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Mass and Decay of a Highly Neutron-Rich Isotope of Phosphorus: 48-sec ^{35}P†

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^{35}P has been produced via the $^{18}O+^{19}F \rightarrow ^{35}P+2p$ reaction using 42–46-MeV ^{19}F ions, and by the $^{36}S(t,\alpha)^{35}P$ reaction using 3.4-MeV tritons. Identification is made from the observed β-delayed γ ray of 1572.41 ± 0.25 keV. By means of the $^{34}S(d,p\gamma)^{35}S$ reaction, the γ ray from the first excited state of ^{35}S has been measured as 1572.24 ± 0.15 keV, in disagreement with previous measurements. The average of the half-lives for ^{35}P as measured by the first two reactions is 48.1 ± 1.4 sec. Upper limits were obtained for β-ray transitions to other excited states in ^{35}S. No information was obtained on a possible β transition to the ^{35}S ground state. The β-ray spectrum measured in coincidence with the 1572-keV γ ray has an end point of 2337 ± 75 keV, establishing a mass excess of $-24\,936\pm 75$ keV for ^{35}P. These results are consistent with the expected mass and spin-parity ($\frac{1}{2}^+$) of the ^{35}P ground state. Comparison of these results with shell-model calculations is presented.

I. INTRODUCTION

Following the accidental discovery[1] of the decay of ^{33}Si, produced via the $^{18}O(^{18}O, 2p+n)^{33}Si$ reaction, it was realized by the authors that heavy-ion compound reactions might be a fruitful method of forming other exotic nuclei. However, the $^{18}O+^{18}O$ data showed no evidence for ^{35}P that might have been made by the $^{18}O(^{18}O, p)^{35}P$ reaction. $^{18}O+^{18}O$ is situated at 29 MeV in the compound nucleus ^{36}S, and at bombarding energies sufficient to exceed the Coulomb barrier it is not likely that only a single nucleon is emitted by the compound system. Two-nucleon emission is presumably more probable, and this argument prompted the authors to try the $^{18}O(^{19}F, 2p)^{35}P$ reaction. This method was successful and the utility of heavy-ion compound reactions for exotic isotope production is further demonstrated.

After the completion of the present work, a report by Grimm and Herzog[2] appeared, describing a delayed 1571.8 ± 0.2-keV γ ray with $T_{1/2}=45\pm 2$ sec which they ascribed to the $^{37}Cl(\gamma, 2p)^{35}P(\beta^-)^{35}S$ reaction. Also a recent report of a delayed 1572.2 ± 0.4-keV γ ray with $T_{1/2}=47.4\pm 0.8$ sec made by the $^{37}Cl(t, \alpha p)^{35}P$ reaction is described in an abstract by Apt and Knight[3] adjacent to the abstract on ^{35}P by the present authors.[4] The present work describes the only reported mass measurement for ^{35}P.

II. $^{18}O(^{19}F, 2p)^{35}P$ REACTION

The $^{18}O(^{19}F, 2p)^{35}P$ reaction was carried out with 42–46-MeV ^{19}F ions accelerated by the second tandem of the Brookhaven National Laboratory (BNL) tandem Van de Graaff facility. Typical beam currents were about 0.2 μA (electrical) of the 5+ charge state. Procedures for preparing the ^{18}O targets have been described previously.[1] The ^{35}P activity was sought by observing delayed γ rays with a 60-cm^3 Ge(Li) detector. Techniques for transferring the target and measuring the spectrum of delayed γ radiations have also been described earlier.[1] The counting period was divided into five adjacent time bins, and 4096-channel γ-ray spectra were recorded for each time bin by an on-line computer. All timing was controlled by a crystal-controlled 10-channel programmer.[5] The Ge(Li) detector was separated from the target at the counting position by 9 mm of graphite and 3 mm of Pb.

Preliminary runs showed an unidentified 1572-keV γ ray with a half-life of about 1 min. Further runs reduced the uncertainty in the half-life and allowed the timing to then be set to maximize the yield of this new line. A bombardment time of 50 sec and five consecutive counting periods of 30 sec each were used in the final runs. Part of the γ-ray spectrum from the first time bin is shown in Fig. 1. The $^{228}Th(\pi)$ line at 1592.70 keV[6] was used to determine the energy of the new line as 1572.36 ± 0.23 keV. The ^{20}F line in Fig. 1 is due to transfer reactions on ^{18}O and ^{19}F, and served as a measure of the gain.

After corrections for dead time were made by observing the yield of γ rays from the decay of ^{28}Al and ^{29}Al in the spectra for each time bin, the decay curve for the 1572-keV line was determined and is shown in Fig. 2. From this figure and other runs a half-life of 47.7 ± 2.9 sec was determined.

At this point some uncertainty existed as to the origin of the 1572-keV line, since two recent measurements of the energy of the first excited state in ^{35}S were 1574.2 ± 1 [7] and 1575 ± 1 keV[8] both of which differ from our γ ray by 2 or more standard deviations. No other unidentified γ rays were seen in our spectra, and test runs on both natural oxygen and carbon targets on tantalum backings did not produce the 1572-keV line.

III. $^{34}S(d, p\gamma)^{35}S$ REACTION

In order to remeasure the energy of the first excited state of ^{35}S, the prompt γ rays from the $^{34}S(d, p\gamma)^{35}S$ reaction were observed. A target of Sb_2S_3 enriched to 86% in ^{34}S was bombarded with 3.3-MeV deuterons provided by the BNL 3.5-MeV Van de Graaff facility. The Ge(Li) detector was accurately located at 90° to the beam to avoid Doppler shifts. A strong 1572-keV line was seen, as is shown in Fig. 3. The 1576.56-keV ^{56}Co line[6] and the $^{228}Th(\pi)$ line were used as references. The energy of the γ ray from the first excited state of ^{35}S was determined to be 1572.24 ± 0.15 keV. (There is an additional uncertainty of ~80 eV in the energy of this line due to the use of double-escape peaks to calibrate the photopeak line.[6] This does not affect the comparison of Fig. 3 with Fig. 1, however, since in Fig. 1 the primary reference line was also a double-escape line. In the final value for the γ-ray energy given in Sec. V, the quoted uncertainty reflects this additional source of error.)

The above result is in disagreement with Refs. 7 and 8, but agrees with the energy obtained in the $^{18}O + ^{19}F$ reaction.

IV. $^{36}S(t, \alpha)^{35}P$ REACTION

In order to further establish the origin of the 1572-keV line seen in Sec. II, the $^{36}S(t, \alpha)^{35}P$ reaction was studied. Targets[9] of metallic silver

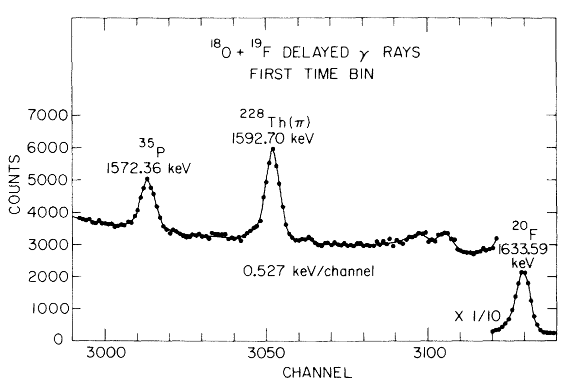

FIG. 1. Part of the spectrum of delayed γ rays following the bombardment of ^{18}O with ^{19}F ions at 42-MeV lab energy. The $^{228}Th(\pi)$ line is due to an external reference source.

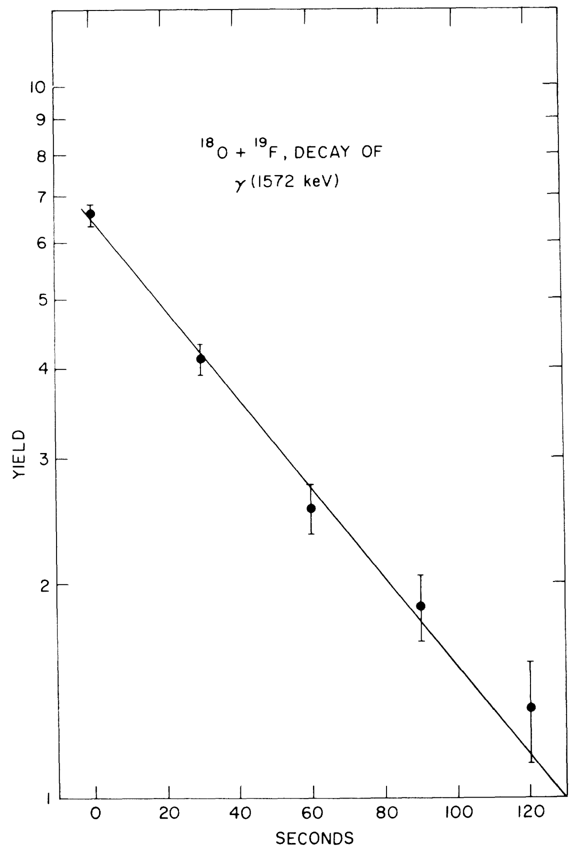

FIG. 2. Decay curve for the 1572-keV γ ray, taken from the $^{18}O + ^{19}F$ work. The solid line is a computed least-squares fit.

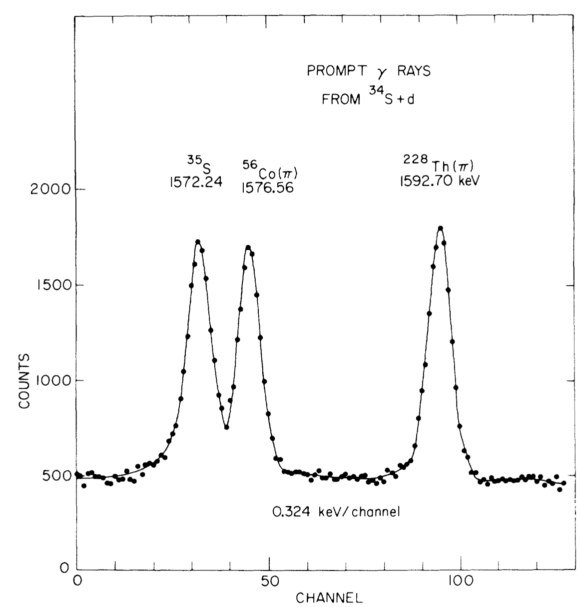

FIG. 3. Part of the spectrum of prompt γ rays from the deuteron bombardment of ^{34}S. The $^{56}Co(\pi)$ and $^{228}Th(\pi)$ lines are due to external reference sources.

which had been sulfided with sulfur enriched to 2% in ^{36}S were bombarded with 3.4-MeV tritons. Although the ^{36}S content of the target was very low, the half-life of the 1572-keV line was known and allowed the (t, α) reaction to be done with optimum timing. The target was bombarded for 60 sec with 0.5 μA of beam, and was then carried to a remote counting location, where delayed γ rays were observed in four consecutive 45-sec time bins. Spectra were stored in 4096 channels for each time bin. Results for the first time bin are shown in Fig. 4. Using the ^{228}Th double- and single-escape lines for reference points, the energy of the new line was determined to be 1572.47 $\pm$0.25 keV. The half-life of this line was found to be 48.2$\pm$1.7 sec in agreement with the result of Sec. II. The combined results of Secs. II–IV establish the origin of the 1572-keV line as due to a γ transition in ^{35}S following the β^- decay of ^{35}P.

In order to measure the mass of ^{35}P, the spectrum of β rays in coincidence with the 1572-keV γ ray was measured. An NE 102 scintillator 2.54 cm long and 4.6 cm in diameter was coupled to an RCA 8575 photomultiplier and used as the β-ray detector. The target was located 2 mm from the center of the scintillator face and was separated from the 60-cm^3 Ge(Li) detector by 1 cm of Bakelite. The latter was used to minimize electron backscattering. Standard electronics modules were used to obtain a time resolution of 4 nsec full width at half maximum (FWHM), and a time gate 10 nsec wide was used. The real-to-random ratio was monitored electronically, and was maintained greater than 600 by limiting the β counting rate to <35 000 per sec. Bipolar pulses 500 nsec wide were used on the β-ray amplifier to minimize pileup.

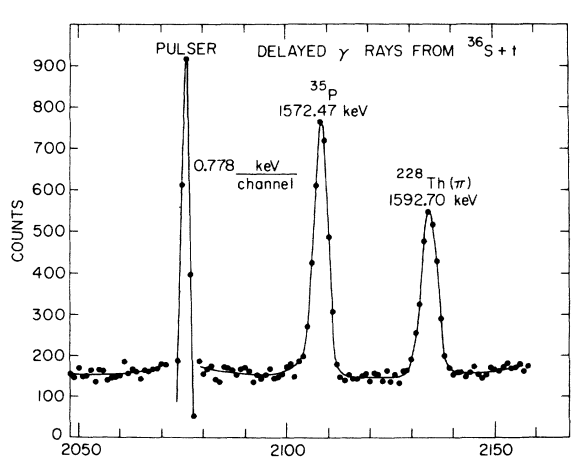

FIG. 4. Part of the spectrum of delayed γ rays following the triton bombardment of ^{36}S.

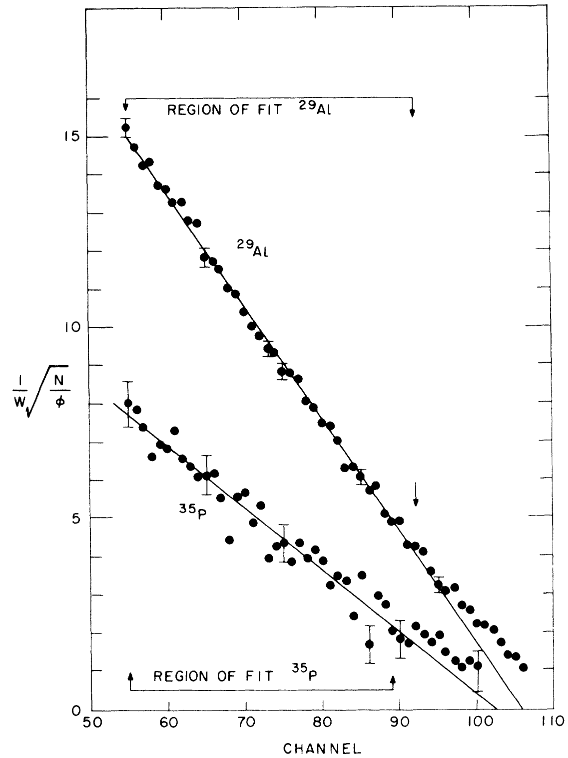

FIG. 5. Fermi-Kurie plots of the delayed-β-ray spectra from ^{29}Al in coincidence with the 1273-keV γ ray and from ^{35}P in coincidence with the 1572-keV γ ray. The energy calibration is 22 keV/channel. The solid lines are least-squares fits to a straight line, using the fitting regions shown by the arrows.

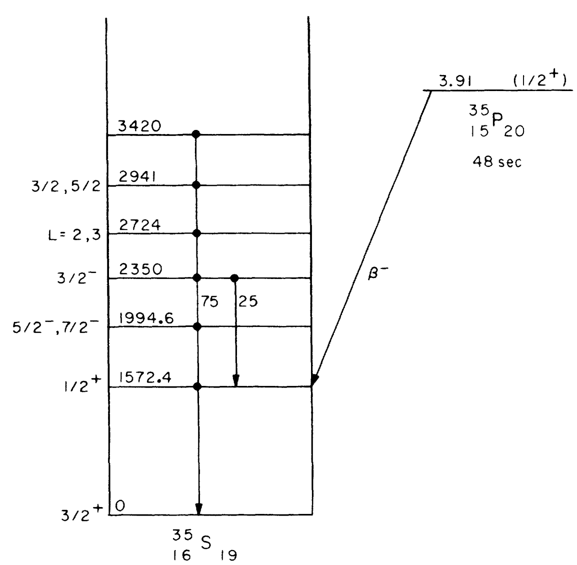

FIG. 6. The decay scheme of ^{35}P as determined from the present work. The spins and parities of ^{35}S levels were taken from Refs. 7, 8, 13, and 14.

The pulses from the γ-ray detector were analyzed and digitally sorted to produce gates for the coincident β-ray spectra. A gate five channels wide centered on the photopeak of the 1572-keV line in Fig. 4 and background gates 25 channels wide were set on either side of this peak. The ^{228}Th source was not present for the β-γ work. The digital gates were checked periodically to insure that the photopeak was centered within the window. In this way, only 20% of the γ-ray pulses within the photopeak window were due to the underlying background. The β-ray spectra in the two side windows were identical within statistics and were subtracted from the β-ray spectrum coincident with the photopeak window.

The system was calibrated by the internal-conversion line from ^{207}Bi and by the observed β end points of ^{28}Al and ^{29}Al. The latter were made by bombarding a thin Al foil with the triton beam and counting the β spectra in coincidence with the 1779- and 1273-keV γ rays, respectively. Background gates above and below the 1273-keV γ ray were set to correct for the underlying Compton continuum due to the 1779-keV ^{28}Al line.

The ^{36}S target was bombarded for 60 sec with 0.5 μA of 3.4-MeV tritons, carried to the detector system and counted for 60 sec. Three separate ^{36}S targets were used to minimize the buildup of long-lived activities, mostly ^{34}Cl^m produced by the ^{32}S(t, n) reaction. 12 cycles of irradiation and counting were carried out on the ^{36}S targets, followed immediately by three cycles of bombarding and counting the ^{28}Al and ^{29}Al activities for calibration, followed by a waiting period of 1 h. Care was taken to maintain approximately equal β counting rates for the Al and S cycles, to minimize count-rate gain shifts. However, tests showed that changing the β counting rate from 2000 to 20 000 per sec had an effect of less than 3% on the gain of the system. This sequence of irradiating and counting the ^{36}S and ^{27}Al targets was repeated 11 times to obtain adequate statistics. The spectra were then corrected for underlying background. Conventional Fermi-Kurie plots for the ^{35}P and ^{29}Al β-ray spectra are shown in Fig. 5. The function Φ used in this figure is that defined by Dismuke *et al.*[10]

The resolution of the β counter was 16% for the ^{207}Bi 975-keV conversion line, and was presumably about 10 channels FWHM for β rays near 2.5 MeV. The high-energy ends of the Fermi-Kurie plots deviate upwards from the straight line because of the finite resolution. However, the ^{29}Al data were fitted to a straight line, using several fitting regions, and the extrapolated end point for ^{29}Al was independent of the fitting region, provided the latter did not include channels above 92. The apparent end point for ^{35}P is a few channels below that of ^{29}Al, and a fitting region consisting of channels 55–89 was chosen for the ^{35}P curve. These regions are indicated by the arrows in Fig. 5. Using the value[11] of 2407 ± 5 keV for the ^{29}Al β end-point energy, we deduce a value of 2337 ± 75 keV for the ^{35}P β end-point energy. This corresponds to a mass excess for ^{35}P of $-24\,936 \pm 75$ keV in agreement with the Garvey prediction[12] of $-24\,920$ keV.

V. RESULTS AND DISCUSSION

Figure 6 shows the results of this work. The energies of the ^{35}S levels above 1.9 MeV are weighted averages taken from Refs. 7, 8, Van der Baan and Leighton,[13] and Moss.[14] Averaging our results of Secs. II–IV gives 1572.38 ± 0.25 keV for the energy of the first excited ^{35}S level and 1572.34 ± 0.25 keV for the γ ray.

Table I gives limits on the possible β branches to other ^{35}S levels, with the exception of the ground-state branch, for which we have no information. The $\log ft$ values assume that the transition to the 1572-keV level is the only β branch.

Wildenthal *et al.*[15] have recently published shell-model wave functions for the ground and first excited states of ^{35}S. There are no published wave functions for ^{35}P, but the largest component in the ground state of ^{35}P is expected to be of the $d_{5/2}{}^{12}s_{1/2}{}^{3}(j=t=\frac{1}{2}, t_z=\frac{1}{2}, v=1)\,d_{3/2}{}^{4}(j=0, T=2, v=0)$ configuration, coupled to a total $J=\frac{1}{2}$ and $T=\frac{5}{2}=T_z$, where v indicates the shell seniority and $t_z(\text{neutron})=+\frac{1}{2}$. Wildenthal *et al.*[15] list four major amplitudes for the ground state of ^{35}S, altogether comprising 83.2% of the ground-state wave function. The Gamow-Teller matrix element coupling the ^{35}P configuration mentioned above with the published ^{35}S(0) wave function vanishes, since none of those four amplitudes for ^{35}S(0) has three nucleons in the $s_{1/2}$ shell. Thus the ground-state β-ray branch is expected to be small.

The above argument is only qualitative, since a single configuration was assumed for ^{35}P(0), and

TABLE I. β-ray branches of ^{35}P to excited states of ^{35}S.

^{35}S Level (keV)	β branch (%)	$\log ft$ Exp.	$\log ft$ Theory (Ref. 16)
0	···	···	6.34
1572	100 [a]	4.06 ± 0.06 [a]	4.19
1995	<2.5	>5.3	···
2350	<5	>4.6	···
2724	<7	>4.0	···
2941	<8	>3.6	···

[a] Assumes no other β transitions exist.

because only the published components of the wave function for $^{35}S(0)$ were considered. The other unpublished configurations, which in this case account for 16.8% of the wave function, cannot be neglected. Recent calculations of Lanford and Wildenthal[16] of β-decay matrix elements using the complete wave functions (only part of which are published in Ref. 15) have been made available to the authors. Lanford and Wildenthal[16] calculate $\log ft$ values for the decay of ^{35}P to the ground and first excited states of ^{35}S as 6.34 and 4.19, respectively. Using our present value for the mass of ^{35}P, Lanford's ft values correspond to a β branch of 6% to the ground state and the remaining 94% to the 1572-keV state. Their predicted half-life for ^{35}P is then 60 ± 4 sec, where the error arises from the uncertainty in our measured mass. This calculated half-life is impressively close to the measured value of 48 ± 1.4 sec. These calculations[16] should be very useful to experimentalists searching for previously unknown nuclei by delayed-γ-ray techniques.

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