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States in ^{29}P via the ^{32}S(p,α)^{29}P reaction*

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α particles from the ^{32}S(p,α) reaction were momentum analyzed with our 100-cm modified broad range magnetic spectrograph to determine accurate excitation energies in ^{29}P. Runs were taken at laboratory observation angles of 60, 90, and 120° using protons with nominal bombarding energies of 15 and 16 MeV. Five previously unreported levels in ^{29}P were identified at 4.6406 ± 0.0030, 5.0473 ± 0.0032, 5.5827 ± 0.0035, 5.7155 ± 0.0036, and 5.8259 ± 0.0048 MeV. Comparisons are made both with theoretical level calculations and the level structure of the conjugate nucleus ^{29}Si. A Breit-Wigner shape was used to fit the group at 4.3371 MeV; the width of this level was determined to be 48.7 ± 2.5 keV.

[NUCLEAR REACTIONS ^{32}S(p, α) E_p = 15 and 16 MeV; θ_{lab} = 60, 90, and 120°. Measured excitation energies; deduced five previously unreported levels below 6 MeV.]

I. INTRODUCTION

A comparison of the known level structure of ^{29}P with its conjugate ^{29}Si, reveals excellent agreement up to 4.08-MeV excitation in both nuclei. In the region between 4.08- and 6-MeV excitation the agreement is poor. Furthermore, recent theoretical structure[1,2] calculations are in good agreement with ^{29}Si but in only fair agreement with ^{29}P. The abrupt change in the quality of agreement between the mirror nuclei ^{29}P and ^{29}Si above 4.08 MeV and the recent structure calculations suggest that the level structure of ^{29}P is not completely known. The present investigation was undertaken with a view to gaining a more complete level structure of ^{29}P. The ^{32}S(p, α)^{29}P reaction was used to measure accurately excitation energies from the ground state to approximately 6 MeV.

Earlier investigations of the energy spectrum of ^{29}P up to 4.08 MeV had been carried out with the ^{32}S(p, α), ^{28}Si(d, n), ^{28}Si(p,γ), and ^{28}Si(^{3}He, d) reactions[3] but no single reaction had been used with sufficient resolution to investigate the level structure over the entire region from the ground state to 6-MeV excitation. Over the same region of excitation the ^{27}Al(^{3}He, n) reaction[4] could not resolve states at approximately 3.3-MeV excitation which differed in energy by approximately 340 keV. It appeared that only from measurements with the ^{32}S(p, α) and ^{28}Si(d, n) reactions had all of the known levels below 4.08 MeV been reported. The region above 4.08 MeV had been investigated primarily with the ^{28}Si + p reaction. Since ^{29}P becomes unbound to protons at 2.745 MeV, the states above threshold and below 6 MeV correspond to incident proton lab energies of approximately 0.37 to 3.37 MeV. In the present investigation, protons with a nominal bombarding energy of 15 and 16 MeV were used to populate all of the previously observed levels below 6-MeV excitation, except for the very broad level (Γ = 425 ± 50 keV) at 5.53 MeV.[3] In addition, five new levels have been observed in the region from 4- to 6-MeV excitation.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

Natural sulfur targets were made by vacuum evaporation of CdS onto 20-μg/cm^2 carbon foil backings. The natural abundance of the sulfur isotopes is 95.0% ^{32}S and 4.2% ^{34}S, with only traces of ^{33}S and ^{36}S.

A proton beam was produced by the Notre Dame FN tandem Van de Graaff accelerator. The nominal bombarding energies of 15 and 16 MeV were determined by magnetic analysis. The University of Notre Dame 100-cm modified broad-range magnetic spectrograph[5] was used to momentum analyze the reaction products. Ilford nuclear track plates, with emulsion thicknesses of 25 and 50 μm, type KO, were mounted on the focal surface of the spectrograph. These plates are insensitive to protons and deuterons and served as detectors for the reaction α particles.

The 250-cm-long focal surface easily allowed simultaneous measurement of the excitation energies from the ground state to over 6-MeV excitation. The bombarding energies for the (p, α) reaction were calculated from the position of the ground state group using the Q value from the 1971 Mass Table.[6] Thus, the excitation energy of a particular level depends primarily on the measured energy difference between the corresponding α group and the ground state group and is quite insensitive to the measured input energy. With an input energy of 16.000 ± 0.009 MeV the error produced in a state at approximately 6-MeV excitation is less than 50 eV.

Contaminant α groups from ^{16}O, ^{12}C, and to a lesser extent ^{14}N and ^{13}C were present in the spectra. Runs were taken at laboratory observation angles of 60, 90, and 120° so that kinematic shifts allowed positive identification of the α groups corresponding to levels in ^{29}P.

A typical α particle spectrum is shown in Fig. 1. A total of six spectra were taken under different reaction conditions. This particular spectrum was taken at an observation angle of 120° and a proton bombarding energy of 16.000 ± 0.004 MeV. This spectrum has several prominent features. The rising background occurs because ^{29}P becomes unbound at 2.745 MeV. Since the experimental resolution is approximately 12 keV full width at half-maximum, the state at 4.337 MeV which has a natural width of 49 keV does not have the triangular shape of the other groups. The triple and double peaking of the contaminant groups from ^{16}O is caused by the presence of oxygen on the target surface and on the surfaces of the carbon foil backings. Furthermore, the new states which occur at the respective excitation energies 4.6406, 5.0473, 5.5827, 5.7155, and 5.8259 MeV are well resolved and very intense under the present reaction conditions.

When the two runs at 120° were taken there was a small uncertainty in the beam spot position relative to the spectrograph axis caused by possible settling of the spectrograph base pad. A correction for a small beam spot shift can be made by an

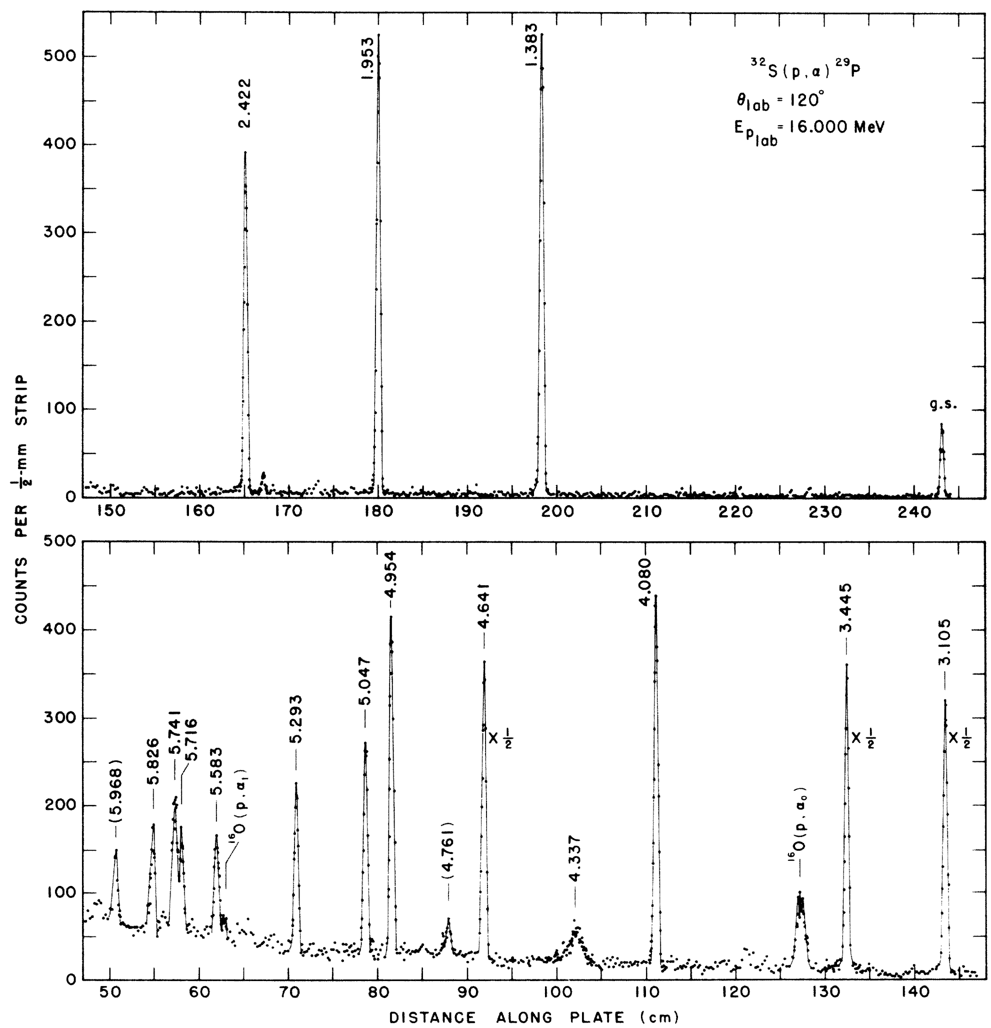

FIG. 1. α spectrum from the $^{32}S(p, \alpha)^{29}P$ reaction obtained with our 100-cm modified broad-range magnetic spectrograph. The numbers above the groups refer to the excitation energies of ^{29}P in MeV.

TABLE I. Excitation energies of ^{29}P below 6 MeV.

Number of runs	Present work Excitation (MeV) ± (keV)	σ_m (keV)	Endt and van der Leun[a] (MeV) ± (keV)	Other measurements ^{28}Si(p,γ)[b] Bardin *et al.* (MeV) ± (keV)	^{28}Si(p,γ)[c] Williams *et al.* (MeV) ± (keV)	^{28}Si(p,γ)[d] Bizzetti *et al.* (MeV) ± (keV)	^{27}Al(^{3}He,n)[e] Greenfield *et al.* (MeV) ± (keV)
6	0	0.1					
6	1.3834 ± 1.4	0.1	1.3836 ± 0.1		1.3842 ± 0.7	1.3836 ± 0.1	1.32 ± 60
6	1.9526 ± 1.6	0.3	1.9533 ± 0.5	1.9500 ± 1.3	1.9543 ± 0.9		1.97 ± 20
6	2.4222 ± 1.9	0.5	2.4217 ± 1.3	2.4217 ± 1.3			
6	3.1047 ± 2.2	0.7	3.105 ± 3				3.33 ± 40
6	3.4451 ± 2.4	0.6	3.447 ± 2				
4	4.0800 ± 2.7[f]	0.7	4.0810 ± 1.5		4.0811 ± 0.8		
4	4.3371 ± 4.6	2.3	4.343 ± 5				4.24 ± 60
6	4.6406 ± 3.0	0.9					
2(3)	(4.7613)		4.764 ± 5				
5	4.9536 ± 3.3	0.7	4.956 ± 2				4.88 ± 60
6	5.0473 ± 3.2	0.5					
5	5.2929 ± 3.5	1.1	5.294 ± 2				
			5.53 ± 20				
5(6)	5.5827 ± 3.5	1.2					
4(5)	5.7155 ± 3.6	0.8					
4	5.7409 ± 4.0	0.9	5.741 ± 4				5.66 ± 70
4(5)	5.8259 ± 4.8	1.7					
1(2)	(5.9679)		5.969 ± 4				

[a] See text Ref. 3.
[b] See text Ref. 10.
[c] See text Ref. 7.
[d] See text Ref. 11.
[e] See text Ref. 4.
[f] This state was used as a normalization point for the two runs at 120°. (See text for discussion.)

adjustment in the nominal magnetic field of the spectrograph. This was done by using the ground state α group and the group from the 4.08-MeV level to determine both the proton bombarding energy and magnetic field of the spectrograph. The value used for the excitation energy of this state was the average of the other four independent runs. This excited state was chosen as the second normalization point since it is a very intense group near the region in which the five new states were observed. Moreover, our value of 4.0800 ± 0.0027 MeV is in excellent agreement with the value of 4.0811 ± 0.0008 MeV obtained from the γ-ray measurement of Williams, Buccino, and Wellborn.[7] The validity of the two point calibration can be judged by the small standard deviation of the mean of the excitation energies obtained from an average of the two 120° and other runs. (See Table I.)

III. RESULTS

The results of the present investigation and other recent works which measured excitation energies in ^{29}P are listed in Table I. In the first column, a number without parentheses indicates how many runs were used to obtain the average excitation energy of that particular state in ^{29}P; a number with parentheses indicates the total number of times the state was observed. Some of the data were such that a reliable number could not be extracted from some of the groups. One such case is the 4.761-MeV state which is populated in only three runs, and in one of those runs that state is weakly populated. The assignment of a new state to ^{29}P was considered definite only if it was seen under at least four different reaction conditions. In Fig. 1 the weak group which appears at a plate distance of approximately 167 cm was observed on this particular data run only and positive identification of this group was not possible. The second and third columns in Table I list the average excitation energy in MeV and the uncertainty in keV. In the second column, parentheses are used to indicate that the measured value is the result of less than four independent runs. Such results are quoted without uncertainties. Quoted uncertainties are the internal errors calculated according to the standard procedures described in Refs. 8 and 9. These include uncertainties in the following quantities: the position of the group on the plate, beam spot position, reaction angle, input energy, spectrograph field, and spectrograph calibration curve. The fourth column lists the standard deviation of the mean in keV for each level. A comparison with other works[3,4,7,10,11] is given in the remaining columns of the table. Agreement within the quoted uncertainties is quite good for the ^{28}Si(p,γ) works, but does not agree with the poor resolution work using the ^{27}Al(^{3}He, n) reaction.

The level at 4.337 MeV was fitted with a Breit-Wigner shape because of its natural width. The group fitting procedure consisted of two parts. First, the shape of a bound state was parametrized by using a split-Gaussian shape. This is a convenient way to account for the asymmetry of the group shape which arises from beam spread, target thickness, and kinematic broadening which are folded into the triangular natural response function of the spectrograph. At 16-MeV bombarding energy, beam spread and target thickness each contribute approximately 8 keV; the contribution from kinematic broadening is approximately 4 keV. In the second part of the procedure, this narrow reference group shape was convoluted with a Breit-Wigner shape. The widths were allowed to vary according to the Coulomb penetrability as a function of the decay channel energy. As a result of this peak fitting procedure, the average value of the width, weighted by the statistical error was determined to be 48.7 ± 2.5 keV. The excitation energy measured was 4.3371 ± 0.0046 MeV. Both the width and excitation energy are in excellent agreement with the values of Endt and van der Leun: $\Gamma = 53 \pm 3$ keV and $E_x = 4.343 \pm 0.005$ MeV.

IV. DISCUSSION

Many theoretical calculations have been done on $2s$-$1d$ nuclei. The results of the most recent and most pertinent structure calculations pertaining to $A = 29$ or more specifically, ^{29}P, are compared with the experimental structure of ^{29}P and are shown in Fig. 2. Excitation energies and spin and parity assignments of the predicted level schemes appear on both sides of the experimental diagram

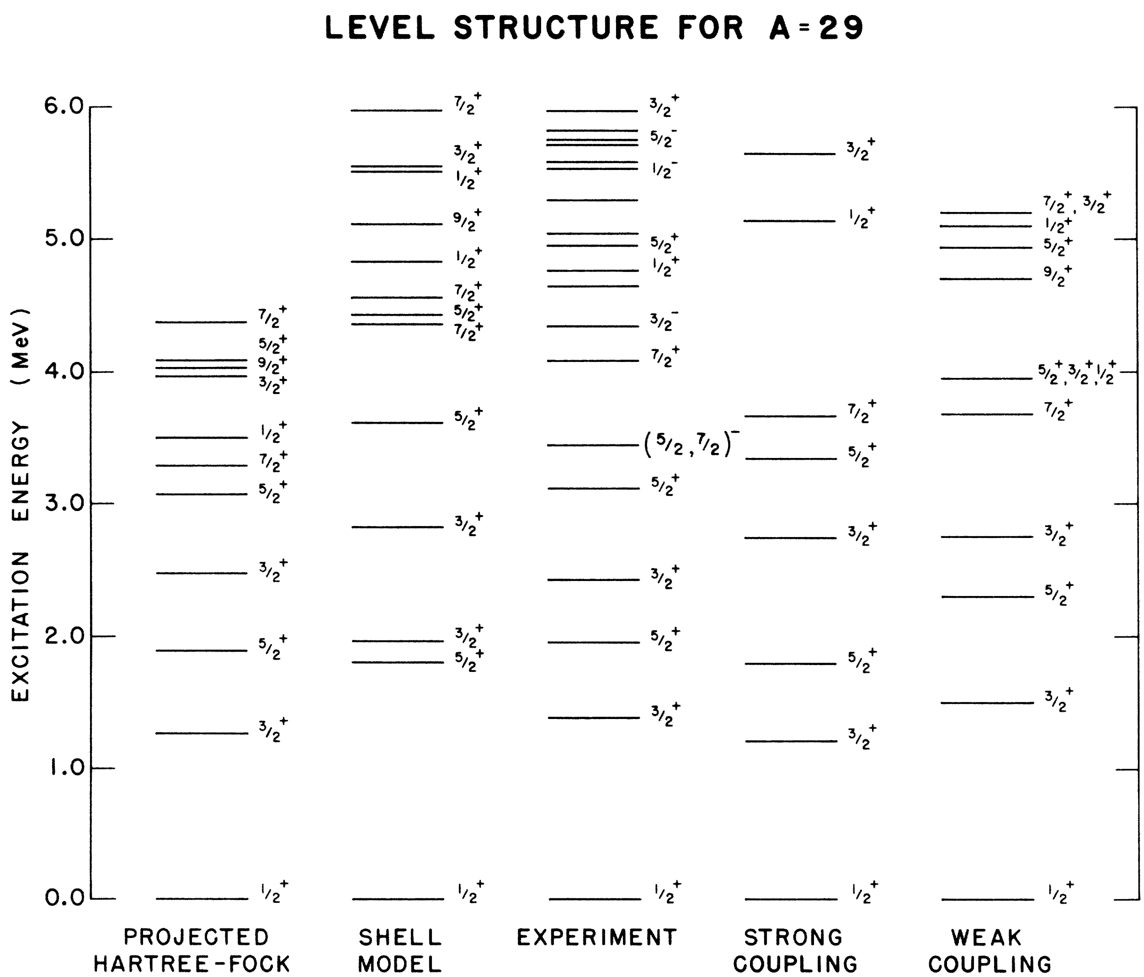

FIG. 2. Theoretical predictions (Refs. 1, 2, and 12) for $A = 29$ compared with the experimental structure of ^{29}P.

shown in the middle of Fig. 2. The type of calculation has been listed below each column. A brief summary of the manner in which the results of each calculation were obtained is given below.

Recent theoretical results of a projected Hartree-Fock calculation[1] (PHF) are shown in the first column. This particular calculation used experimental parameters of ^{29}Si and considered a quasiparticle to be coupled to a ^{28}Si core whose properties had been determined by another PHF calculation. The core-quasiparticle interaction is of the quadrupole-quadrupole type. The authors used a single coupling parameter which is chosen to be the best fit to the ^{29}Si spectrum.

The most recent calculation for $A = 29$ with specific application to ^{29}Si has been carried out by Wildenthal and McGrory.[2] The calculation is based on a microscopic shell model which includes a modified surface δ interaction Hamiltonian (MSDI). The authors point out that the accuracy of excitation energies is limited for two reasons: the use of a set of parameters determined from other

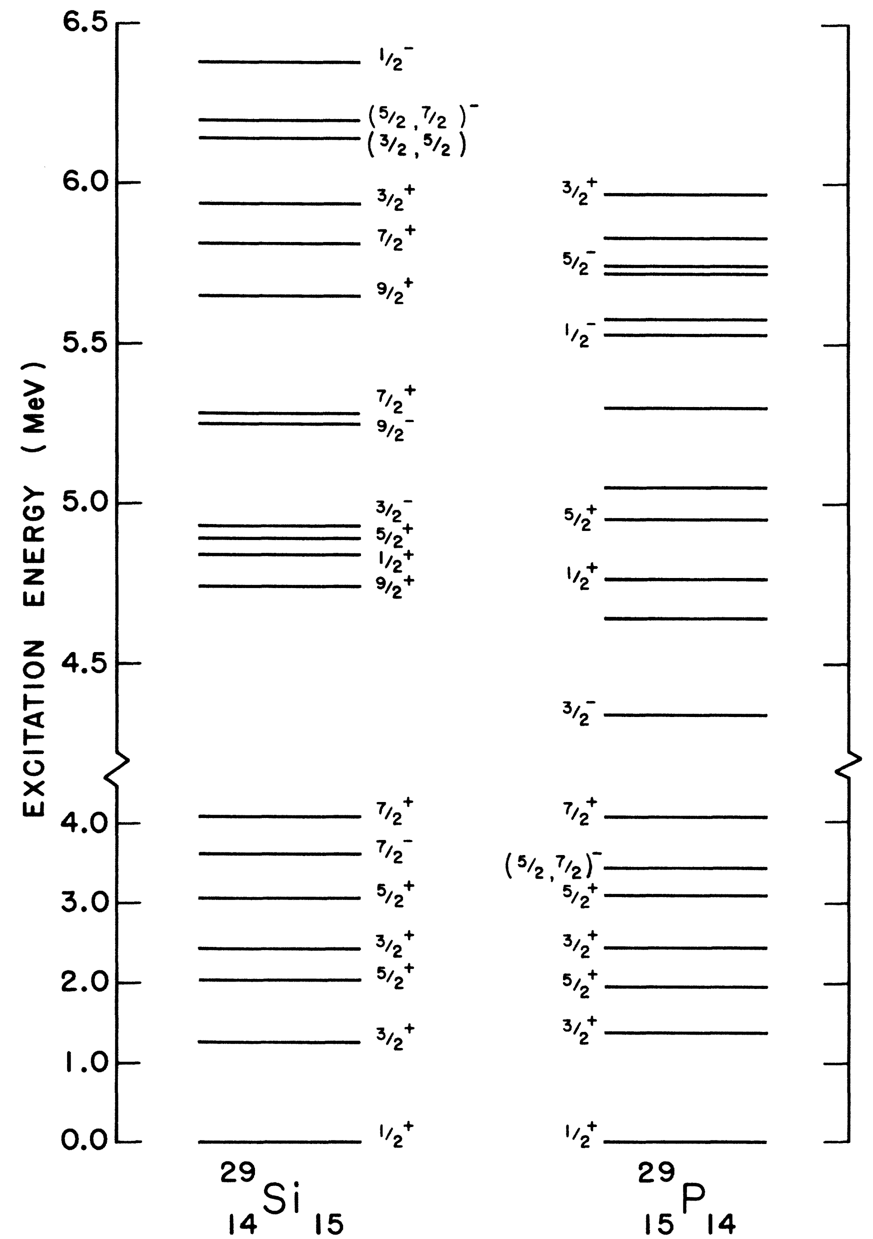

FIG. 3. Level structure of mirror nuclei ^{29}Si and ^{29}P. The 5.2929 level and the five new levels are shown without spin and parity assignments. Spin and parity assignments of other levels are taken from Refs. 3 and 13. (Note the expanded energy scale above 4.08 MeV).

mass regions of the s-d shell and severe truncation on the number of $d_{5/2}$ holes in the model space.

In the calculated level structure for $A = 29$, experimental energies of several levels of ^{29}Si, not ^{29}P, were used in the search for optimum MSDI Hamiltonian parameters. Also, only excitation energies of the first four states with a particular spin and parity were calculated, since meaningful correspondence between model and experiment was not expected beyond that point. The microscopic shell model results are shown in column 2.

Columns 4 and 5 show earlier calculations for ^{29}P based on the unified model.[12] In this model the nucleus is pictured as a system in which the collective vibrational and rotational modes are coupled to the independent motion of a few loosely bound nucleons. In the strong-coupling case Nilsson eigenfunctions are used and rotation vibration coupling and rotational particle coupling are taken into account. In the weak-coupling calculation a single proton is considered to be coupled with the phonons of surface excitation of the core ^{28}Si.

The experimental spectrum is shown in the third column. Spin and parity assignments for levels in ^{29}P have been taken from Refs. 3 and 13, and excitation energies are from the present work. The state at 5.53 MeV was not observed by us and the value of Endt and van der Leun was used.[3] One specific observation emerges when the theoretical spectra are compared with the experimental results. In the region between 4 and 6 MeV in ^{29}P no state has been identified as $\frac{9}{2}^+$ although three of the four calculations predict such a state. In particular the shell-model calculations predict a $\frac{9}{2}^+$ state at 5.11-MeV excitation. There is a new state with unknown spin and parity at 5.0473 MeV. Also in this region only one state at 4.0800 MeV has been identified as $\frac{7}{2}^+$. The microscopic shell-model calculation indicates three such states. The new states seen in ^{29}P are candidates for these high-spin states.

Further information on the level structure can be gained by comparison of ^{29}P with its conjugate nucleus ^{29}Si. The most recent experimental results for spins, parities, and excitation energies for ^{29}Si have been taken from Ref. 3. The spin and parity assignments for ^{29}Si are shown together with those of the mirror nucleus ^{29}P in Fig. 3. (Note the region above 4.08 MeV is shown on an expanded energy scale.) There are two immediate observations resulting from comparison. First, there is excellent agreement up to and including the 4.08-MeV level in both nuclei. Second, in the region up to 6-MeV excitation, there is a noticeable absence of high-spin states in ^{29}P. Based on these two observations it is reasonable to suggest that the newly found levels are prime candidates for high-spin states which are missing in this region of excitation energy.

In summary, the level structure of ^{29}P has been investigated up to 6-MeV excitation using the ^{32}S(p, α) reaction. Five new states in the region between 4- and 6-MeV excitation in ^{29}P have been identified. Previous investigations of this region had been done mainly by ^{28}Si$(p,p)^{28}$Si and ^{28}Si$(p,p'\gamma)^{28}$Si. Comparison of the present experimental spectrum of ^{29}P with theory and with the mirror nucleus ^{29}Si suggests that the newly identified levels at 4.6406, 5.0473, 5.5827, 5.7155, and 5.8259 MeV, which are populated by 15- and 16-MeV protons in the ^{32}S(p, α) reaction, are candidates for high-spin states in ^{29}P. Clearly an unambiguous assignment of spins and parities to these new levels would be desirable to test the theoretical calculations presented in Fig. 2.

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