STATES IN ^{28}Si STUDIED THROUGH THE $^{27}Al(p, \alpha)^{24}Mg$ REACTION AT LOW ENERGIES

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ABSTRACT: The excitation curve for the $^{27}Al(p, \alpha)^{24}Mg$ reaction was measured in the proton energy range of 1.32-2.05 MeV, to study excited states in ^{28}Si. Angular distributions of α_0-particles were measured at 6 of the 11 resonances. The analysis shows good agreement with Abuzeid et al.[1] assignments. Three angular distributions not reported in Abuzeid's work were measured and possible assignments are reported.

INTRODUCTION

The study of excited states in ^{28}Si through the proton bombardment of ^{27}Al has previously been undertaken using different outgoing radiations. In

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particular, several investigations have been made on (p, γ) reactions, from where information has been extracted concerning spins, parities, and branching ratios of the various states. In the region where resonances are reasonably well separated, angular correlation methods are usually employed to extract quantum characteristics.

Less work, however, has been done with (p, α) reactions. The region from $E_p = 1.0$ to 2.5 MeV has been covered by Abuzeid et al.[1], including angular distributions of some of the resonances encountered. The present work was carried out to complement the existing information in this energy region and discuss spin and parity assignments.

The region studied with a 90° laboratory excitation curve is from 1.32 to 2.05 MeV. Angular distributions were measured on most of the resonances encountered. In general, experimental results agree with those of reference[1]. Three new angular distributions were measured.

EXPERIMENTAL TECHNIQUE

The proton beam from the Instituto de Física 3 MeV Dynamitron accelerator was analyzed in a 90° magnet and focused onto the target inside a 65 cm radius scattering chamber. Slits at the analyzer were set to give a 0.2% energy resolution. Since no precise energy calibration was made, we have adopted the same energy and number of each level given in reference[1]. A large Faraday cup with a ¯150 volt repulsive potential for secondary-electron suppression was used, and the current was monitored and integrated by an Eldorado Model CI-110 current integrator.

The target used was thin ($\sim 5\ \mu gm/cm^2$) aluminum evaporated on a "Formvar" backing. Two detectors were used, one movable and one fixed at 90° laboratory angle for monitoring purposes. Both were high-resistivity, surface-barrier Nuclear Diodes detectors. The solid angle subtended by the detectors was $\sim 2 \times 10^{-3}$ sterad. The pulses, after passing through Tennelec 100 A preamplifiers, were fed to a T. M. C. 400 channel analyzer which was slaved to the current integrator.

Figure 1 shows a spectrum taken on resonance, where the alpha-particle peak of the ground state $^{27}Al\,(p, \alpha)^{24}Mg$ reaction ($Q = 1.601$ MeV) shows up well. This level is the only positive Q-value reaction possible, so that there was no difficulty in separating it from the elastic peaks in the spectrum. Pulse pile-up, however, turned out to be bothersome; the pile-up from the elastic peaks almost always falling close to the alpha peak. For this reason, the beam current was kept between 0.03 and 0.06 microampere.

The 90° laboratory angle excitation curve obtained is shown in figure 2, from 1.32 to 2.05 MeV. In general, 5 keV steps were taken, except near resonances, where they were reduced to 3 keV. The charge collected at each point was 75 microcoulombs. An estimate of the differential cross section was made by comparing counts in the alpha peaks with the corresponding elastic proton peaks at different energies. The values obtained are about half of those of reference 1. Neither of them are considered very reliable because of the resonant structure of the elastic excitation curve[2]. In the present calculation, however, several energies were used and a Rutherford curve was fitted to the whole 90° elastic excitation curve.

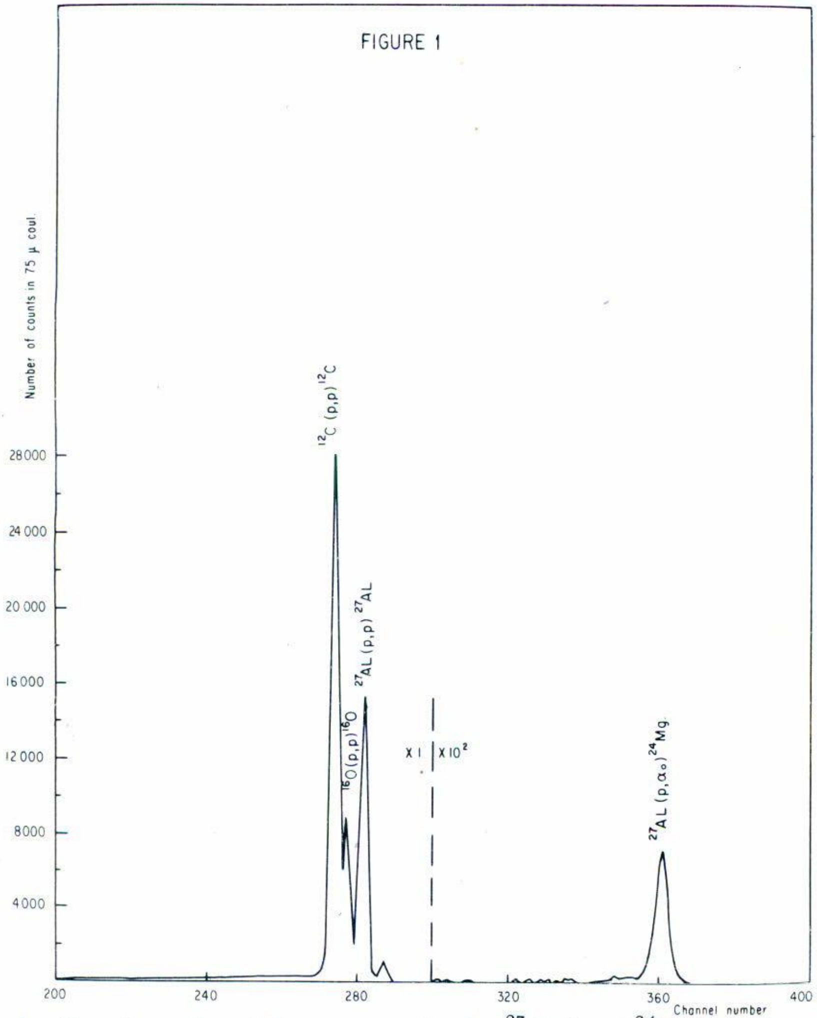


Fig. 1. The charged particle spectrum for the ^{27}Al$(p, \alpha_0)^{24}$Mg reaction obtained with a surface barrier detector located at $\theta = 90^\circ$ at a proton energy of 1.372 MeV.

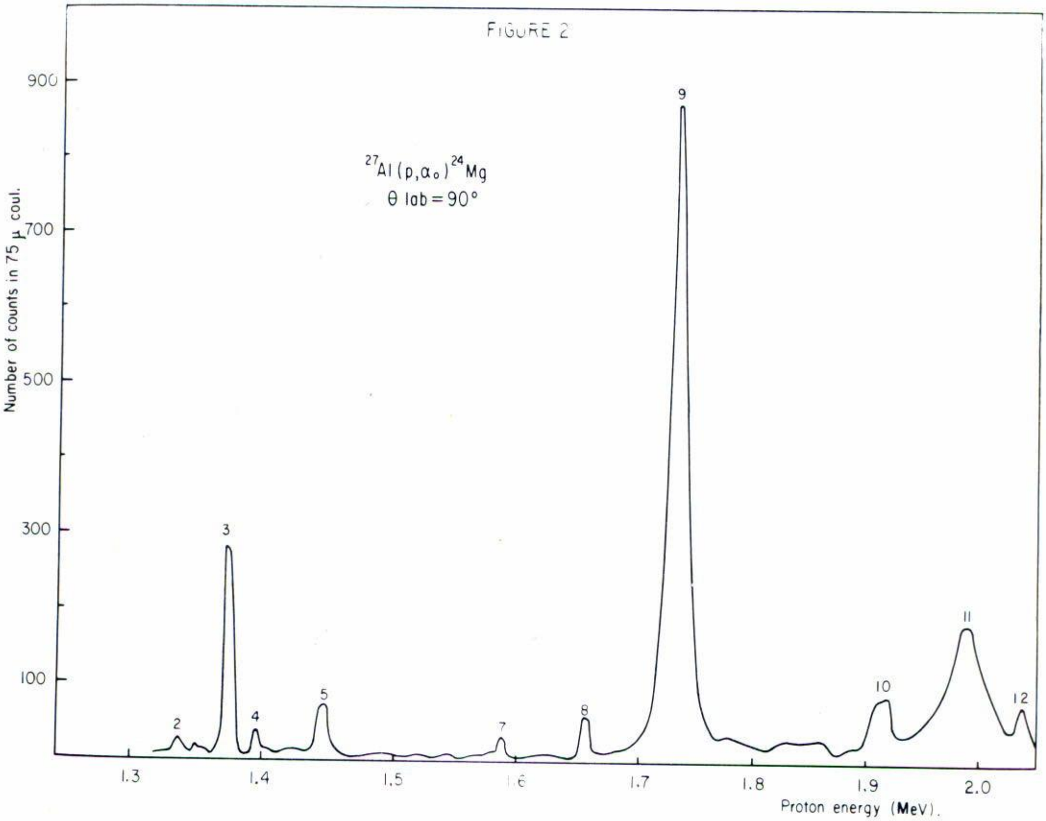


Fig. 2. The 90° excitation curve of the $^{27}Al(p, \alpha_0)^{24}Mg$ reaction with a target estimated to be $5 \mu g/cm^2$ thick.

Angular distributions were measured at the maxima of peaks number 4, 5, 7, 8, 9 and 11, the new distributions being levels 4, 7, and 11. The shapes of some of these are shown in table 1,together with other information relevant to the forthcoming discussion. The relative center-of-mass differential cross section with possible theoretical fits is plotted versus $\cos^2\theta_{CM}$. The error bars indicate the square root of counts.

THEORY

The analysis of the angular distributions was undertaken using angular correlation theory based on the statistical tensor formalism described by

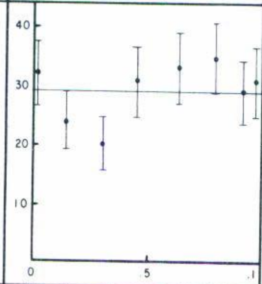
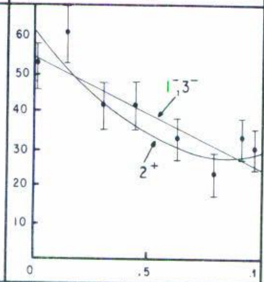
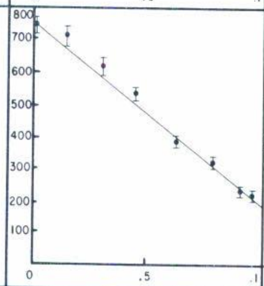
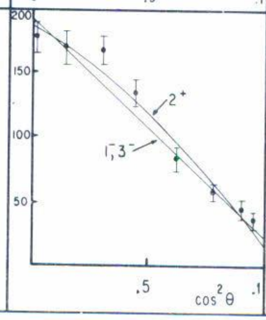
Reference 1) N°	Reference 1) E_p	J^π	Present results.	Possible Configurations	δ
4	1.395			1) $2^+(2)0^+(0)0^+$ 2) $\frac{3}{2}^+(3)1^-(1)0^+$ 3) $2^+(^3_1)1^-(1)0^+$ 4) $2^+(0)2^+(2)0^+$ 5) $\frac{3}{2}^+(1)3^-(3)0^+$	 .59 .56 .59
8	1.650	3^-		1) $\frac{3}{2}^+(3)1^-(1)0^+$ 2) $2^+(^2_0)2^+(2)0^+$ 3) $\frac{3}{2}^+(1)3^-(3)0^+$	2.2 1.2 2.2
9	1.726	3^-		1) $\frac{3}{2}^+(3)1^-(1)0^+$ 2) $\frac{3}{2}^+(2)2^+(2)0^+$ 3) $\frac{3}{2}^+(1)3^-(3)0^+$	4.7 3.8 4.7
11	1.985			1) $\frac{3}{2}^+(3)1^-(1)0^+$ 2) $\frac{3}{2}^+(2)2^+(2)0^+$ 3) $\frac{3}{2}^+(1)3^-(3)0^+$	8.0 12.3 8.0

Table 1. Results and possible assignments to states in ^{28}Si from the $^{27}Al(p, \alpha_0)^{24}Mg$ reaction.

Ferguson[3]. This theory is particularly useful for cases where the initial, intermediate, and final states are well defined, and by applying it, quantum numbers may be obtained for the different steps involved.

According to this method, the angular distribution of a reaction of these characteristics may be expressed as a sum of even order Legendre polynomials, or of even powers of cos θ, whose coefficients contain geometrical factors and reduced matrix elements. In order to avoid calculating the reduced matrix elements, a parametrization is carried out by defining mixing parameters δ, and this makes the expressions model-independent within the limitation of these parameters.

Let us consider the reaction $a(l_1)\,b(l_2)\,c$, where a is the incoming channel spin, l_1 is the incoming orbital angular momentum, b is the spin of the intermediate state, l_2 is the outgoing orbital angular momentum, and c is the outgoing channel spin. In our particular case, the ground state of ^{27}Al is $(5/2)^+$, which when coupled to the $(1/2)^+$ proton gives $a = 2$ or 3. On the other hand, the outgoing channel spin is zero, in view of the alpha particle and the 0^+ ground state of ^{24}Mg. From conservation of parity in the outgoing channel, b^{π} (also called J^{π}) may only take the values, 0^+, 1^-, 2^+, 3^-, etc., according to the value of l_2 (0, 1, 2, 3, etc.).

The incoming channel-spin mixing parameter is defined according to Ferguson[3], and using his notation, as

$$\delta_0 = \left| \frac{\langle b \| l_1' | a' \rangle}{\langle b \| l_1 | a \rangle} \right|^2 ,$$

the square of the absolute value of the ratio of reduced matrix elements. An incoming orbital angular momentum mixture is also present, defined as

$$\delta_1 = \frac{\langle b \| l_1' | a \rangle}{\langle b \| l_1 | a \rangle} ,$$

the ratio of reduced matrix elements. Double mixtures (in a and l_1) are not considered.

Angular distributions were calculated in this manner according to

$$W(\theta) = \sum_k B_k \cos^k \theta$$

with $k = 0, 2, 4$, etc., for all possible combinations of quantum numbers up to and including $b = 3$, consistent with angular momentum and parity conservation. Case 2^+ (2) 0^+ (0) 0^+ allows no mixtures and is isotropic. All the other cases were computed using the coefficients of Table 2, which depend on the mixing parameters, and which were calculated according to Ferguson's definitions[3]. The quantities ξ^l_1 correspond to phase shifts containing a Coulomb part and a hard-sphere part. The lower index refers to incoming channel. They were calculated from the graphs of Sharp et al.[4].

DISCUSSION

Our results are presented in compact form in table 1. The first three columns contain, respectively: number of the level, proton energy, and J^π assignments, all taken from reference 1. The fourth column shows the present experimental results and theoretical curves calculated as least square fits using the coefficients of table 2, for the configurations of column five, yielding the mixing parameters of column six. These configurations were chosen by comparison with previously calculated curves and anisotropies (as defined by Frauenfelder[5]), covering a wide range of mixing parameters. In the notation of column five, the upper quantum number in the mixing corresponds to the upper number (primed) in the definition of δ.

In order to assess the feasibility of assignments, an indicator was estimated proportional to the product of penetration factors of incoming and outgoing channels at a single energy, using the graphs of Coulomb functions of reference 4. For the configurations studied, these numbers give the relative probabilities of different reaction modes, based on barrier penetration only. They have the following values:

Proton 1	alpha 1	indicator
2	0	1.4
3	1	0.04
1	1	6.7
0	2	7.7
1	3	.45
2	2	.24

CASE	B_0	B_2	B_4	B_6
$^{3^+}_{2^+}(3)\,1^-(1)\,0^+$ $^{3^+}_{2^+}(1)\,3^-(3)\,0^+$	$(0.6+1.5\delta_0)\,\nu$	$(1.2-1.5\delta_0)\,\nu$		
$^{3^+}_{2^+}(2)\,2^+(2)\,0^+$	$(1.429+1.339\delta_0)\,\nu$	$(3.214+0.536\delta_0)\,\nu$	$(3.214-0.803\delta_n)\,\nu$	
$^{3^+}_{2^+}(3)\,3^-(3)\,0^+$	$(0.087+1.167\delta_0)\,\nu$	$(11.987-2.625\delta_0)\,\nu$	$(28.437-8.749\delta_0)$	$(18.229-7.290\delta_0)\,\nu$
$2^+\binom{3}{1}1^-(1)\,0^+$	$(0.911+1.47\delta_1\cos(\xi_1^1-\xi_1^3)+6\delta_1^2)\,\mu$	$(0.3-4.409\delta_1\cos(\xi_1^1-\xi_1^3)+1.2\delta_1^2)\,\mu$		
$2^+\binom{2}{1}2^+(2)\,0^+$	$(1+1.195\delta_1\cos(\xi_1^0-\xi_1^2)+1.428\delta_1^2)\,\mu$	$(3.586\delta_1\cos(\xi_1^0-\xi_1^2)+3.214\delta_1^2)\,\mu$	$3.214\delta_1^2\,\mu$	
$2^+\binom{3}{1}3^-(3)\,0^+$	$(0.6-0.458\delta_1\cos(\xi_1^1-\xi_1^3)+0.087\delta_1^2)\,\mu$	$(1.2+8.249\delta_1\cos(\xi_1^1-\xi_1^3)+11.988\delta_1^2)\,\mu$	$\delta_1^{-2}(11.456\delta_1\cos(\xi_1^1-\xi_1^3)+28.439$	$18.23\delta_1^2\,\mu$
$3^+\binom{3}{1}3^-(3)\,0^+$	$(1.5+1.62\delta_1\cos(\xi_1^1-\xi_1^3)+1.167\delta_1^2)\,\mu$	$(1.5+9.72\delta_1\cos(\xi_1^1-\xi_1^3)+2.625\delta_1^2)\,\mu$	$(8.1\delta_1\cos(\xi_1^1-\xi_1^3)+8.751\delta_1^2)\,\mu$	$7.293\delta_1^2\,\mu$

Table 2. Angular distribution coefficients B_k from different angular momentum combinations. $W(\theta) = \sum_k B_k \cos^k(\theta)$.

The angular distribution of level 4, not previously measured, is isotropic, although the statistical error is of the order of 20%. As can be seen from the possible configurations, the isotropic shape is compatible with J^{π} assignments: 0^{+}, 1^{-}, 2^{+}, and 3^{-}. The same can be said of level 5 (not shown), which was also isotropic, in agreement with reference 1. Level 7 (not shown) was found to be isotropic also, but with errors of the order of 30%.

For level 8, possible J^{π} assignments for 1^{-}, 2^{+}, and 3^{-}. According to the indicators mentioned, configuration 3 would be expected to be about 10 times more probable than configuration 1, since the mixing parameters are the same. Also, since the mixing parameters are larger than one, a parallel spin mechanism is expected in the incoming channel.

The same can be said about level 9, where in the three possible configurations, incoming channel spin 3^{+} is preferred.

The angular distribution of protons leading to level 11 has not been previously measured. The possibilities are the same as for level 9, but here the mixing parameters are larger, so the parallel spin mechanism is strongly preferred.

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REFERENCES

1. M.A. Abuzeid, F.M. Aly, Y.P. Antoufiev, A. T. Baranik, T.M. Nower, and P.V. Sorokin, Nuclear Phys. 45 (1963) 123.
2. F.C. Shoemaker, J.E. Faulkner, G.M.B. Bouricius, S.G. Kaufmann, and F.P. Mooring, Phys. Rev. 83 (1951) 1011.
3. A.J. Ferguson, Angular Correlation Methods in Gamma-Ray Spectroscopy, (North-Holland, 1965).
4. W.T. Sharp, H.E. Gove, and E.B. Paul, Graphs of Coulomb Functions, (AECL-268, 1961).
5. H. Frauenfelder, in Beta and Gamma Ray Spectroscopy, Ed. K. Siegbahn, (North-Holland, 1955) p. 531.

RESUMEN

Se midió la curva de excitación para la reacción de $^{27}Al(p, \alpha)^{24}Mg$ en un rango de energías del protón comprendido entre 1.32 y 2.05 MeV con objeto de estudiar estados excitados del ^{28}Si. Se midieron distribuciones angulares de las partículas α_0 en 6 de las 11 resonancias que se presentaron. El análisis muestra un buen acuerdo con las asignaciones de Abuzeid et al[1]. Se reportan tres distribuciones angulares no mencionadas en el trabajo de Abuzeid, y se proponen posibles asignaciones de espín y paridad a los niveles.