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Identification and decay of neutron-rich ^{36}P

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The previously unreported decay of ^{36}P to levels in ^{36}S has been studied from activity generated by the ^{37}Cl$(n,2p)^{36}$P reaction using neutrons produced through the stopping of 70-MeV deuterons in a Be target. The half-life for ^{36}P was measured to be 5.9 ± 0.4 s. From γ singles and coincidence measurements excited states in ^{36}S at 3290.7(2^+), 4192.7(3^-), and 5830.8($4^-,5^-$) keV were established. The ^{36}S levels are compared with results from $(d,^3\text{He})$ and (t,p) reactions and shell-model calculations, and the nature of the negative-parity states is discussed.

[RADIOACTIVITY ^{36}P [from ^{37}Cl$(n,2p)$], neutrons from 70-MeV deuterons; measured $T_{1/2}$, E_γ, I_γ, $\gamma\gamma$ coin. Ge(Li) detectors; ^{36}S deduced levels, J, π, logft. Natural target.]

I. INTRODUCTION

The $(n,2p)$ reaction can be useful for synthesizing very neutron-rich nuclides outside of the region accessible by fission even though the $(n,2p)$ cross section is quite low. Recently[1] this reaction has been used to identify and characterize ^{39}S produced by ^{40}Ar$(n,2p)^{39}$S.

The nuclide ^{36}P has been previously observed[2] as a fragment from the reaction of 290-MeV ^{40}Ar on Th targets, thus proving its particle stability, but no other information was obtained. We report here the first observation of the decay of ^{36}P to levels in ^{36}S. Preliminary results were reported[3] earlier.

The level structure of ^{36}S has been previously studied[4-8] via the ^{37}Cl$(d,^3\text{He})^{36}$S and ^{34}S$(t,p)^{36}$S reactions. The (t,p) studies[6-8] revealed a number of levels in ^{36}S up to 7.12 MeV. Using $p\gamma$ correlations and level lifetime measurements[6] the first-excited 2_1^+ state was established at 3.29 MeV. Also $p\gamma$ correlations[6] and linear polarization measurements[7] were used to establish the 3_1^- state at 4.19 MeV.

The spectrum of low-lying positive parity levels in ^{36}S has been calculated[5,9] using a ^{40}Ca core and considering $(1d_{3/2},2s_{1/2})^{-4}$ hole configurations. The spectrum of negative-parity states has been calculated[10] considering the configurations $(1d_{3/2}{}^3,1f_{7/2})$ outside of a ^{32}S core. Although the 3_1^- state in ^{36}S is well established,[7] the character of the higher-lying negative-parity states is not so clear. In Sec. II the experimental results are presented and are used in Sec. III to establish a decay scheme for ^{36}P. Also in Sec. III, our results are compared with those from reaction studies and a discussion of the nature of the negative-parity states in ^{36}S is given.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

The sources of ^{36}P were produced by the ^{37}Cl$(n,2p)^{36}$P reaction. The targets consisted of solid cylinders of PVC$[CH_2CHCl]_x$ of mass 14 g, which were transferred from the position of irradiation to the Ge(Li) detectors by a compressed air "rabbit" system. The transit time was about one second. The neutrons were generated by bombardment of a Be target thick enough to stop the beam of 70 MeV deuterons from the JULIC cyclotron. The deuteron energy was chosen so as to produce by stripping a beam of neutrons peaked at forward angles, with energies around 35 MeV. The deuteron beam currents used ranged from 150 nA to 1.5 μA. For the neutron irradiation the targets were placed about 4 cm behind the Be-beam stop, at an angle of 0° with respect to the deuteron beam. Lead absorbers of various thicknesses were placed between the sample and the detectors, in order to reduce the intense annihilation radiation from ^{34}Cl ($T_{1/2}=1.5$ s) produced in the $^{35}Cl(n,2n)^{34}Cl$ reaction.

B. Data collection and analysis

The γ singles data were collected using a 140 cc Ge(Li) detector with a resolution of about 2.3 keV for the 1332-keV γ ray in ^{60}Co. The PVC target was irradiated for 5 s in a 1 μA deuteron beam. After return of the rabbit to the counting position, a sequence of five 4096 channel spectra was recorded of successively 2, 4, 8, 16, and 32 s duration. A 3 cm thick Pb absorber was placed between target and detector. The process was repeated for a total of 40 irradiations. After 2 irradiations a fresh PVC target was used in order to minimize the buildup of long-lived ^{34}Cl ($T_{1/2}=32.0$ m).

A γ spectrum covering the energy range from 800 to 3600 keV and composed of the sum of the first two time bins is shown in Fig. 1. No γ peaks were observed below 511 keV, possibly due to the large Compton background from the intense annihilation radiation. Between 511 and 800 keV the only line observed was the double escape peak from the ^{28}Al γ ray of 1779 keV.

Peaks at 902, 1638, and 3291 keV have been attributed to the ^{36}P decay and are indicated on Fig. 1 in keV. Contamination from the 1642-keV γ ray from ^{38}Cl generated in the $^{37}Cl(n,\gamma)^{38}Cl$ reaction was insignificant in the singles spectrum, due to the very low flux of thermal neutrons present. All peaks not belonging to ^{36}P have been identified and are labeled by nuclide. Isotopes of Cl, S, P, and Si were produced by reactions of fast neutrons on Cl, and the Al isotopes were produced from reactions with Si impurities in the target and reactions of the type $^{37}Cl(n,2\alpha xn)$.[11] A run similar to the one described above was carried out in order to search for γ transitions between 3 and 8 MeV. No other γ rays from ^{36}P decay were observed, but lines at 6129 and 7115 keV from ^{16}N decay were seen. The ^{16}N was probably produced in the $^{16}O(n,p)^{16}N$ reaction.

A ^{56}Co γ ray energy standard was used to establish the energies of the 3291-keV γ ray and γ rays from $^{34}Cl^m$ decay. The $^{34}Cl^m$ γ rays were used as secondary standards to determine the energies of the 902- and 1638-keV γ rays from the $\gamma\gamma$ coincidence spectra where background corrections were smaller than in the singles spectra.

The efficiency as a function of γ ray energy was determined for our detector by a thin ^{56}Co source

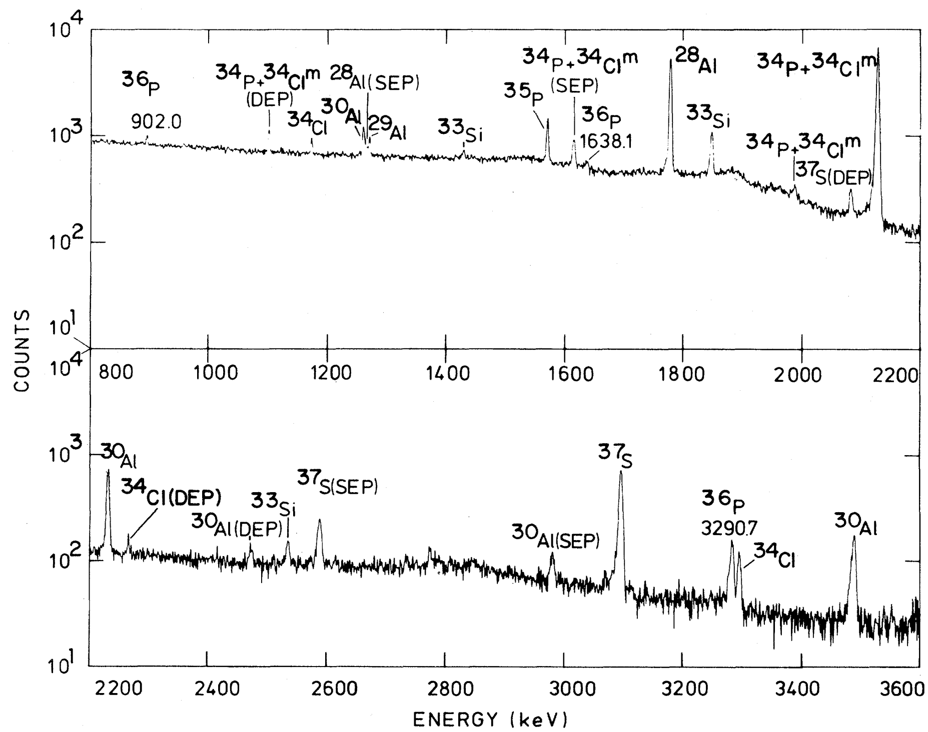

FIG. 1. Spectra of γ rays accompanying the decay of ^{36}P. Peaks with energies in keV are from ^{36}P decay.

inserted in the middle of a PVC target cylinder which was then placed at the normal counting position in front of the 3 cm Pb absorber. Owing to poor counting geometry and low statistics for the 902- and 1638-keV γ rays, the intensity errors are fairly large. The results of the above measurements are given in Table I. The energies are in satisfactory agreement with those from $(t,p\gamma)$ studies.[8]

The half-life for ^{36}P was determined in a separate run again using a 3 cm Pb absorber. After a 5.5 s irradiation and a delay of 2 s to allow the sample to be positioned in front of the detector, a series of 8 2048 channel spectra each 2.6 s in duration was accumulated. Dead time and other corrections were made by normalizing the peak intensities to the 3103-keV peak from ^{37}S whose half-life of 5.06 m is well established. The resulting decay curve is shown in Fig. 2. A value of 5.9 ± 0.4 s for the ^{36}P half-life was determined from a least-squares fit to the decay curve for the 3291-keV γ ray. Statistical and background subtraction errors were much greater for the 902- and 1638-keV γ rays, so they were not used to determine the ^{36}P half-life, but the results are consistent with those for the 3291-keV γ ray within the errors.

For coincidence measurements a second Ge(Li) detector with characteristics similar to the one used in singles was added to the system in a 180° geometry. In order to enhance the 902-keV peak compared to past runs, only 1 cm of Pb absorber was used between the sample and each detector; therefore a lower deuteron beam intensity of 200 nA was necessary. A total of 648 irradiations were carried out in which the sample was irradiated for 6 s. A 15 s count began after a 2 s delay. The data was recorded in event mode on magnetic tape, and a total of 2.86×10^6 events were gathered.

The results of the coincidence runs are summarized in Table II and the coincidence spectrum from 1000 to 3500 keV, obtained by gating on the 902-keV γ ray, is shown in Fig. 3.

TABLE I. ^{36}P γ ray energies and intensities.

Energy (keV) this work	Energy (keV) Ref. 8	Relative[a] intensity	Placement
902.0 ± 0.5[b]	901.5 ± 0.4	77 ± 19	4193-3291
1638.1 ± 0.8[b]		38 ± 10	5831-4193
3290.7 ± 0.3	3290.8 ± 0.6	100 ± 10	3291-0

[a]Intensities normalized to 100 for the 3291-keV γ ray.
[b]Energies determined from $\gamma\gamma$ coincidence spectra.

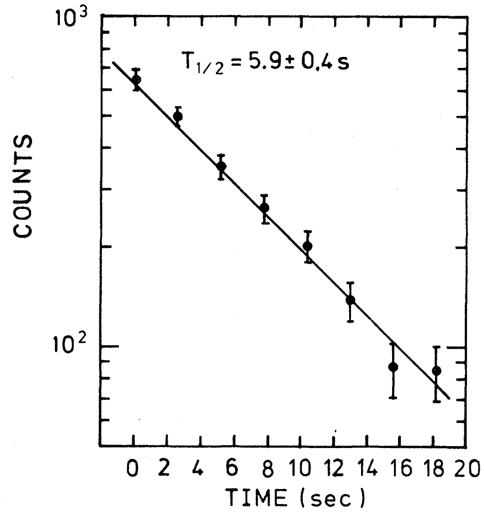

FIG. 2. Decay curve for the 3291-keV γ ray from ^{36}P decay.

III. DECAY SCHEME AND DISCUSSION

A. Construction of ^{36}P decay scheme

The measured γ ray energies and intensities and coincidence information were used to construct a decay scheme for ^{36}P which is shown in Fig. 4. The element assignment was not made on the basis of chemical analysis, but the designation as ^{36}P decay is based on the observation of the 3291- and 902-keV γ rays which were observed in ^{34}S$(t,p\gamma)^{36}$S studies[6–8] and our detection of coincidences between these above two γ rays. The activity is unlikely to be a β decaying isomer in ^{36}Cl which could be populated in the ^{37}Cl$(n,2n)$ reaction, since the structure of ^{36}Cl is well known and little opportunity exists for an undiscovered low-spin isomer. Also, it is unlikely that it is an isomer in ^{36}S, since no isomerism has been observed for even-even S nuclei or even-even nuclei with $N=20$. Finally, the relative yield of ^{35}P from the $(n,2pn)$ reaction compared to that for ^{36}P from the $(n,2p)$ reaction is similar to $(n,2pn)/(n,2p)$ yield ratios measured for ^{40}Ar (Ref.

TABLE II. $\gamma\gamma$ coincidences from ^{36}P decay.

Gating transition (keV)	Definite coincidences
902	1638, 3291
1638	902, 3291
3291	902, 1638

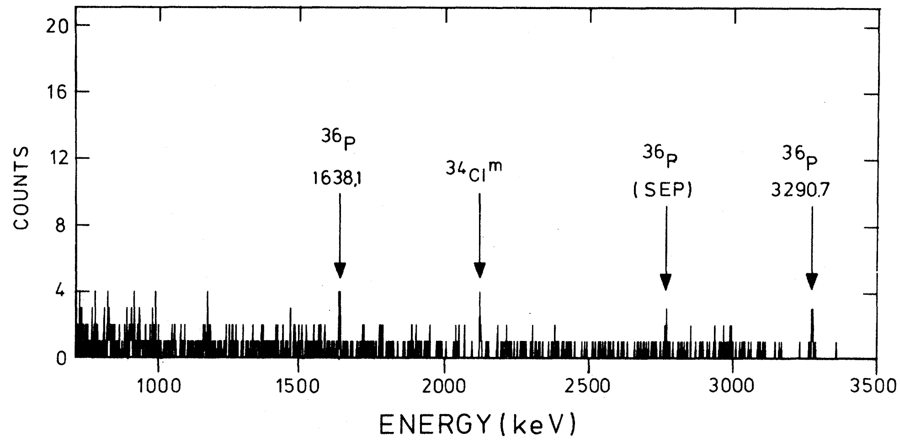

FIG. 3. Spectrum in coincidence with the 902-keV γ ray from ^{36}P decay.

1) and other targets[12] using spallation produced neutrons.

The value for the ^{36}P half-life of 5.9$\pm$0.4 s is in good agreement with the gross theory of β decay,[13] which predicts a range of values from 1.5 to 9 s. The log*ft* calculations are based on a Q_{β^-} of 9.9 MeV from the mass table of Wapstra and Bos.[14]

We assume no β feeding to the ground state or the 2_1^+ state. Weak feeding to the 2_1^+ state might be possible, but it should not be large enough to alter our arguments given below concerning the J^π for various levels. Observation of an allowed β^- transition to the well established[7] 3^- level at 4193 keV

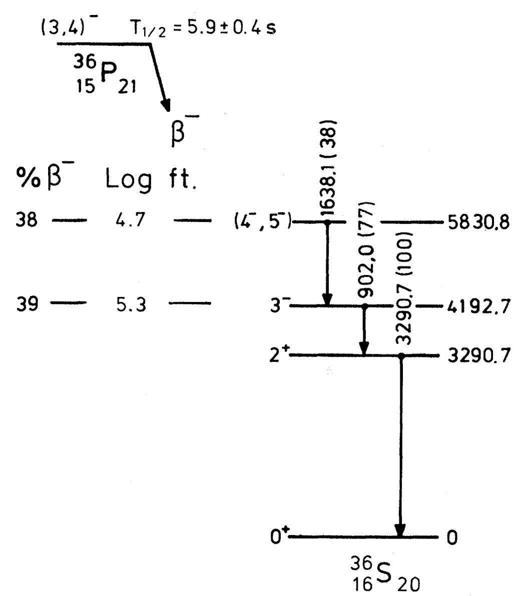

FIG. 4. Decay scheme for ^{36}P deduced from this work.

limits J^π for the ^{36}P ground state to 2^-, 3^-, or 4^-. We favor 3^- or 4^- based on the assignment of 4^- or 5^- to the level at 5831 keV, but 2^- is not absolutely excluded (see discussion below). A discussion of excited states of ^{36}S observed in this work is given below.

1. *3290.7$\pm$0.3-keV level.* The energy is that of the 3291-keV γ ray and is in good agreement with the value of 3291.0$\pm$0.6 keV from $(t,p\gamma)$ studies.[8] The 2^+ assigment is based on level lifetime and $p\gamma$ angular correlation measurements.[6] From the γ intensities of Table I a β^- feeding to this level of 23$\pm$21% is obtained giving a log*ft* of 5.6. This is less than the Raman limit[15] of 5.9 for first-forbidden β transitions, but within the error the log*ft* could go up to 6.6. Also the log*ft* value obtained by us might be too small due to unobserved weak γ transitions from high-lying levels that feed the 2_1^+ state directly. Owing to the low yield of ^{36}P and the large uncertainties discussed above we have chosen not to give a log*ft* for β feeding to the 3291-keV level, so the sum of β feeding to the other two excited states observed now sums to only 77%.

2. *4192.7$\pm$0.6-keV level.* The energy obtained from the 902- and 3291-keV γ rays is in good agreement with that of 4192.5$\pm$0.7 keV from $(t,p\gamma)$ studies.[8] The placement is based on coincidences between the 902- and 3291-keV γ rays. The 3^- assignment is based on $p\gamma$ correlations[6] and linear-polarization measurements.[7] A β^- feeding of 39% gives a log*ft* of 5.3$\pm$0.3. The β transition must be allowed, which with the 3^- assignment for the level limits J^π for the ^{36}P ground state to 2^-, 3^-, or 4^-. No evidence for a $E3$ crossover transition of energy 4193 keV to the ground state was seen. We determined an upper limit of 4 for the relative intensity

of such a transition.

3. *5830.8±1.0 keV level.* This level is based on the coincidence of the 1638-keV γ ray with both the 902- and 3291-keV transitions. Its energy was obtained from the sum of the three γ ray energies in the cascade. This level was not observed in previous reaction work.[4-8] A β^- feeding of 38% gives the level a log*ft* of 4.7±0.2. The allowed nature of the β transition along with the negative parity for the ^{36}P ground state establishes the parity of the 5831-keV level to be negative. The limit of J to 2, 3, or 4 for the ^{36}P ground state gives a range of J for the 5831-keV level of 1 to 5. In order to limit the J values a search was made for a crossover transition of energy 2540 keV to the 2_1^+ level. No such transition was observed in the singles spectrum, but the presence of a γ ray at 2537 keV from ^{33}Si ($T_{1/2}=6.2$ s) limited our ability to establish a small upper limit. From the spectrum in coincidence with the 3291-keV γ ray an upper limit of 5 for the relative intensity of a 2540-keV γ ray was determined. 1^- is ruled out. For the case of 2^- or 3^-, an $M1$ transition of 1638 keV would have to compete with an $E1$ transition of 2540 keV. The Weisskopf estimate for the corresponding transition probabilities gives 2.27×10^{13} s^{-1} and 1.79×10^{16} s^{-1}, respectively. Although a situation in which the $E1$ transition would be hindered relative to the $M1$ transition by about a factor of the order of 10^3 is only mildly restrictive, we still prefer an assignment of 4^- or 5^- for the 5831-keV level.

B. Systematics and interpretation

The J^π assignment of $(3^-,4^-)$ for the ^{36}P ground state is understandable in simple shell-model terms. The lighter even A, P nuclei have ground states with positive parity, understood as a coupling of the *sd* shell proton with a *sd* shell neutron. For ^{36}P the negative parity can be understood since the odd neutron is now in the $f_{7/2}$ shell. From the odd A, P nuclei it can be seen that the $d_{3/2}$ proton state lies more than 1 MeV above the $s_{1/2}$ ground state, although information is not available for ^{35}P. Therefore the ^{36}P ground state J^π is understandable in terms of a $\pi(s_{1/2})\nu(f_{7/2})$ configuration with possibly a small amount of mixing from $\pi(d_{3/2})\nu(f_{7/2})$.

Much information is available on levels in ^{36}S from $(d,{}^3\text{He})$ (Refs. 4 and 5) and $(t,p\gamma)$ (Refs. 6–8) reaction studies. In the $(t,p\gamma)$ studies 13 excited states in ^{36}S up to 7.12 MeV were observed, whereas in our decay study only three excited states were observed, in spite of a large Q_β value. The β interaction in this case favors population of negative parity states, whereas many positive parity states were populated in the reaction experiments. Although the 3^- state at 4192 keV is well established,[7] the experimental status of possible higher-lying odd-parity states observed in reaction studies[6,8] is still unclear.

Two simple mechanisms exist for allowed β^- decay to negative parity states in ^{36}S. In the first case, the odd $f_{7/2}$ neutron in ^{36}P can decay to a $f_{7/2}$ proton in ^{36}S which can then couple with the $s_{1/2}$ proton to produce a proton p-h state. In the second case, one member of the $s_{1/2}$ neutron pair in ^{36}P can decay to a $s_{1/2}$ proton in ^{36}S. The net effect is that a neutron pair is broken and a proton pair formed in ^{36}S, leaving a neutron p-h state. In both cases only the states 3^- and 4^- can be formed. In order to produce 2^- or 5^- states there must be mixing from the $d_{3/2}$ proton in the ^{36}P ground state or the ^{36}S negative parity states.

Since the 3^- state in ^{36}S at 4193 keV is a natural parity state populated in the $(t,p\gamma)$ reaction,[6-8] it probably is a neutron p-h state. In our case the simple mechanism outlined above implies that the β^- decay involves the transformation of a $s_{1/2}$ neutron in ^{36}P to a $s_{1/2}$ proton.

The state observed in this work at 5810 keV was not reported in $(t,p\gamma)$ (Refs. 6 and 8) studies, although the γ ray measurements would have detected the transition at 1638 keV if the state had been appreciably populated. Several conclusions can be drawn from this fact. If J^π for the 5810-keV level is 4^-, then it would be an unnatural parity state for the (t,p) reaction and not strongly populated. The state could therefore be either a proton or neutron p-h state. If the J^π is 5^- (natural parity) then the absence of population in the (t,p) reaction but strong population in β^- decay would suggest that the state is a proton p-h state populated by decay of the $f_{7/2}$ neutron in ^{36}P. In order to get 5^-, the proton hole state would have to be $d_{3/2}$.

The only calculation available to us on negative-parity levels in ^{36}S is that of Erne.[10] An inert ^{32}S core is assumed with one extra core particle in the $f_{7/2}$ shell and the rest in the $d_{3/2}$ shell. For ^{36}S, the lowest seniority configurations give four states at $3.85(3^-)$, $4.64(4^-)$, $4.67(5^-)$, and $4.82(2^-)$ MeV. The energies are too low since our level at $4.193(3^-)$ MeV is probably the lowest negative-parity neutron p-h state. In the calculation the effect of the $s_{1/2}$ shell was not considered, which is almost certainly an important factor in the description of the 4.193-MeV state. Also, since the core was ^{32}S no consideration of proton p-h states was given. It would be of interest to extend the calculations using the ^{32}S core to include the effects of the $s_{1/2}$ shell to determine if a lowering in the energy of the 3^- state could be obtained.

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