.			
1.1841	2^+	0	0.0	0	0	0.25	34.	2	0.41	74.
1.2008	3^-	1	0.0	0		5.4	320.	3	<0.005	3.2
		1	0.9	0	0	5.4	320.	3	<0.005	3.2
1.2637	3^-	1	g	0	0	0.10	4.5			
1.3183	4^+	2	1.0			0.030	9.6	4	0.005	11.
1.3300	$(2)^+$	0	0.0	0		0.040	0.43			
	$(3)^+$	0	1.0		0	0.030	0.32			
1.3656	2^+	0	0.03	-6	90	0.55	11.	2	0.40	36.
1.3826	2^+	0	0.0	0		0.78	7.0			
1.3893	3^+	0	1.0		0	0.60	5.3			
1.3895	2^+	0	0.0	0		0.20	1.7	2	0.030	2.5
1.4406	1^-	1	0.0	0		0.25	5.7	1	1.45	42.
1.4575	4^-	1	1.0		0	2.3	50.			
	$(3)^-$	1	0.10	0	0	2.3	50.			
		1	0.75	0	0	2.3	50.			
1.5033	3^+	0	1.0		0	0.55	3.4			
1.5196	2^-	1	0.32	0	0	3.7	65.			
1.5660	4^+	2	0.80			0.010	1.4	4	0.010	8.2
1.5784	4^-	1	1.0		0	2.4	35.			
1.5788	2^+	0	0.0	0		0.050	0.26	2	0.080	3.5
1.6472	3^-	1	0.71	0	0	0.28	3.4	3	0.060	8.6
1.6625	2^+	0	0.00	17		1.85	20.	2	<0.010	0.34
		0	0.09	0	90	1.85	20.	2	<0.010	0.34
1.6645	1^+	2	g			0.45	38.			
1.6798	2^+	0	0.0	0		0.21	0.84			
	$(3)^+$	0	1.0		0	0.15	0.60			
1.7055	2^+	0	0.0	0		1.1	4.2			
1.7234	3^-	1	0.96	0	0	8.0	79.	3	1.6	153.
1.7243	5^-	3	0.65			0.20	215.			
1.7481	2^-	1	0.05	0	0	6.6	62.			
1.7974	$(3)^-$	1	0.10	0	0	1.3	10.8			
		1	0.75	0	0	1.3	10.8			
	$(4)^-$	1	1.0		0	1.1	9.1			
1.7998[h]	1^+	2	g			0.20	11.			
1.8410	4^+	2	0.7			0.55	2.7	4	0.006	1.9

[a]Laboratory energies are quoted. The absolute energies should be accurate within 2 keV. Except for very large resonances, the relative energies over a small energy range should be accurate within a few hundred eV.

[b]Spin assignments have been listed according to the following convention: 2^+, definite spin and parity; 3^+,$(2)^+$, definite l value, preferred spin outside of parentheses; $(2)^+$,$(3)^+$, definite l value, spin not completely determined. Several possible solutions may be listed for each J^{π}.

[c]For $\psi_2 = 90°$ with $\xi = 0.0$, $\psi_3 = 90°$ with $\xi = 1.0$, or $\psi_2 = \psi_3 = 90°$, the higher l value is listed.

[d]When determined, the relative phase is indicated by + or −.

[e]Errors in the widths are estimated to be 20% for resonances with widths less than 300 eV and 10% for widths greater than 300 eV.

[f]Total reduced widths corresponding to the total laboratory widths listed are calculated according to Eq. (4).

[g]Parameter is undetermined for this resonance.

[h]This resonance has strong inelastic decay: $l_1 = 0$, $s_1 = 1$, $\Gamma_{p_1} = 0.20$ keV, $\gamma_{p_1}^2 = 16.$ keV; $l_2 = 0$, $s_2 = 1$, $\Gamma_{p_2} = 50$ eV, $\gamma_{p_2}^2 = 16.$ keV.

typical values.

The measured widths of three resonances may be compared with the lifetimes measured by Otto *et al.*[13] using the crystal blocking technique. The widths deduced by Otto *et al.* for the resonances at $E_p = 1.365$, 1.439, and 1.647 MeV are $\Gamma > 350$ eV, $\Gamma = 74$ eV, and $\Gamma = 37$ eV, respectively. Our values for these widths are $\Gamma = 950$, 1700, and 350 eV, respectively. The results for the two higher energy resonances disagree by more than an order of magnitude. The analysis of the crystal blocking experiments assumes that the alpha decay from lower energy resonances is blocked by the target crystal and thus has no

TABLE II. Comparison of ^{27}Al(p,p) resonance parameters.

Compilation[a]		Present work				Previous work[b]			
E_p (MeV)	$J^{\pi c}$	E_p (MeV)	$J^{\pi c}$	$\Gamma_p{}^d$ (keV)	Γ_{α_0} (keV)	E_p (MeV)	$J^{\pi c}$	$\Gamma_p{}^d$ (keV)	Γ_{α_0} (keV)
0.9373	3^-	0.9370	3^-	0.10	0.008				
0.9919	$(2^+,3)$	0.9919	$(2,3)^+$	0.10					
1.0019	4^+								
1.0253	2	1.0253	2^+	0.11					
1.0897	$(2,3)^+$								
1.0973	$(3^-$–$5^-)$								
1.1186	4^-	1.1189	4^-	0.70		1.1186	4^-	0.62	
1.1718	$(1,2)^+$								
1.1834	2^+	1.1841	2^+	0.25	0.41	1.1835	2^+	0.28	0.38
1.2004	3^-	1.2008	3^-	5.4	0.005	1.1998	3^-	5.5	
1.2131	$(1^-,2^+)$								
1.2628	$(3,4^+)$	1.2637	3^-	0.10					
1.2773	4^+								
1.3171	4^+	1.3183	4^+	0.030	0.005				
1.3289	$(2,3)^+$	1.3300	$(2,3)^+$	0.040					
1.3641	2^+	1.3656	2^+	0.55	0.40	1.3649	2^+	0.90	0.50
1.3658									
1.3816	$(2,3)^+$	1.3826	2^+	0.78		1.3815	2^+	0.72	
1.3884	2^+	1.3893	3^+	0.60		1.3884	2^+	0.54	
		1.3895	2^+	0.20	0.030	1.3886	2^+	0.24	0.050
1.438	1^-	1.4406	1^-	0.25	1.45	1.4393			
1.4570	3^-	1.4575	$4,(3)^-$	2.3		1.4564	3^-	2.0	
1.5021	3^+	1.5033	3^+	0.55		1.5030	$(2,3)^+$	0.51	
1.5197	2^-	1.5196	2^-	3.7		1.5194	$2,(1)^-$	4.75	
1.5650	4^+	1.5660	4^+	0.010	0.010				
1.5776		1.5784	4^-	2.4		1.5792	3^-	2.75	0.027
1.5778	2^+	1.5788	2^+	0.050	0.080				
1.5875	3					1.5883			
1.6471	3^-	1.6472	3^-	0.28	0.060	1.6473	3^-	0.10	0.05
1.6630	2^+	1.6625	2^+	1.85	0.010	1.6628	$(2,3)^+$	1.65	
1.6644		1.6645	1^+	0.45		1.6646			
1.6796	$(2,3)^+$	1.6798	$2,(3)^+$	0.21		1.6795	$(2,3)^+$	0.175	
1.6836	2					1.6828			
1.7056	2^+	1.7055	2^+	1.1		1.7060	$(2,3)^+$	0.82	
1.7231		1.7234	3^-	8.0	1.6	1.7231	3^-	9.0	0.97
1.7243	5^-	1.7243	5^-	0.20		1.7243	5^-	0.20	
1.7490	2^-	1.7481	2^-	6.6		1.7477	$(2,1)^-$	6.9	
		1.7974	$(3,4)^-$	1.3					
1.7998	$(1^+$–$3^-)$	1.7998	1^+	0.20					
1.8415	$(2^+,3^-)$	1.8410	4^+	0.55	0.006				

[a]Reference 4.
[b]Reference 5.
[c]Spin assignments have been listed according to the following convention: 2^+, definite spin and parity; $2,(3)^+$, definite l value, preferred spin outside of parentheses; $(2,3)^+$, definite l value, spin not completely determined; $(2^+,3^-)$, possible J^π values.
[d]Widths correspond to the first J value listed.

effect on the measured angular distribution. Otto *et al.* suggest that a contribution from the lower energy (p,α) resonances to the measured angular distribution may account for the disagreement between the two types of measurements.

V. ANALOG STATES

Identification of analog states for odd-mass targets in this region has been discussed in a previous paper.[1] Nine resonances in the present energy range are listed by Endt[4] as analogs of states in ^{28}Al. For six of these states we obtain good agreement with the previous results. The level at $E_x=12.72$ MeV ($E_p=1.1721$ MeV) was not observed in this experiment. The two remaining states are located in a group of overlapping $l=0$ resonances. The spin assignments and spectroscopic strengths of the present work allow the assignment of the resonance at $E_p=1.3893$ MeV as the analog of the $E_x=3.67$ MeV state in ^{28}Al,

TABLE III. Analog state parameters in ^{28}Si.

J^π	E_x[a] (MeV)	l	E_p^{lab} (MeV)	E_c (MeV)	Γ_{sp}[b] (keV)	Γ_p[c] (keV)	$(2T_0+1)S_p$	S_{dp}[d]	S_{dp}[e]
3^+	3.30	0	0.992	5.382	15.6	0.070	0.009	0.018	0.008
		2			0.32	<0.035	<0.22	0.037	0.086
2^+	3.35	0	1.025	5.364	18.8	0.11	0.012	0.022	0.012
		2			0.40	<0.055	<0.28	0.024	0.048
4^-	3.47	1	1.119	5.333	8.4	0.70	0.17	0.11	0.087
		3			0.030	<0.015	<1.0	0.62	0.58
3^-	3.59	1	1.201	5.292	12.8	5.4	0.84	0.19	0.13
		3			0.052	<0.026	<1.0	0.60	0.59
3^+	3.67	0	1.389	5.393	82.	0.60	0.015	0.006	0.004
		2			2.7	<0.060	<0.044	0.019	0.060
2^+	3.71	0	1.383	5.347	82.	0.78	0.019	0.040	0.024
		2			2.7	<0.060	<0.044	0.076	0.14
2^-	3.88	1	1.520	5.308	42.	3.7	0.18	0.074	0.060
		3			0.26	<0.13	<1.0	0.28	0.18
1^+	3.90	2	1.665	5.428	7.4	0.45	0.12	0.050	
2^+	3.94	0	1.663	5.386	164.	1.7	0.021	0.012	0.004
		2			7.4	0.15	0.041	0.040	0.096
5^-	4.03	3	1.724	5.358	0.58	0.20	0.69	0.85	0.43
1^+	4.12	2	1.800	5.341	11.8	0.20	0.034	0.057	0.060

[a]Excitation energies from Ref. 4.
[b]Single particle widths Γ_{sp} are averages; see text.
[c]Upper limits for $l=2$ widths are determined from the fitting procedure. Upper limits for $l=3$ widths were chosen to make the analog spectroscopic factor less than 1.
[d]Spectroscopic factors from Ref. 15.
[e]Spectroscopic factors from Ref. 16.

and the $E_p = 1.3826$ MeV resonance as the analog of the $E_x = 3.71$ MeV level in ^{28}Al. In addition, three new analog assignments have been made. The Coulomb displacement energies and proton and (d,p) spectroscopic factors are listed in Table III. The proton single particle widths were calculated by the method of Harney and Weidemüller.[14] The diffuseness and radius parameters of the potential well were the same as those used in the analysis of the (d,p) experiments.[15,16] Since two values of the particle total angular momenta and the principal quantum number (for $l=1$) are possible, averages were used in calculating the single particle widths. All of the individual single particle widths were within 12% of their average value. Due to penetrability effects, determination of the spectroscopic factors for the higher l values of l-mixed resonances is much less certain than for the lower l values. In many cases comparison of the spectroscopic factors is made uncertain by the poor mutual agreement of the two (d,p) experiments. In these cases the analog assignments are based on the Coulomb energies and the J^π assignments.

For most of the states listed in Table III there is at least qualitative agreement of the (d,p) spectroscopic factors and the analog spectroscopic factors. The disagreement between the analog and (d,p) spectroscopic factors for the $E_x = 3.59$ MeV state in ^{28}Al is severe. This difference may be due to difficulty in distinguishing between different l values in the (d,p) analysis, or to misidentification of the analog. Possible difficulty in assigning l values in the (d,p) analysis is indicated by similar (although smaller) discrepancies for other states, such as the $E_x = 3.88$ MeV level in ^{28}Al. No resonance was observed which could be the analog of the $J^\pi = 1^+$ state at $E_x = 3.54$ MeV in ^{28}Al.

VI. DETERMINATION OF ENTRANCE l-MIXING RATIOS

The $J^\pi = 2^+$ resonance at $E_p = 1.366$ MeV has been used to test time reversal invariance (TRI) through a test of detailed balance.[7] Although the results of this experiment were consistent with detailed balance, and thus with time reversal invariance, the sensitivity of this experiment to any possible TRI violating phase is strongly dependent upon the mixing ratio ϵ_2. The previous elastic scattering experiment[5] provided only an upper limit of $|\epsilon_2| \leq 0.25$, as did the present elastic scattering study. The value adopted by Driller *et al.*[7] ($\epsilon_2^2 = 0.01$) was based on penetrability considerations. We performed a study of the (p,α_0) angular distribution in order to measure the value of ϵ_2.

The angular distribution of the α_0 decay of the $E_p = 1.366$ MeV resonance was measured at five angles (90°, 120°, 135°, 150°, and 160°) with Si surface barrier detectors. The 90° spectrum is shown in Fig. 4. Pulse pileup rejection electronics and a beam current of 200 nA were employed to minimize the background due to pileup. The only other background was due to ^{19}F(p,α_2), which was separated from the ^{27}Al(p,α_0) peak at all angles except 160°, where partial overlap of the peaks occurred. The normalized Legendre coefficients are

$$a_2 = -0.08 \pm 0.02 \text{ and } a_4 = 0.00 \pm 0.02 .$$

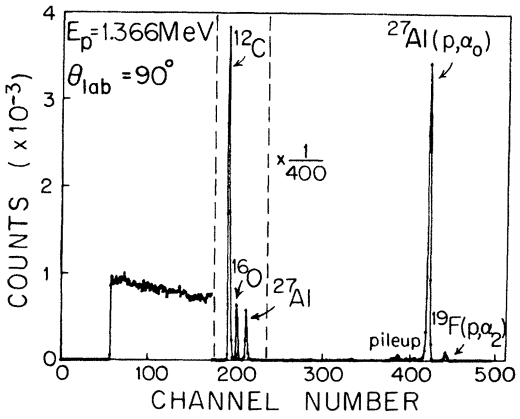

FIG. 4. The 90° spectrum from the ^{27}Al(p,α_0) angular distribution measurement at the $E_p=1.366$ MeV resonance. The small background due to pileup and the ^{19}F(p,α_2) reaction is shown in addition to the elastic scattering peaks.

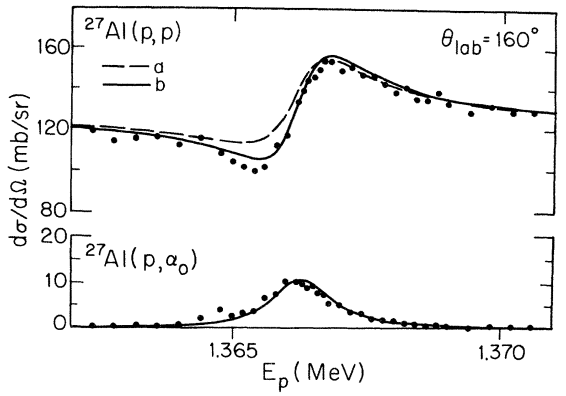

FIG. 5. The 160° data and R-matrix fits corresponding to the two mixing ratio solutions obtained from the α_0 angular distribution for the resonance at $E_p=1.366$ MeV. The total width of the resonance was varied slightly to achieve the best possible fit for each solution. Uncorrected laboratory energies are plotted.

The theoretical expressions for the a_2 and a_4 coefficients in terms of the mixing ratios are

$$a_2=\frac{-\frac{15}{49}\epsilon_2^2-\frac{40}{49}\delta_3^2-\frac{2}{7}\sqrt{70}\cos(\bar{\phi}_0-\bar{\phi}_2)\epsilon_2}{1+\epsilon_2^2+\delta_3^2}$$

and

$$a_4=\frac{\frac{36}{49}\epsilon_2^2-\frac{9}{49}\delta_3^2}{1+\epsilon_2^2+\delta_3^2}\ , \tag{5}$$

where we define the squared l mixing ratio

$$\delta_3^2=\Gamma_{p,s=3,l+2}/\Gamma_{p,s=2,l}\ , \tag{6}$$

$\bar{\phi}_l$ is the sum of the Coulomb and hard sphere phases, and $l=4$ has been neglected.

Using the experimentally determined values for a_2 and a_4, and the value $\cos(\bar{\phi}_0-\bar{\phi}_2)=-0.22$ calculated for protons on ^{27}Al at 1.366 MeV, two pairs of solutions are obtained:

(a) $\epsilon_2=0.28$, $\delta_3=\pm0.54$;

(b) $\epsilon_2=-0.11$, $\delta_3=\pm0.18$.

The elastic scattering data are used to choose between the two solutions for ϵ_2, since the difference in the amount of l mixing between the two solutions leads to different elastic scattering resonance shapes. Figure 5 shows the 160° data and R-matrix fits corresponding to the two solutions obtained above (the sign of δ_3 does not affect the cross sections). The total width of the resonance was varied to achieve the best possible fit to the data for each solution. Since the solid line fit is better than the dashed line fit, solution (b) is preferred. Thus the value of $\epsilon_2^2=0.01$ assumed by Driller *et al.* is very close to the measured value, and the sensitivity of their experiment is unchanged.

Other resonances should be studied to test further for possible violation of detailed balance. For example, Driller *et al.* point out that it is possible that the TRI violating phases were large but of nearly the same magnitude. Ideally, a resonance for which ϵ_2 is very large is desired. Unfortunately, such resonances are rare in the lower energy region where the states are well isolated. Because the detailed balance experiments are difficult and tedious, it seems important to identify suitable resonances for further study. Accurate measurements of the coherent l mixing for the known $J^\pi=2^+$ states should be performed. In addition, more (p,α) data should be obtained on neighboring odd mass targets to identify other resonances suitable for such studies.

VII. SUMMARY

The ^{27}Al(p,p) and (p,α_0) excitation functions have been measured in the energy range $E_p=0.92$—1.85 MeV with an overall resolution of 350 to 400 eV. Resonance parameters were extracted for 31 resonances with a multilevel, multichannel R-matrix analysis code. Several new spin and parity assignments were made and new doublet structure resolved. These measurements extend our detailed spectroscopic studies to the more complicated analysis of data from higher spin targets. Channel spin mixing ratios were determined for a number of resonances. For one resonance the entrance l-mixing ratio was determined and its relation to a previous test of time reversal invariance discussed. More suitable resonances for such tests may be identified among the higher energy ^{27}Al(p,α_0) resonances or in other neighboring odd-mass targets. Eleven analog states were identified and their spectroscopic factors determined.

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[1]R. O. Nelson, E. G. Bilpuch, C. R. Westerfeldt, and G. E. Mitchell, Phys. Rev. C 27, 930 (1983).
[2]R. O. Nelson, E. G. Bilpuch, C. R. Westerfeldt, and G. E. Mitchell, Phys. Rev. C (to be published).
[3]D. Halderson, K. W. Kemper, J. D. Fox, R. O. Nelson, E. G. Bilpuch, C. R. Westerfeldt, and G. E. Mitchell, Phys. Rev. C 24, 786 (1981).
[4]P. M. Endt and C. Van der Leun, Nucl. Phys. A310, 1 (1978).
[5]A. Tveter, Nucl. Phys. A185, 433 (1972).
[6]M. A. Meyer, I. Venter, and D. Reitmann, Nucl. Phys. A250, 235 (1975).
[7]H. Driller, E. Blanke, H. Genz, A. Richter, G. Schrieder, and J. M. Pearson, Nucl. Phys. A317, 300 (1979).
[8]C. R. Westerfeldt, G. E. Mitchell, E. G. Bilpuch, and D. A. Outlaw, Nucl. Phys. A303, 111 (1978).
[9]E. G. Bilpuch, A. M. Lane, G. E. Mitchell, and J. D. Moses, Phys. Rep. 28, 145 (1976).
[10]M. L. Roush, L. A. West, and J. B. Marion, Nucl. Phys. A147, 235 (1970).
[11]J. W. Maas, E. Somorjai, H. D. Graber, C. A. Van den Wijngaart, C. Van der Leun, and P. M. Endt, Nucl. Phys. A301, 213 (1978).
[12]A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958).
[13]G. Otto, E. Zschau, and A. Al-Khafaji, Ann. Phys. (Leipzig) 38, 298 (1981).
[14]H. L. Harney and H. A. Weidenmüller, Nucl. Phys. A139, 241 (1969).
[15]T. P. G. Carola and J. G. Van der Baan, Nucl. Phys. A173, 414 (1971).
[16]S. Chen, J. Rapaport, H. Enge, and W. W. Buechner, Nucl. Phys. A197, 97 (1972).