FIRST OBSERVATION OF THE DECAY OF THE NEUTRON-RICH NUCLEUS P-36

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Abstract

Sources of ^{36}P were prepared using the ^{37}Cl(n,2p) ^{36}P reaction. The neutrons were generated by 70 MeV deuterons on a thick Be target. The ^{36}P half-life was measured to be 5.9 ± 0.4 sec. The observed γ rays were postulated to depopulate levels in ^{36}S at 3291 (2^+) and 4193(3^-) keV. Our results are compared with results from the (d,t) and (t,pγ) reactions and the reason for the predominance of ß decay to the 3^- level is discussed.

1. Introduction

1.1 Production of neutron-rich nuclides

The production and study of neutron-rich nuclei outside of the region accessible by fission is generally more difficult than similar studies in other parts of the nuclide chart due to the lack of suitable production reactions and large contamination from neutron-deficient species with high production cross-sections. Fast neutrons generated by spallation of appropriate targets with high-energy protons have been used at both the high and low A ends of the nuclide chart to identify and characterize new neutron-rich nuclei$^{1)}$.

A survey of the nuclide chart shows that in principle it would be possible to produce and study many new nuclear species using the (n,2p) reaction, but such experiments are hindered by the low (n,2p) cross-section, which is due to suppression of proton emission by the Coulomb barrier. The above reaction has been used at the isotope separator ISOLDE to synthesize ^{207}Hg($T_{1/2}$ = 2.9 m)$^{2)}$ with fast secondary neutrons generated by spallation of a Pb target by 600 MeV protons. Also ^{39}S ($T_{1/2}$ = 11.5 s)$^{3)}$ was synthesized by the reaction of fast neutrons with an Ar target. The neutrons were generated by spallation of Cu by 800 MeV protons from the LAMPF accelerator and fast radiochemical procedures were required.

Although spallation generated neutrons are useful, neutrons produced in stripping reactions offer several practical advantages. In the reaction of 70 MeV deuterons on C the outgoing neutrons are strongly peaked in the forward direction with an energy distribution peaked at roughly one half of the energy of the incident deuteron. One can also avoid the generation of large quantities of (n,γ)-products from thermal neutrons and very neutron deficient nuclides from the high energy neutron tail of the typical spallation spectrum.

1.2 Status of knowledge on ^{36}P

The nuclide ^{36}P has been previously observed as a fragment from the reaction of 290 MeV ^{40}Ar on Th targets$^{4)}$, but no information on its decay is available. Levels in the daughter nucleus ^{36}S have been studied using the ^{37}Cl(d,^{3}He)^{36}S reaction$^{5)}$, but the most extensive information was obtained in a study of the ^{34}S(t,pγ)^{36}S reaction$^{6)}$ in which 13 excited states up to 7.12 MeV were observed.

2. Experimental methods and results

2.1 Source preparation

Sources of ^{36}P were prepared using the ^{37}Cl(n,2p) ^{36}P reaction. Neutrons were generated by a beam of 70 MeV deuterons from the JULIC cyclotron stopped on a thick Be target. The Cl target was a cylinder of commercial PVC $](CH_2CHCl)_x[$ having a mass of 14 grams and placed at 0° to the deuteron beam. After irradiation the target was transfered in a time of about 1 sec a distance of 7 meters to a shielded counting position by a compressed air "rabbit" system.

In initial runs it was found that in the first few seconds of counting, the spectrum was completely dominated and the Ge(Li) detector paralyzed by annihilation radiation from ^{34}Cl($T_{1/2}$ = 1.53 s) produced in the ^{35}Cl(n,2n)^{34}Cl reaction. Thereafter most runs were carried out with 3 cm of Pb between the source and the detector.

2.2 Half-life measurement

In order to measure the ^{36}P half-life the PVC target was irradiated for 5.5 sec. The current of the deuteron beam was about 500 nA. After a 2 sec delay to allow the target to arrive at the counting position, a series of 8 successive 2K channel γ spectra each 2.6 sec long were accumulated. Each target was irradiated twice before exchange for a fresh one to minimize the buildup of activities of intermediate half-life. A total of 216 irradiations were carried out on a set of 18 targets.

A decay curve for the γ ray from ^{36}P at 3291 keV is shown in Fig. 1 (a). The change of the dead time in the analyzer with time has been corrected by normalizing the intensity of the ^{36}P γ peaks to that of the 3103 keV γ ray from ^{37}S($T_{1/2}$ = 5.06 s). From the decay curve in Fig. 1 (a) we determine the half-life of ^{36}P to be 5.9 ± 0.4 s. The half-life curve for the 902 keV γ ray from ^{36}P is shown in Fig. 1 (b). The error is much larger due to the very high compton background in that energy region. The plotted results were obtained by adding 2 successive time bins for better statistics. The resultant half-life of 7.8±4.7 sec is consistent with the half-life determined from the 3291 keV transition, but because of the large error was not used in determining the ^{36}P half-life.

2.3 γ ray singles measurements

The γ spectrum for our PVC target was measured after an irradiation of 5 sec in duration, using 3 cm of Pb absorber between the target and the Ge(Li) detector. After return of the target from the irradiation position a series of five 4K spectra were collected successively in time bins of 2, 4, 8, 16 and 32 sec duration. A total of 40 irradiations were made.

A spectrum resulting from summing the results from the first two time bins (first six seconds of counting) is shown in Fig. 2. The spectrum below 500 keV is completely dominated by Compton events from very strong annihilation radiation and no other γ peaks were observed. All γ peaks between 500 and

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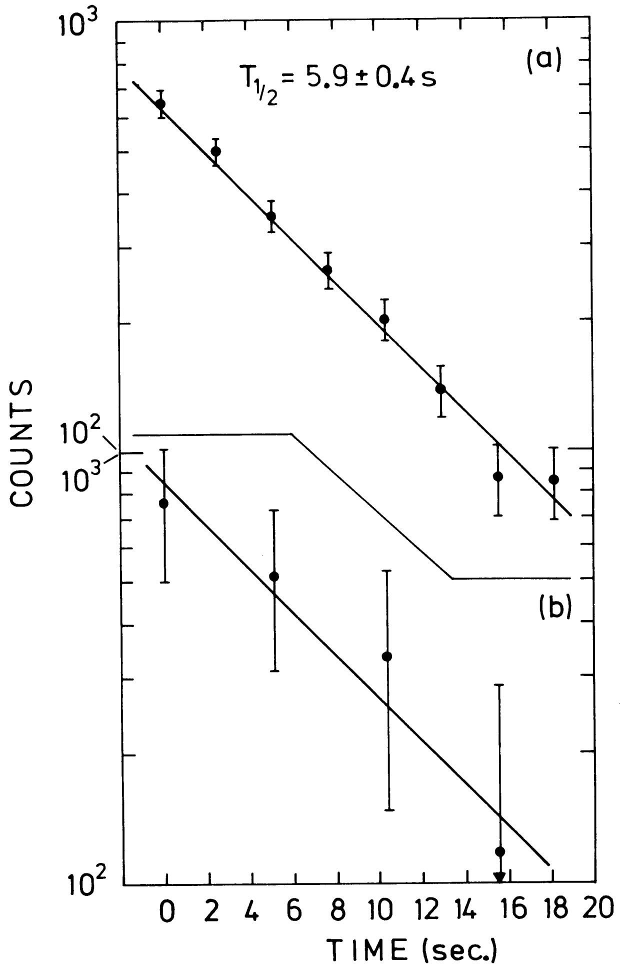

Fig. 1: Decay curve for the (a) 3291 and (b) 902 keV γ rays from ^{36}P decay.

3600 keV have been identified. On Fig. 2 peaks from isotopes other than ^{36}P are labeled by isotope and γ rays from ^{36}P decay are labeled by energy in keV. All γ lines result from nuclides produced from Cl isotopes except for lines from the decay of ^{28}Al, ^{29}Al, and ^{30}Al probably produced from Si impurities. In a second similar experiment γ rays with energies from 2 to 7 MeV were measured. Lines from the decay of ^{16}N were seen but no γ rays above 3.5 MeV could be attributed to ^{36}P decay.

The energies of the ^{36}P γ rays were measured by simultaneously counting the irradiated PVC targets and sources of ^{137}Cs and ^{56}Co. In order to calibrate the efficiency of our Ge(Li) detector the ^{56}Co source was sandwiched between two halves of a PVC target and placed inside the rabbit tube in front of the 3 cm Pb absorber. The resulting energies and intensities for the ^{36}P γ rays are given in Table 1.

Table 1: Energies and relative intensities for γ rays from ^{36}P decay.

E_γ(keV)	I_γ
902.4 ± 0.5	73 ± 9
3290.8 ± 0.2	100 ± 15^a

a) Intensity normalized to 100 for 3291 keV γ ray.

3. Decay scheme and discussion

3.1 Construction of decay scheme

The above information along with data on levels in ^{36}S from charged particle reactions$^{5,6)}$ was used to construct a preliminary decay scheme for ^{36}P which is shown in Fig. 3. Our measured half-life of 5.9 ± 0.4 s is in good agreement with the gross theory of β decay$^{7)}$ which predicts a range of values from 2 to 8 s. The 2^+ level at 3291 keV is well established from reaction studies$^{5,6)}$. In the $^{34}S(t,p)^{36}S$ reaction study a 3^- level was established at 4193 keV. This is the only level definitely postulated to have negative parity$^{6)}$ and appears to receive most of the strength in the ^{36}P β decay.

We postulate the 4193 keV level to receive about 73 % of the β^- feeding, but there is a large error in the relative intensities of the two ^{36}P γ rays. It is unlikely that there is very much feeding to the 2^+ level so any extra feeding could be accounted for by the decay of weakly - populated high-lying levels to the 2^+_1 state. Coincidence measurements are in progress in order to search for such transitions.

The log ft for β^- decay of the 3^- level was calculated assuming a feeding of 73 % and a mass-excess for ^{36}P of - 20.82 MeV from an update by Jänecke of the Garvey-Kelson relations$^{8)}$. A value of 9.85 for Q_β resulted in a log ft of 5.0 for feeding to the 3^- state. This implies an allowed β^- transition and thus limits J^π for the ^{36}P ground state to 2^-, 3^- or 4^-. This is consistent with the single-particle model picture in which a $f_{7/2}$ neutron couples to a $s_{1/2}$ or $d_{3/2}$ proton. In ^{31}P and ^{33}P the ground state is $1/2^+$ with the $3/2^+$ state at 1.266 and 1.431 MeV respectively. The situation in ^{35}P is unknown, but we favor a $s_{1/2}$ assignment for the 15th neutron thus a J^π of 3^- or 4^- for ^{36}P.

3.2 Comparison with reaction studies and conclusions

In the study of levels in ^{36}S by the $^{34}S(t,p\gamma)$ ^{36}S reaction$^{6)}$ 13 excited levels from 3.29 to 7.12 MeV were observed. Our level energies of 3290.8 ± 0.2 and 4193.2 ± 0.6 keV are in fairly good agreement with values of 3291.0 ± 0.6 and 4192.5 ± 0.7 obtained in the (t,pγ) study. In contrast to the reaction study where 13 excited levels were observed, we detected β^- feeding to only the 3^- state at 4193 keV. The low log ft of 5.0 suggests a decay process in which the 21st $f_{7/2}$ neutron in ^{36}P decays to a $f_{7/2}$ proton (the 16th proton) in ^{36}S. This proton could then couple to the odd $s_{1/2}$ ($d_{3/2}$) proton to give a J^π of 3^- for the 4193 keV level. A similar situation is observed in the decay of the 2^- ground state of $^{38}_{17}Cl_{2}$, to a 3^- state at 3.81 MeV in $^{38}_{18}Ar_{20}$ with a log ft of 4.9.

3.3 Use of fast neutrons to produce new nuclear species

A glance at the latest chart of the nuclides shows that a number of unstudied neutron-rich nuclides outside of the region accessible by fission could be synthesized and their decays established using fast neutrons. About 30 unstudied species could be reached by the reactions (n,2pn), (n,2p) or (n,αp). Such studies are difficult due to the anticipated low cross-sections, but many could be carried out successfully using fast radiochemical procedures.

Products from all three of the above reactions on ^{37}Cl have been observed and in Table 2 we present a list of "relative cross-sections" normalized to the $^{37}Cl(n,p)^{37}S$ reaction. The estimates though crude should give the reader an idea of the magnitude of useful cross-sections for the synthesis of neutron-rich nuclides.

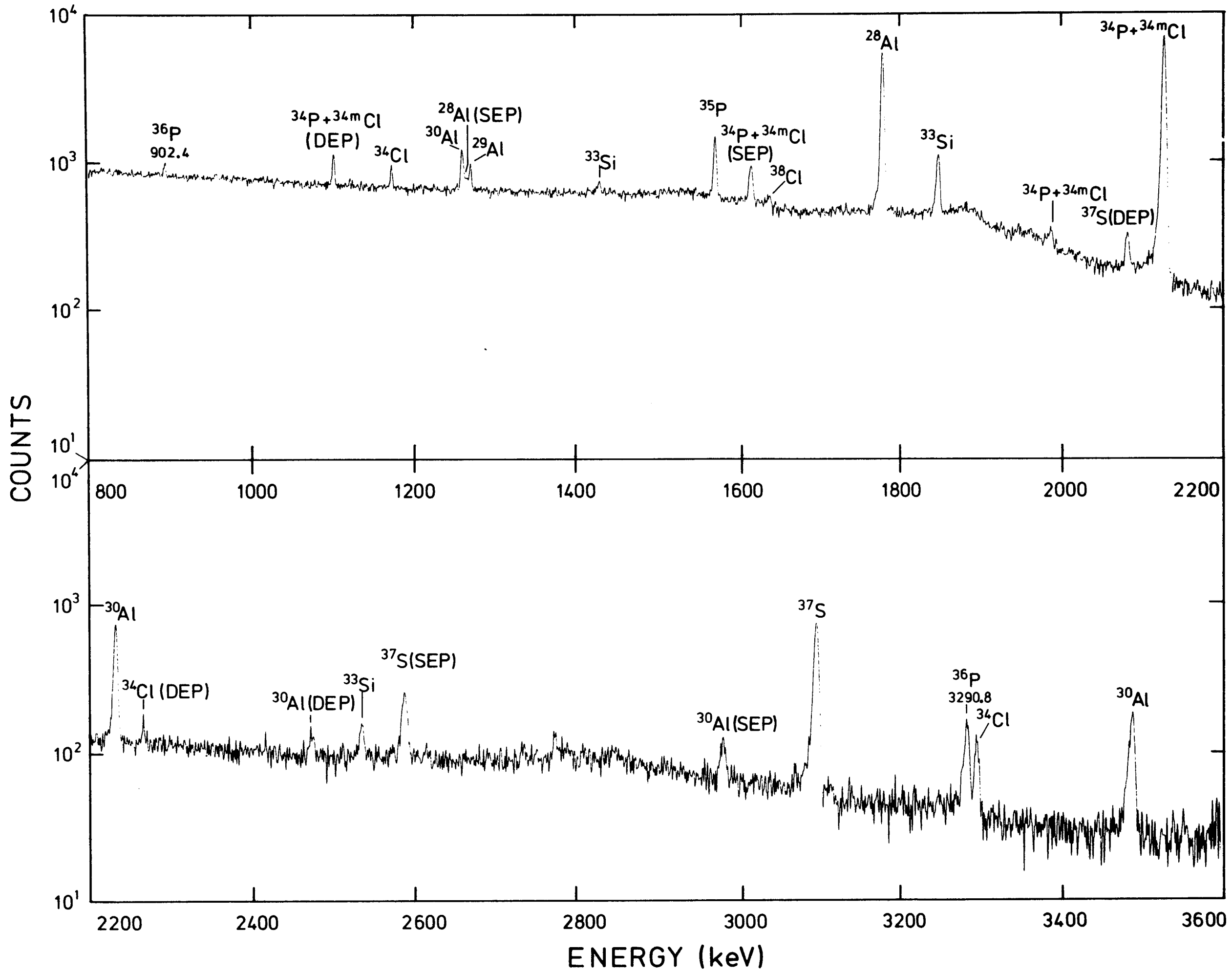

Fig. 2: γ ray spectrum from 800 to 3600 keV for a PVC target. Energies for γ rays from ^{36}P decay are given in keV.

Table 2: "Relative cross-sections" for various reactions from fast neutrons on ^{35}Cl and ^{37}Cl.

Reaction	$\sigma_R/\sigma_{(n,p)}$
^{37}Cl(n,α)^{34}P	3.4
^{35}Cl(n,2n)^{34m}Cl	1.9
^{37}Cl(n,p)^{37}S	1.0
^{37}Cl(n,γ)^{38}Cl	0.87
^{37}Cl(n,2pn)^{35}P	0.11
^{37}Cl(n,αp)^{33}Si	0.057
^{37}Cl(n,2p)^{36}P	0.012

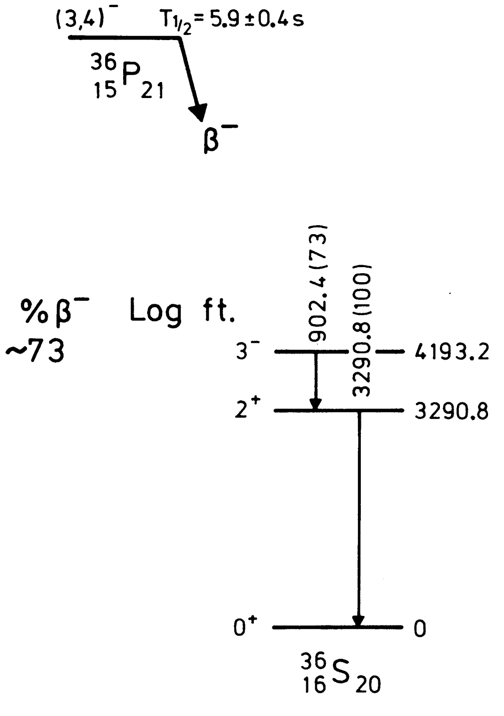

Fig. 3: Decay scheme of ^{36}P.

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DISCUSSION

W.B. Walters: As you see ^{28}Al, ^{29}Al, and ^{30}Al most likely produced in the ^{37}Cl(n,4pxn)$^{34-x}$Al reactions or the ^{37}Cl(n,2αxn) reactions, have you used these yields to estimate whether you can also produce enough ^{31}Al to observe its decay?

J.C. Hill: It is not entirely clear what is the source of the Al isotopes we see, but some part may come from (n,p) reactions on Si impurities in the target. Assuming that all the Al comes from (n,4pxn) reactions, the yield of ^{31}Al from the ^{37}Cl(n,α2pn) reaction would probably be roughly a factor of 10 lower than that of ^{30}Al (seen by us) from the ^{37}Cl(n,2d) reaction. Unfortunately, ^{31}Al has a half-life of about 600 ms, thus is a bit too short for us to easily observe.