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Identification of new excited levels in ^{28}Si through the ^{27}Al(d,n)^{28}Si reaction

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Neutron spectra from the ^{27}Al(d,n)^{28}Si reaction have been measured with an energy resolution of better than 10 keV. Bombarding energies ranged from 2.5 to 8 MeV, permitting various regions of excitation in ^{28}Si to be populated with 1 to 3 MeV outgoing neutrons. Levels corresponding to contaminants could be identified by the energy shift with angle. We have identified four new levels below 13 MeV and 22 new levels above 13.4 MeV. The (d,n) reaction at low bombarding energies appears to be nonselective; we observe every previously known level as well as the new ones, with the only exception being those which are unresolved ($E_1-E_2 \lesssim 8$ keV) from neighboring levels. We are not able to deduce the spins and parities of these levels from the present data.

I. INTRODUCTION

Examination of the level schemes presented by Endt and van der Leun[1] reveals that most of the levels known in the *s-d* shell nuclei have been identified using either charged particles or gamma rays. The ultimate resolution is normally best for gamma rays, so the most precise energy determinations (<1 keV) are found when the gamma rays corresponding to population of a given level are measured. Such investigations do suffer from drawbacks, however. It is necessary to find a reaction which is very nonselective to produce the levels, whose gamma ray decay is to be observed. Such reactions will populate many levels simultaneously, each of which may emit many different gamma rays in its decay. Thus, not only are many gamma lines observed, but the measured energies will not necessarily correspond directly to the level energies, since more than one gamma ray can be emitted in the decay of an excited state. It is, therefore, possible that weakly excited levels could be missed, either because the reaction mechanism was not sufficiently unselective or because of the complicated analysis procedures.

Charged-particle reactions have also provided considerable information on level schemes. They can be done with good resolution and low background, but the Coulomb barrier imposes restrictions on the incoming and outgoing particle energies. The best resolution is obtained when excitation functions are measured; in this case, the levels are observed in the compound nucleus. This procedure obviously cannot reach bound levels. To study these, one needs to look at the levels populated as final states. This technique can be quite effective, but it is necessary to find a reaction which populates all levels.

Neutron reactions are usually not useful in this mass range because of the requirement of very good resolution. However, the fact that the energy resolution of a time-of-flight spectrometer improves rapidly as the neutron energy is reduced allows measurements to be made with resolution (5—10 keV) which approaches that of the typical charged-particle experiment if low energy neutrons are observed. A (d,n) or (p,n) reaction study carried out with a suitably thin target could, therefore, yield level density information comparable to that obtained from charged-particle measurements if low energy neutrons are studied. With a time resolution of about 1 ns, a flight path of over 15 m will yield a resolution better than 10 keV for neutrons of energy about 2 MeV. The primary question then involves the extent to which these reactions are nonselective and will result in the population of all or nearly all states. It would obviously be desirable to test for this feature by studying a nucleus for which many levels are known. The ^{27}Al(d,n)^{28}Si reaction was chosen for this test since ^{28}Si has been studied frequently and a large number of levels have been identified at excitation energies up to 14 MeV.

II. EXPERIMENTAL PROCEDURE

Beams of deuterons were accelerated to energies between 2.5 and 8 MeV by the Ohio University tandem van de Graaff accelerator. The deuterons were pulsed and bunched in bursts of about 1 ns duration. A thin (~ 50 μg/cm^2) self-supporting foil of ^{27}Al was mounted in a scattering chamber which was attached to a swinger magnet assembly.[2] This latter device permitted us to rotate the beam and target so that a single 30 m flight path could be used to detect neutrons emitted at various angles to the deuteron beam. After passing through the foil, the deuteron beam traveled an additional 15.0 cm to a Faraday cup, where the current was integrated.

An assembly of seven NE213 scintillators was used to detect the neutrons at the end of a 28 m flight path. The scintillators were cylinders of height 5 cm and had a diameter of 11.5 cm. Background pulses produced by gamma rays were largely eliminated through use of pulse-shape discrimination.

As mentioned in the Introduction, the rapid energy dependence of the energy resolution made it important to choose the bombarding energy (if possible) so as to populate the levels in the region of interest leaving 1 to 3 MeV neutrons in the exit channel. This led us to utilize runs at a number of bombarding energies so as to move the win-

TABLE I. Energy resolution of the two detector sets. Deuteron energy is 4.5 MeV. Target thickness is 50 μm/cm^2. Flight path is 28 m. Old set is 20.3 cm diameter by 10.2 cm deep NE213 scintillator. New set is 11.4 cm diameter by 5.1 cm deep NE213 scintillator.

Neutron energy in MeV	Old set Calculated in keV	Old set Observed in keV	New set Calculated in keV	New set Observed in keV
1.5	12	10	8	7–8
2.0	15	18	10	10
3.0	22	20	15	13–14
4.0	30	26	20	18–20
5.0	38	34	27	26–28
13.0	113	123	94	90

dow of best resolution over a significant range of excitation energy.

The resultant energy resolution has contributions from incident energy fluctuations and width, energy loss and straggling in the target, time width of the beam, and thickness of the scintillator. Estimates of the total experimental width were based on the assumption that these could be added in quadrature and the resulting sum agreed well with the measured values. Incident beam energy fluctuations and instantaneous energy width give a contribution of about 4 keV, while the energy loss and straggling in the target produced a similar energy width. The contributions to energy resolution produced by the beam time width and the finite scintillator thickness are similar, in that they produce a widely varying energy smearing depending on the outgoing neutron energy, with the best resolution occurring at low energies. For neutrons with energies between 1 and 2 MeV, the contribution of the beam time width is negligible and that of the scintillator thickness is about 3–4 keV. Thus, the best resolution obtained was about 8 keV, the resolution deteriorating to about 100 keV for neutrons of 13 MeV (see Table I).

III. DATA ANALYSIS AND RESULTS

The accuracy with which energies can be determined depends not only on the energy resolution but also on certain other parameters. Most important of these are the input energy, the flight path, and the time calibration of the spectrometer. The bombarding energy was determined by bending the beam in a magnet whose field was determined with a nuclear magnetic resonance (NMR) probe. To verify that the results for level energies are not biased by known uncertainties or unknown small errors in the determination of the bombarding energy, we allowed the input energy to be varied slightly around the input value in order to optimize the fit to four peaks of known excitation energy. In every case the best-fit value for this energy was within 4 keV of the measured value, which is consistent with the estimated error in the input parameter. Similarly, the flight path could be uncertain by a small amount ($\lesssim 1$ cm) because of the motion of the beam trajectory as the swinger magnet is rotated with angle. The flight path was also allowed to vary in order to best fit the excitation energies of known levels; this resulted in small changes (1–2 cm) in the nominal 28 m flight path. Thus, for both the flight path and the bombarding energy, small variations ($\lesssim 0.1\%$) in these parameters, so as to optimize the fit to a number of levels with known Q values, eliminated the need for a separate determination of these quantities to better than 0.1%.

Calibration of the time scale of the spectrometer was achieved with the use of a radioactive source and with delay cables of known time length. The time of decay of a radioactive atom will not depend on the time of arrival of a pulse from an oscillator at the time-to-amplitude converter (TAC); thus, if the TAC is started by the pulses from the radioactive source and stopped by the pulse from the oscillator, the distribution of counts should be random in time if the count rate is small. Accumulation of such a spectrum in an analog-to-digital converter (ADC) will give a measure of the combined relative nonlinearity of the TAC and ADC by simply comparing the number of counts in each channel.

An absolute time scale can be determined by shifting the time-of-flight spectrum by a known time delay. The use of these two measurements then gives an absolute time width per channel for the entire spectrum. An ADC of 4096 channels was used for data acquisition and the relative time width of each channel was determined to about 1% using this approach. Absolute time differences between channels far apart were determined to an accuracy of about 0.5%.

As has already been discussed, the rapid change in energy resolution as a function of outgoing energy made it desirable to observe levels under conditions where a low energy neutron was produced. For this reason, measurements were made at a number of bombarding energies. Because of the positive Q values, the lowest states in excitation energy could not be populated with low energy outgoing neutrons; thus, the excitation energies for levels with excitation energies below 6 MeV are not accurately determined ($\Delta E \approx 5$ keV) in these measurements. This is not a severe problem, both because of the paucity of levels in this region (making it less likely that two levels will be separated in energy by less than this amount) and because the level energies are already well known in this excitation energy region. To distinguish new levels in ^{28}Si from peaks due to impurities, a peak was not identified as a new level unless it was observed at enough bombarding energy-observation angle combinations to establish that the proper kinematics were observed. Thus, all new levels were observed at least five times with some being seen more than ten times.

Figure 1 shows a typical experimental spectrum. Note the vast difference between the highest and lowest energy portions of the spectrum. At the high energy end of the spectrum, levels are well resolved with very few counts in regions between peaks. Low energy peaks, on the other hand, are found on top of a large "background." This is not believed to be due to an experimental background, since it is not found when the target is removed. It is probably dominated by contributions to the spectrum from ^{27}Al(d,p + n)^{27}Al reactions, which can contribute a continuum of neutrons once the neutron binding energy of ^{28}Si is exceeded. Also, the peaks in this energy region have smaller spacings and larger widths than levels at low excitation, compounding the difficulty of resolving peaks. Improved experimental resolution would be of value but would not produce a spectrum with peaks as cleanly separated as in the region of low excitation energy.

Since the publication of the Endt and van der Leun tabulation, Nelson *et al.*[3] have studied unbound levels of ^{28}Si through use of the ^{27}Al(p,p) reaction. They analyzed excitation functions at low bombarding energies obtained with energy resolution $\simeq$300 eV. This study resulted in the identification of 73 new levels, all of which were in the range of excitation energy between 13.4 and 14.5 MeV. Obviously, such an experiment can resolve some levels which are separated by too small an energy to allow them to be resolved in the present measurement. On the other hand, the results obtained from such a study may miss levels which have spins and parities such that the Coulomb penetrability is too small and will also not allow the study of bound levels. Thus, we might expect to miss some levels seen by Nelson *et al.* but could possibly see some missed in the earlier experiment.

Table II shows the level energies and errors for states above 14 MeV identified in the present experiment which are also seen in (p,p) data,[3] but which have not been tabulated in Endt and van der Leun. Energies for levels which are included in Endt and van der Leun are not listed, since they are in general not as precisely determined by our results as they were previously known. We find evidence for all levels included in Endt and van der Leun, although in some cases level spacing was small enough that two levels were seen as one peak. Similarly, our measurements support the results of Nelson *et al.* in that all levels proposed by these authors have been seen by us, but in some cases two or three levels are clumped together in one peak. In all cases where this appears to have happened, the spacing of proposed levels is small compared to our resolution.

The level proposed by Nelson *et al.* at 14 090.4 keV is listed twice, since at some bombarding energies we observe a peak at 14 089.0 keV and at others a peak at 14 094.0 keV, the latter of which presumably includes contributions from not only this level but also those at 14 095.7 and 14 097.1 keV.

Table III shows level energies between 13.4 and 14 MeV

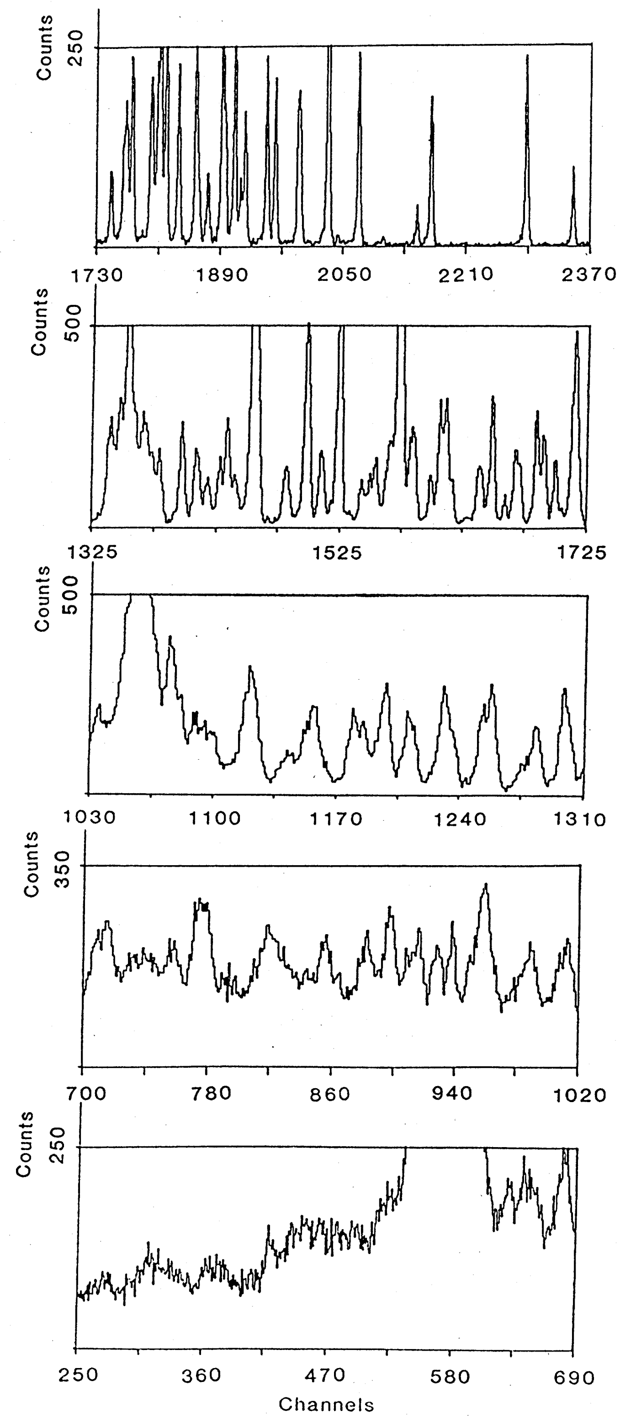

FIG. 1. Time-of-flight spectrum for the ^{27}Al(d,n)^{28}Si reaction at 150° for 8.0 MeV deuterons.

as observed in this experiment compared with the measurements of Nelson *et al.*[3] and Meyer *et al.*[4] Neither of these data sets is included in Endt and van der Leun.[1] Agreement with the results of Nelson *et al.* is good, with the one exception being the level at 13 902.8 keV proposed

TABLE II. Energies for the levels observed above 14.0 MeV compared to (p,p) data (Ref. 3) (all in keV).

This experiment	Ref. 3	This experiment	Ref. 3
14 012.0±1.5	14 013.0	14 300.0±1.5	14 295.2
14 026.0±1.5	14 025.7		14 299.9
14 037.0±1.5	14 038.4		14 307.5
14 050.0±1.5	14 049.7	14 331.0±4.0	14 329.8
	14 050.4		14 334.4
14 065.0±1.6	14 066.6	14 349.0±1.5	14 350.9
14 079.0±1.5	14 076.3	14 361.0±1.5	14 358.0
14 089.0±1.5	14 090.4		14 359.4
14 094.0±1.5	14 090.4		14 360.0
	14 095.7	14 377.0±3.0	14 376.5
	14 097.1	14 398.0±2.0	14 392.7
14 106.0±2.0	14 106.1		14 393.0
14 164.0±2.0	14 160.6		14 402.1
14 200.0±2.3	14 202.0	14 433.0±2.0	14 435.7
14 215.0±2.0	14 210.1	14 478.0±2.0	14 475.4
	14 211.8	14 498.0±2.0	14 495.0
	14 214.6	14 519.0±2.0	14 516.8
14 230.0±2.6	14 228.8		14 525.1
14 246.0±2.4	14 246.3		
	14 249.0		

in Ref. 3, which we do not see. Similarly, our results are in good agreement with those of Ref. 4, except for the level at 13 585 keV suggested in the latter reference.

As can be seen from Table IV, we find evidence for 4 new levels at energies below 13 MeV (see Fig. 2), 14 new levels at energies between 13.4 and 14.5 MeV (the 13 567 and 13 686 keV levels were proposed by Meyer *et al.* but were not seen by Nelson *et al.*), and 8 new levels above 14.5 MeV (beyond the energy range covered by Nelson *et al.*). For the very top energies covered by the present experiment, the level widths have increased and the separation has decreased to the point where some peaks may not be resolvable even with very good experimental energy resolution. It is interesting to note that the present results produce level energy values which are in some cases as good as 1.5 keV. This value is derived from internal dispersion of the numerous determinations of the level energy (various bombarding energies and reaction angles). This error is smaller than the energy resolution itself because peak centroids can be determined to an un-

TABLE III. Energies for levels observed between 13.4 and 14 MeV which were previously known (all the energies are in keV).

Ref. 4	Ref. 3	This experiment	Ref. 4	Ref. 3	This experiment
13 417	13 414.3	13 410.5±2.6	13 707	13 706.4	
	13 421.9		13 709	13 707.4	13 703.0±1.5
	13 424.8	13 422.1±3.2		13 712.5	13 712.4±1.5
	13 477.6			13 735.4	13 736.2±3.4
13 484	13 481.7	13 482.8±2.0		13 790.0	13 789.0±2.2
	13 510.1	13 510.0±2.0	13 806	13 806.6	
13 547	13 544.3	13 545.3±2.5	13 814	13 813.7	
13 557	13 556.0			13 815.1	13 810.6±2.2
	13 559.3	13 558.3±4.2	13 831	13 832.4	13 831.0±2.0
13 569		13 567.0±3.1	13 861	13 862.1	13 863.6±3.1
13 584			13 874	13 874.0	13 875.5±1.5
13 612				13 890.5	13 890.0±1.5
13 616	13 615.7	13 612.5±2.1		13 902.8	
13 636	13 634.3	13 633.0±2.0	13 941	13 940.0	13 939.0±2.0
	13 638.7			13 969.0	
13 640	13 639.2	13 639.0±1.6	13 973	13 972.4	13 970.3±2.5
13 663	13 661.9		13 980	13 979.7	
13 668	13 666.4		13 984	13 984.0	
13 678	13 677.6	13 667.0±3.8		13 985.1	13 982.0±3.0
13 686		13 686.0±2.0			

TABLE IV. Energies for the new levels seen in this experiment.

Below 14.5 MeV (in keV)	Above 14.5 MeV (in keV)
8819.4±9.1	
10 777.7±9.4	14 537.0±3.5
11 241.5±5.5	14 561.0±2.5
12 265.8±2.3	14 625.0±4.0
13 467.0±3.1	14 641.6±2.5
13 500.0±2.1	14 709.3±4.0
13 567.0±3.1	14 755.8±3.0
13 603.5±3.6	14 785.3±2.5
13 626.0±1.5	14 852.0±2.0
13 686.0±2.0	
13 744.6±1.5	
13 797.5±2.2	
13 821.0±1.5	
14 151.8±2.5	
14 271.7±3.0	
14 287.6±2.5	
14 318.0±3.5	
14 417.3±2.0	

certainty which is less than the peak width. That this internal error provides a reasonable estimate of the absolute energy uncertainty may be seen from the comparison of our level energies to the more precise values of Nelson *et al.* for those levels seen in both experiments.

It is obviously desirable to determine not only the level energy but also the spin and parity of the new levels. In this respect, our results are somewhat disappointing. We examined both angular distributions and integrated cross sections for systematics which would allow determination of spin and parity with unsatisfactory results. The integrated cross sections increase with J for small J and then decrease with J for higher values. The value obtained for a given J for levels of known spin fluctuates sufficiently from level to level, that no unique J assignment can be made based on the cross section. Angular distributions do not show sufficient regularity to allow the assignment of unique spin and parity values. One important reason for this is that our thin targets and good energy resolution in incoming beam energy causes Ericson fluctuations to be significant in cross sections and angular distributions. Averaging the data over a range of 100—200 keV in bombarding energy would average these fluctuations out but would require repeating these measurements about 15 to 20 times at neighboring energies. A direct measurement of the average cross sections with a thicker target is not possible because it would not allow resolution of the final states. Thus, at present, only very crude limits on spins could be set with data of this type.

IV. SUMMARY

A study of the $^{27}Al(d,n)^{28}Si$ reaction with good energy resolution has yielded evidence for 26 new energy levels with excitation energies between 8.82 and 14.85 MeV. We find no evidence that any of the levels tabulated in Endt and van der Leun are spurious and generally support the additional levels proposed in Refs. 3 and 4, but in each case one level was not observed in our measurements. In each case, some of the levels are separated by too small an amount for us to resolve, but we do observe peaks for every level or group of levels expected on the basis of the schemes proposed by Endt and van der Leun, Nelson *et al.*, and Meyer *et al.*, with only two exceptions. The (d,n) reaction can locate levels which are not seen as resonances in the (p,p) or (p,α) reaction, either because the level is bound or because it has too small a Coulomb penetrability. The present results suggest the need for $^{27}Al(d,n\gamma)$ studies to improve the precision of the excitation energies and to determine spins and parities for the newly identified levels.

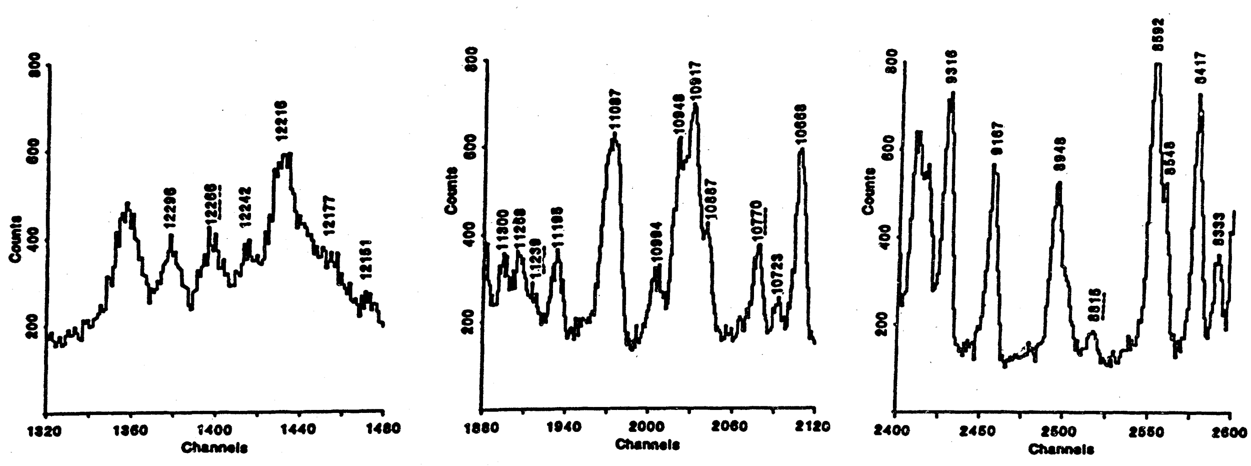

FIG. 2. Portions of time-of-flight spectrum showing four new levels below 13 MeV excitation (underscored numbers) seen in ^{28}Si through the $^{27}Al(d,n)^{28}Si$ reaction.

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