Decay of a New Isotope, S^{30}†

E. L. ROBINSON, J. I. RHODE, AND O. E. JOHNSON
Physics Department, Purdue University, Lafayette, Indiana
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Scintillation techniques were used to study the beta and gamma radiation from high-purity natural silicon targets after irradiation with 8-Mev He^3 ions. In addition to activities associated with well-known radioisotopes, an activity with a (1.35 ± 0.10)-sec half-life was observed. A (677 ± 10)-kev gamma ray was associated with the 1.35-sec half-life. Decomposition of decay curves constructed from data obtained by observing annihilation radiation revealed a component with the same half-life. Half-life measurements using positrons with energies in excess of 3.15 Mev also indicated the presence of a 1.35-sec activity. The beta spectrum in coincidence with two annihilation quanta extended to ≈5.0 Mev, a higher energy than can be accounted for by positrons from the known reaction products. The beta spectrum in coincidence with the (677 ± 10)-kev gamma ray had an end-point energy of (4.30 ± 0.15) Mev. The assignment of the (1.35 ± 0.10)-sec activity to the decay of S^{30} produced in the reaction $Si^{28}(He^3,n)S^{30}$, and the proposed decay scheme are supported by arguments formulated from the known characteristics of reaction products, half-life studies using both beta and gamma radiation, the features of the experimental beta and gamma spectra, beta-gamma coincidence spectra, nuclear systematics, and nuclear theory. The decay of the ground state of S^{30} takes place by at least two positron transitions: β_1, a (4.98 ± 0.15)-Mev superallowed transition to the $1+$, $T=0$ ground state of P^{30}; β_2, a (4.30 ± 0.15)-Mev superallowed transition to the $0+$, $T=1$ (0.677 ± 0.010)-Mev first excited state of P^{30}. No evidence was found for β_3, presumably an allowed transition to the $1+$, (0.704 ± 0.005)-Mev second excited state of P^{30}, but an experimental upper limit of 25% is placed on its branching percentage. Branching percentages of $(19\pm2)\%$, $(73\pm7)\%$, and $(8\pm10)\%$ for β_1, β_2, and β_3 were calculated using the measured S^{30} half-life, a S^{30}-P^{30} mass difference of (6.01 ± 0.15) Mev, assumed charge independence of nuclear forces, and the fact that log *ft* for 0^+ to 0^+ positron transitions within $T=1$ charge multiplets is almost constant.

I. INTRODUCTION

THE conclusions to be presented here were formulated from the complete analysis of experimental data whose partial reduction formed the basis of a brief preliminary report appearing elsewhere[1] and from the reduction of experimental data obtained from measurements made after the writing of the aforementioned report.

The mass excess of the previously unobserved isotope, S^{30}, as calculated from the semiempirical formulas of Fermi[2] and Cameron[3] is -8.836 and -7.138 Mev, respectively. On the same basis, it would be concluded that the S^{30} ground state is stable to heavy-particle emission, and should decay by positron emission to one or more of the states of P^{30}. The Q value for electron capture, using the known mass excess[4] of P^{30} and the calculated mass excess for S^{30}, is either 2.45 or 4.14 Mev according as the Fermi or Cameron S^{30} mass excess is used.

A more reliable calculation of the energy available for the positron decay of S^{30} can be made using the formula for Coulomb energy differences in light nuclei given by Peaslee.[5] A direct application of this formula yields the result that the $0+$, $T=1$ ground state of S^{30} should be ≈5.4 Mev above the $0+$, $T=1$ first excited state of P^{30}. Combining this result with the measured energy for the first excited state of P^{30}, (684 ± 4) kev,[6] the Q value for the electron capture of S^{30} to P^{30} should be ≈6.1 Mev. The ground state of P^{30} then decays by positron emission to Si^{30}.[7] The present investigation was undertaken in an attempt to produce the S^{30} and study the properties of its decay.

II. EXPERIMENTAL

The experimental apparatus, circuit configurations, and experimental procedures used in this investigation have been described for the most part elsewhere.[8] There are, however, some differences in detail which will be discussed below, and for purposes of convenient reference some of the essentials will be repeated here.

The targets were transported from bombarding position inside the cyclotron shielding to a counting position outside the shielding by a pneumatic target transfer system. The nominal travel time was 0.3 sec.

The target assemblies, consisting of the sample to be irradiated, target carrier, and target-carrier hardware, could be interchangeably assembled so that the contribution of the various materials to the gross beta and gamma spectrum could be systematically studied. Measurements supported the conclusion that the target car-

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[1] Research in Nuclear Physics Progress Report No. 10, June 15, 1960; Purdue Research Foundation, Lafayette, Indiana TID-6074 (Office of Technical Services, Department of Commerce, Washington, D. C.).

[2] N. Metropolis and G. Reitwiesner, U. S. Atomic Energy Commission Report NP-1980, 1950 (unpublished).

[3] A. G. W. Cameron, Atomic Energy of Canada Limited, Report No. 433, CRP-690, 1957 (unpublished).

[4] W. H. Wapstra, Physica **21**, 367 (1955).

[5] D. C. Peaslee, Phys. Rev. **95**, 717 (1954).

[6] C. van der Leun and P. M. Endt, Phys. Rev. **110**, 96 (1958).

[7] It may be generally assumed, unless otherwise specified, that properties of nuclei referred to in this report have been taken from one or more of the following compilations of nuclear data: (a) P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957); (b) D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 584 (1958); (c) F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959); (d) *Nuclear Data Sheets* (National Academy of Science-National Research Council, Washington, D. C., 1958–1960).

[8] E. L. Robinson and O. E. Johnson, Phys. Rev. **120**, 1321 (1960).

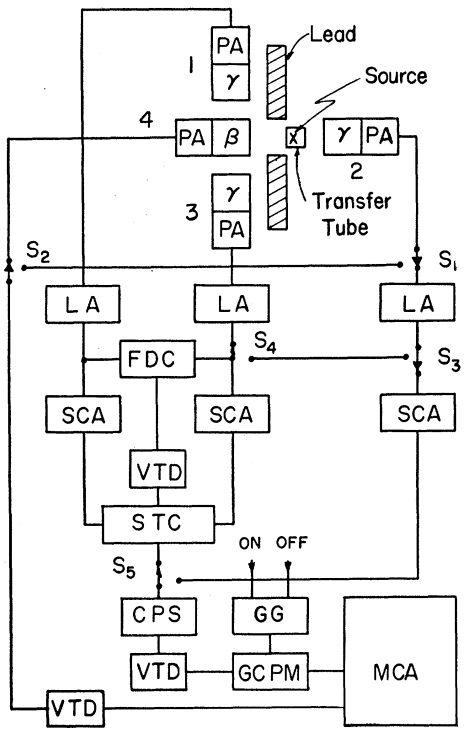

FIG. 1. A block diagram of the coincidence and spectrometer circuit configurations used in this investigation. PA = preamplifier; LA = linear amplifier; SCA = single-channel pulse-height analyzer; FDC = fast double coincidence circuit; STC = slow triple coincidence circuit; VTD = variable time delay; CPS = coincidence pulse shaper; GCPM = gate-coincidence pulse mixer; GG = on-off gate generator; MCA = multichannel analyzer.

rier and hardware made negligible contribution, if any, to the spectra measured in these investigations.

The targets were cylinders (nominally $\frac{5}{8}$-in. diameter $\times\frac{1}{16}$-in. height) of high-purity silicon (Merck, zone-refined). Three similar targets, short bombardments, and scheduled measurements were used to avoid ambiguities introduced by the accumulation of the longer lived activities.

The gamma detectors consisted of cylindrical (3-in. $\times$3-in.) NaI(Tl) crystals optically coupled to 6363 DuMont photomultiplier tubes. The energy calibration of the gamma-ray scintillation spectrometer was accomplished using well-known gamma radiations. The resolution was about 9% for the 0.662-Mev gamma ray associated with the decay of Cs^{137}. The beta detector consisted of a cylindrical ($1\frac{1}{2}$-in. height$\times 2\frac{1}{2}$-in. diameter) Pilot-B plastic phosphor optically coupled to a 6363 DuMont photomultiplier tube. The Pilot-B phosphor was covered with an aluminum light shield having a 1-mil aluminum foil window. The beta-ray scintillation spectrometer was calibrated using well-known internal conversion lines and beta spectra end points. Fifteen-percent resolution was obtained for the 0.624-Mev internal conversion line of Ba^{137m}.

The beta spectrum in coincidence with energy-selected gamma radiation was measured by positioning a gamma detector coaxially with the beta detector on the opposite side of the source (refer to Fig. 1, detectors 4 and 2). The pulses from the beta detector were delayed and passed to the multichannel pulse-height analyzer. The pulses from the gamma detector were amplified and pulse height analyzed in a single-channel differential discriminator. The output of the discriminator was shaped, delayed, and mixed with the on-off gate signal of the multichannel analyzer. The resolving time of this coincidence system was $\approx 1.5\ \mu$sec.

In Fig. 1 is also shown the coincidence system used in the measurement of positron spectra. This coincidence configuration was used to make it possible to measure the spectrum of a fraction of those positrons for which both annihilation quanta escaped from the beta phosphor. The gamma detectors were shielded from the source and viewed the beta phosphor as shown in Fig. 1. The two channels associated with detectors 1 and 3 comprise a conventional fast-slow coincidence system with a resolving time $\approx 0.15\ \mu$sec. The single-channel differential discriminators were set to accept pulses corresponding to a gamma-ray energy interval of ≈ 120 kev centered at 511 kev. The output of the fast-slow coincidence system was shaped, delayed, and mixed with the on-off gate signal for injection into the prompt coincidence circuit ($\tau = 1.5\ \mu$sec) which is an integral part of the multichannel analyzer.

The 14.5-Mev, external He^3 beam of the Purdue University 37-in. cyclotron was focused, collimated, and passed through several windows before impinging on the silicon targets. The nominal beam energy and current at the target were 8 Mev and 5×10^{-8} amp, respectively.

III. MEASUREMENTS, RESULTS, AND DISCUSSION

Many nuclear reactions are energetically possible when natural silicon is bombarded with 8-Mev He^3 ions. The identification of the product radioisotopes was accomplished through the use of experimental beta and gamma spectra obtained using various bombardment and counting programs; studies of the secular changes in beta and gamma spectra after bombardment; beta-gamma coincidence measurements; and the previously established characteristics of the reaction products and their decay modes.[7] The identification of the known product radioisotopes which might be expected solely from energy considerations was complicated by the almost complete absence of strong labelling gamma radiations. Examination of a list of the energetically-allowed, unstable reaction products and their properties indicates that all the negative electron emitters have long half-lives (>2.5 hr) and all the positive electron emitters have short half-lives (<2.6 min).

A half-life measurement was made using the gamma radiation, predominantly annihilation radiation, in an 80-kev interval centered at 511 kev. The counting period was started 0.3 sec after a 1.1-sec bombardment. The data accumulated in a series of similar runs were

combined to form a decay curve. The decay curve, as expected, indicated the presence of more than one activity and could be interpreted by assuming that P^{30} ($\approx$2.5 min); S^{31}($\approx$2.6 sec); P^{29}($\approx$4.5 sec) and/or Si^{27}($\approx$4.4 sec); and an unidentified activity with a half-life less than 2 sec were produced.

To verify the presence of P^{30}, a half-life measurement was made using the beta detector and an integral count of all pulses corresponding to beta energies above $\approx$900 kev. The measurement was started 1.5 min after a 25-sec bombardment and extended over a 15-min period. Analysis of the resulting decay curve yielded a single half-life of (2.52$\pm$0.04) min which is in good agreement with two of the most accurate values reported for P^{30}, (2.52$\pm$0.02) min[9] and (2.51$\pm$0.02) min[10] but disagrees with a third accurate measurement of (2.62$\pm$0.02) min.[11] Similar beta half-life determinations were made using a series of integral bias values between 0.900 and 3.15 Mev in which the measurements were started $\approx$0.3 sec after a 1.1-sec bombardment. For each bias setting a complex decay curve was obtained; however, the relative contribution of the short half-lived component increased with increasing energy bias. From the data obtained in the measurement using an integral bias corresponding to 3.15 Mev, a half-life of (1.48$\pm$0.3) sec was determined for the short-lived activity. The data obtained in these beta half-life measurements may be interpreted consistently on the same basis as the half-life data obtained by detecting annihilation radiation.

Several measurements of gamma spectra were made under the following bombardment and counting schedule (referred to as a "short program with subtraction"): irradiation, 1.1 sec; delay (target transit time), 0.31 sec; first measurement of spectrum for 3.0 sec; delay 5 sec; second measurement of spectrum for 3.0 sec. A difference spectrum was formed by subtracting the second from the first. A series of such difference spectra was combined to form the final resultant spectrum. Spectra accumulated in this manner should favor the observation of gamma radiation associated with the short-lived activities. A gamma spectrum extending up to $\approx$3.1 Mev showed some slight evidence for gamma rays between 1.0 and 2.5 Mev; however, the counting statistics were not good enough to permit peak identification and location. This radiation could be attributed to the known, weak gamma transitions in P^{29}, P^{30},[7] and S^{31}.[12] The prominent peaks at energies lower than 1.0 Mev will be discussed below. A second gamma spectrum was measured at increased amplifier gain and extended up to $\approx$1.4 Mev. This spectrum, as well as the previous one, showed prominent peaks at (0.677$\pm$0.010) and (0.514$\pm$0.010) Mev. A portion of this gamma-ray spectrum is shown in Fig. 2. The errors assigned to these energies are estimated "limits of error" based on the probable error in the calibration, uncertainty in peak location, and possible gain changes due to changing source intensity. The probable error neglecting the latter effect for the 0.677-Mev gamma ray is $\approx$6 kev. A third gamma spectrum extending to $\approx$2.2 Mev was formed from a series of measurements each made for a period of 3.0 sec delayed 5.0 sec after a 1.8-sec bombardment. This spectrum differed from that obtained using the "short program" only in that the ratio of the "677-kev peak" to the "514-kev peak" was reduced, indicating that the 677-kev radiation is associated with the short-lived activity.

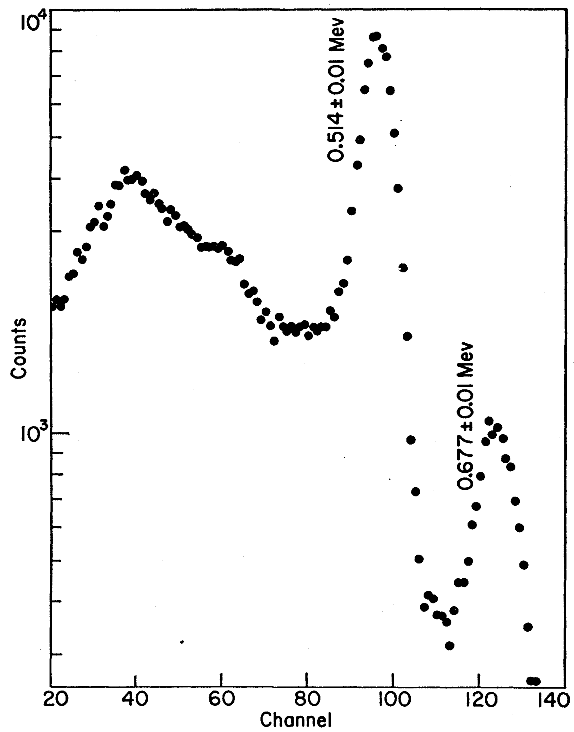

FIG. 2. A gamma-ray spectrum from natural silicon targets after irradiation with 8-Mev He^3 ions. The spectrum was formed from the sum of a series of difference spectra. Each difference spectrum was formed by subtracting two spectra measured at different times after a single 1.1-sec bombardment: the first measurement was made over a 3.0-sec time interval 0.31 sec after bombardment, and the second was measured for the same time interval 8.31 sec after bombardment.

The gamma radiation in a 100-kev interval centered at 677 kev was used in a series of half-life measurements and yielded an average value of (1.33$\pm$0.10) sec for the short-lived activity. This value agrees within experimental error with that found for the short-lived component observed using high-energy beta radiation, and is presumably the half-life of the short component (<2 sec) observed using the annihilation radiation.

The extremely high purity of the silicon makes it highly improbable that the 1.3-sec activity arises from impurities inherent to the silicon. The possibility of the

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[10] S. E. Arnell, J. Dubois, and O. A. Almen, Nuclear Phys. **6**, 196 (1958).
[11] J. E. Cline and P. R. Chagnon, Bull. Am. Phys. Soc. **3**, 206 (1958).
[12] W. L. Talbert, Jr. and M. G. Stewart, Phys. Rev. **119**, 272 (1960).

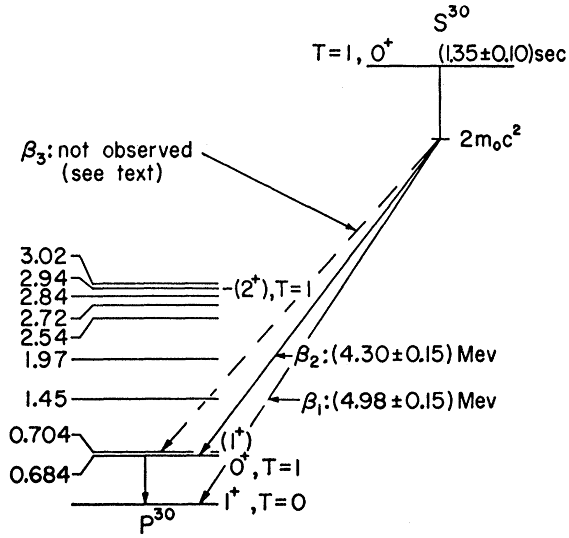

FIG. 3. The low-lying level structure of P^{30} as taken from recent compilations of nuclear data (see reference 7) and a decay scheme for S^{30} proposed on the basis of this investigation.

activity being produced by He^3 reactions with surface contamination can be ruled out because of the use of several targets which had been carefully cleaned. In any case, the targets would probably not have been contaminated to the same extent with the same foreign material. It was therefore concluded that an activity having a half-life of (1.35±0.10) sec is produced by a nuclear reaction involving 8-Mev He^3 ions and one of the three isotopes of natural silicon. This half-life value is based on all the results obtained in the various measurements. The assigned probable error was determined from statistical considerations plus appraisals of each experimental measurement and the methods used in the reduction of the data.

Since there is no known single isotope among the energetically-allowed reaction products which has a 1.3-sec half-life, a positron transition in excess of 3.15 Mev, and a 677-kev gamma ray, the possibility of a new isotope as a reaction product must be considered. The presence of a (684±4)-kev[6] first excited state in P^{30} is suggestive. The low-lying level structure of P^{30} is rather well known and is shown in Fig. 3 as taken from recent compilations of nuclear data.[7] The remainder of Fig. 3 is the decay scheme of S^{30} proposed on the basis of the present investigation. The ground state of S^{30} would be a 0+, $T=1$ state, and the first excited state of P^{30} is known to have even parity, spin 0, and $T=1$. A superallowed positron transition between these states would be expected to be the principal decay mode. The gamma transition to the ground state would then be a dominant feature in the gamma spectrum. The assignment of the (1.35±0.10)-sec activity to S^{30} would be consistent with experimental results that have been presented up to this point.

Measurements of the positron distribution associated with the decay of activities produced in the He^3 bombardment of natural Si were made using two different types of coincidence requirements: the coincident detection of two annihilation quanta and a particle in the beta detector, $(2\gamma+\beta)$; and the coincident detection of a single energy-selected pulse (677 kev) and a particle in the beta detector $(\gamma+\beta)$. The $(2\gamma+\beta)$-coincidence positron spectrum measured using a short program with subtraction would be a composite of the contributions of the short-lived isotopes S^{31}, P^{29}, and Si^{27} with nominal end-point energies of 4.5, 3.95, and 3.76 Mev, respectively. The experimental spectrum showed a continuous positron distribution extending to 5.0 Mev. The presence of S^{31}, P^{29}, and Si^{27} cannot, however, account for the positrons between 4.5 and 5.0 Mev. It was pointed out in the introduction that a positron transition between the ground states of S^{30} and P^{30} would be expected to have an end-point energy of ≈5.1 Mev. The presence of S^{30} could explain the higher energy portion of the positron distribution. It cannot be immediately concluded that the transition between the S^{30} and P^{30} ground states does occur. The coincident detection of a positron and a Compton electron from the 677-kev gamma ray could contribute to the positron distribution in the region above 4.5 Mev. The contribution of such Compton electron-positron summing was calculated for the geometry used and was found to be at least an order of magnitude too small to account for the high-energy (4.5 to 5.0 Mev) portion of the positron spectrum. This is then taken as experimental evidence that a positron transition with ≈5.0-Mev end point occurs.

The $(\gamma+\beta)$-coincidence positron spectra were measured using a short program without subtraction. In Fig. 4 is shown a Fermi plot formed from a $(\gamma+\beta)$-coincidence positron spectrum for which the gamma radiation in a 100-kev interval centered at 677 kev was used. The turning-up of the Fermi plot at lower energies is interpreted as due to source thickness, backscattering out of the beta detector, and finite, energy-dependent resolution. The tailing-out in the high-energy portion of the Fermi plot is interpreted as due to finite energy resolution and the summing of Compton electrons from the annihilation radiation with the positrons. The error introduced into the determination of the end-point energy by this latter effect was studied using positron emitters with known end points. The linear extrapolation of the body of the Fermi plot shown in Fig. 4 yields an end-point energy of (4.30±0.15) Mev, where the error is an estimated probable error based on the study indicated above.

In the following discussion it will be assumed that three beta transitions are associated with the decay of the S^{30} ground state: β_1, a (4.98±0.15)-Mev transition to the ground state of P^{30}; β_2, a (4.30±0.15)-Mev transition to the first excited state of P^{30}; and β_3, a (4.28±0.15)-Mev transition to the second excited state of P^{30}. The sum of the three partial transition probabilities λ_1, λ_2, and λ_3 corresponding to the respective beta transitions is equal to (0.514±0.038) sec^{-1}.

The two ground-state to ground-state transitions $S^{30} \rightarrow P^{30}$ and $P^{30} \rightarrow Si^{30}$ are so-called analog transitions. The $P^{30} \rightarrow Si^{30}$ transition is well measured with an end-point energy of 3.24 Mev, a half-life of 2.52 min, and $\log ft = 4.85$. This is one of the superallowed transitions with an anomalously large ft value. If the charge independence of nuclear forces is assumed, the $\log ft$ of the $S^{30} \rightarrow P^{30}$ ground-state transition may be calculated from that of the analog transition. Taking into account the difference in initial state spins, 0 for S^{30} and 1 for P^{30}, a $\log ft = 4.37$ is obtained for the $S^{30} \rightarrow P^{30}$ ground-state transition. The branching percentage for this transition is $(19 \pm 2)\%$ if the energy of the positron transition to the (0.684 ± 0.004)-Mev state of P^{30} is assumed to be (4.30 ± 0.15) Mev and the S^{30} half-life is taken to be (1.35 ± 0.10) sec. The data from the present investigation are not of such a nature that a reliable calculation of this branching percentage can be made. However, a branching of 19% is not inconsistent with very crude estimates and their assigned errors.

On the basis of the accepted spin, parity, and isotopic spin assignments for the ground state of S^{30} and the first excited state of P^{30}, the positron transition connecting these two states is a member of a rather unique class, $0+ \rightarrow 0+$ positron transitions within $T=1$ charge multiplets. Experimentally, this class of transitions has been found to possess, within experimental errors, an extremely homogeneous group of ft values (≈ 3140 sec). Insofar as nuclear forces are charge independent and Fierz interference is nonexistent in the beta decay process, theory predicts that the ft values for this class of transitions should be constant.[13] Weighting the experimental ft values for this class of transitions inversely as the squares of the quoted errors, an average ft value of (3138 ± 35) sec is obtained. It would seem reasonable to assume that the transition in question should have a similar ft value which, when used with the measured half-life and end point, gives a branching of $(73 \pm 7)\%$.

Using the relation $(0.514 \pm 0.038)\ \text{sec}^{-1} = \lambda_1 + \lambda_2 + \lambda_3$ and the results above, a β_3 branching of $(8 \pm 10)\%$ is found. No experimental evidence for this transition was seen; however, on the basis of experimental considerations an upper limit of 25% was placed on the β_3 branch. The most probable value of λ_3 and the transition energy for β_3 yields a $\log ft = 4.46$. The β_3 transition is presumably allowed ($\Delta I = 1$,no), and a $\log ft = 4.46$ is certainly within the range of values expected for allowed transitions.

In the calculations above it has been assumed that charge independence holds rigorously; the error in the $P^{30} \rightarrow Si^{30}$ ground-state $\log ft$ is negligible; and the $\log ft$ value taken as characteristic of the $0+ \rightarrow 0+$ positron transitions within the $T=1$ charge multiplets has a negligible error. It follows then that the error in

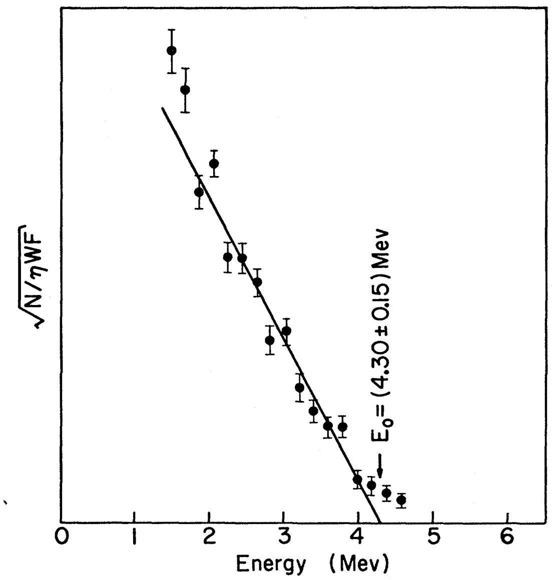

FIG. 4. Fermi plot formed from the experimental distribution of positrons in coincidence with the 677-kev gamma ray (see text for details).

λ_1 and λ_2 is essentially all due to the error in the β_2 end-point energy, while the error in λ_3 arises from the experimental errors in both the S^{30} half-life and the β_2 end-point energy. Of course, the error in all of the branching percentages is due to both the half-life and β_2 end-point energy errors.

IV. CONCLUSIONS

In the preceding sections experimental results have been presented and interpreted in support of the following conclusions[14]: (1) A radioisotope with a (1.35 ± 0.10)-sec half-life is produced in the bombardment of high-purity silicon with 8-Mev He^3 ions. (2) The observed half-life is that of the new isotope S^{30} produced in the reaction $Si^{28}(He^3,n)S^{30}$. (3) The decay of the $0+$, $T=1$ ground state of S^{30} takes place by at least two positron branches: β_1, a (4.98 ± 0.15)-Mev superallowed transition to the $1+$, $T=0$ ground state of P^{30}; β_2, a (4.30 ± 0.15)-Mev superallowed transition to the $0+$, $T=1$, (0.677 ± 0.010)-Mev first excited state of P^{30}. No evidence for a third transition, β_3, to the $1+$, (0.704 ± 0.005)-Mev second excited state was found; however, an experimental upper limit of 25% is placed on its branching percentage. (4) The S^{30}-P^{30} mass difference is (6.01 ± 0.15) Mev. (5) The branching percentages for β_1, β_2, and β_3 were calculated to be $(19 \pm 2)\%$, $(73 \pm 7)\%$, and $(8 \pm 10)\%$ by combining the experimental half-life of S^{30} and the S^{30}-P^{30} mass difference with the theoretical predictions based on the charge

[13] A brief summary of this topic, related considerations, and further references are given by W. M. MacDonald, in *Nuclear Spectroscopy, Part B*, edited by F. Ajzenberg-Selove (Academic Press, New York, 1960), p. 932 ff.

[14] *Note added in proof:* Insofar as the experimental measurements coincide, the experimental results and interpretations of the present investigation are in agreement with those of R. G. Johnson, L. F. Chase, and W. L. Imhof, Bull. Am. Phys. Soc. **5**, 406 (1960), and the corresponding oral report.

independence of nuclear forces. These conclusions are summarized graphically in Fig. 3.

ACKNOWLEDGMENTS

The invaluable service of Professor D. J. Tendam and the cyclotron crew in maintaining the He^3 beam during the course of these measurements is gratefully acknowledged. Discussions concerning various theoretical aspects of this work with Professor R. W. King have been of great value. B. T. Lucas is thanked for his aid in the reduction of data and servicing the experimental apparatus.

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Excited States in N^{14} from the Elastic Scattering of Protons by C^{13}†

E. KASHY,* R. R. PERRY, R. L. STEELE,‡ AND J. R. RISSER
Rice University, Houston, Texas
(Received December 19, 1960)

Excited states in N^{14} have been observed by measuring the differential elastic scattering cross section of $C^{13}(p,p)C^{13}$ for proton energies from 2.6 to 5.0 Mev. Resonances were observed at proton energies of 2.743, 2.87, 3.105, 3.20, 3.78, 3.980, 4.04, and 4.14 Mev, corresponding to excited states in N^{14} at 10.092, 10.21, 10.428, 10.52, 11.05, 11.240, 11.30, and 11.39 Mev, respectively. Single-level dispersion theory analysis indicates assignments $J^\pi=1^+(2^+)$, 1^-, 2^+, 1^-, 1^+, 3^-, 2^-, and 1^+, respectively, for these states. Analysis of previously published $C^{13}(p,p)C^{13}$ data at lower energies confirms the assignments 1^-, 0^+, 0^-, 3^-, and 1^+ for the states at 8.05, 8.61, 8.75, 8.90, and 8.98 Mev. A resonance at 4.265 Mev corresponding to the known narrow state at 11.504 Mev was not found in the elastic scattering data although it was found to be strong in $C^{13}(p,p')C^{13*}$.

THESE experiments were an extension of our experiments[1] with deuterons on C^{12} involving a number of the same states in N^{14*}. The experimental techniques and method of analysis were essentially the same in the two experiments. States in N^{14*} at 11.05, 11.30, 11.39, and 11.504 Mev, which show clearly in $C^{12}(d,d)C^{12}$, $C^{12}(d,p_0)C^{13}$, and/or $C^{12}(d,p_1)C^{13*}$ at $E_d=0.92$, 1.19, 1.31, and 1.446 Mev, have large proton partial widths to the ground and/or first excited state of C^{13}. From the analysis of the deuteron data it was possible to make J^π assignments and estimate the proton partial widths. In addition, the results of the $C^{12}(d,p_0)C^{13}$ analysis imply the operation of selection rules other than those arising from the conservation of angular momentum and parity.[2] In view of the question of the validity of isotopic spin selection rules and the extensive interest[3,4] in the states of N^{14*}, it appeared important to check these results directly by elastic scattering of protons on C^{13}. In taking the elastic scattering data, the range of energies was extended down to 2.6 Mev and up to 5.0 Mev. The states at 11.05, 11.30, and 11.39 Mev in N^{14*} produced resonances in $C^{13}(p,p)C^{13}$ at $E_p=3.78$, 4.04, and 4.14 Mev. Additional resonances at 2.743, 2.87, 3.105, 3.20, and 3.980 Mev corresponding to states in N^{14*} at 10.092, 10.21, 10.428, 10.52, and 11.240 Mev were observed in the elastic scattering data. A resonance due to the narrow 11.504-Mev state at $E_p=4.265$ Mev[5] was not observed in the elastic scattering data although it showed up strongly in $C^{13}(p,p')C^{13*}$ ($Q=-3.09$ Mev). Theoretical fits to the elastic scattering data were attempted, using dispersion theory in the single-level approximation. A preliminary report of this work has been given.[6]

Elastic scattering experiments with protons on C^{13} in the range 0.4 to 1.6 Mev have been reported by Milne,[7] and in the range 1.6 to 3.3 Mev by Zipoy, Freier, and Famularo.[8] We have included in this paper a theoretical fit to the data of Milne, confirming his assignments. Extensive information on the states of N^{14*} has been accumulated through experiments on reactions.[3] Specific references will be given with the discussions of individual states where pertinent.

The ground state of C^{13} has $J^\pi=\frac{1}{2}^-$ and the character $^2P_{\frac{1}{2}}$. The elastic channel spin S can thus be 0 or 1 for protons on C^{13}. As compared with $C^{12}(d,d)C^{12}$ channel-spin-one scattering,[1] there is the added problem of the

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* Now at Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts.
‡ Now at Rocketdyne, Canoga Park, California.
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