tion of this lifetime is impossible as long as the slowing-down process is not better understood. This is true for most measurements employing the attenuated-Doppler-shift technique.

The lifetime for this transition has been predicted by Arima *et al.*[13] who used the $(d_{5/2},s_{1/2})$ model of oxygen, fluorine, and neon. Their value

$$\tau=0.48\times10^{-14}\text{ sec}$$

is well within the experimental limits.

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Lifetimes of the First Two Levels in ^{30}P†

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The lifetimes of the first two levels in ^{30}P were measured by the attenuated-Doppler-shift technique. The measurements were analyzed by use of the universal stopping cross section given by Lindhard, Scharff, and Schiott, and a mean life $\tau=(1.55\pm0.30)\times10^{-13}$ sec was obtained for the first level; for the second level only a lower limit ($\tau\geq3.0\times10^{-12}$ sec) was obtained. The experimental result for the first level is compared with the value calculated from the corresponding Gamow-Teller β transition according to the relation given by Kurath. Slightly revised energies of 677.0±1.0 and 709.0±1.0 keV are assigned to these levels.

INTRODUCTION

THE probabilities of $M1$ transitions involving an isospin change $|T_f-T_i|=1$ can be calculated from a simple relation derived by Kurath[1] and discussed in the preceding paper.[2] When used to calculate the lifetime of the first excited state of ^{30}P$(T=1, J^\pi=0^+)$, this relation yields a mean life $\tau=4\times10^{-13}$ sec if the orbital part of the interaction is neglected. This value is in the range measurable by use of the attenuated-Doppler-shift technique.

MEASUREMENTS

In the present experiment, the two lowest levels in ^{30}P were populated by means of the ^{27}Al$(\alpha,n)^{30}$P reaction at a resonance located at 3.95 MeV, which is 130 and 100 keV above the thresholds for production of these states. Both lifetimes could be measured at the same resonance because the second level is known[3] to decay to the ground state only. Since the neutrons were emitted with low energies, the ^{30}P nuclei recoiled in the forward direction with little spread in angle and initial velocity. The Al metal targets were inclined at an angle of 45° to the α beam from the Argonne 4-MeV Van de Graaff accelerator; they ranged in thickness from 10 to 50 μg/cm^2 and were evaporated onto carbon deposited on the tantalum beam stop. The intermediate layer of carbon, in thicknesses of 50 and 125 μg/cm^2, assured a stopping material with a slowing-down time similar to that of aluminum. For vacuum recoil measurements, 10-μg/cm^2 Al metal was evaporated onto a 20-μg/cm^2 carbon backing which faced the incident α beam.

A 9-cm^3 planar germanium counter having a resolution width of 4.5 keV was placed 4.5 cm from the target. The γ-ray spectra were fed through a biased amplifier and recorded in 1024 channels covering the energy range 0.540–0.920 MeV. The radiation coming from the target was registered along with two reference γ lines from radioactive ^{137}Cs(0.66162 MeV) and ^{95}Zr (0.7240 MeV). Runs at 0° and 90° were alternated to eliminate effects of drift. The background, measured carefully by lowering the proton energy below threshold, was flat under the lines of interest and hence could not contribute a measurable shift in the line positions.

The energy of the ^{95}Zr line was measured to be 0.7240 ±0.0007 MeV, with ^{137}Cs(0.66162 MeV) and ^{54}Mn (0.8350 MeV) sources[4] as energy standards. The ^{95}Zr

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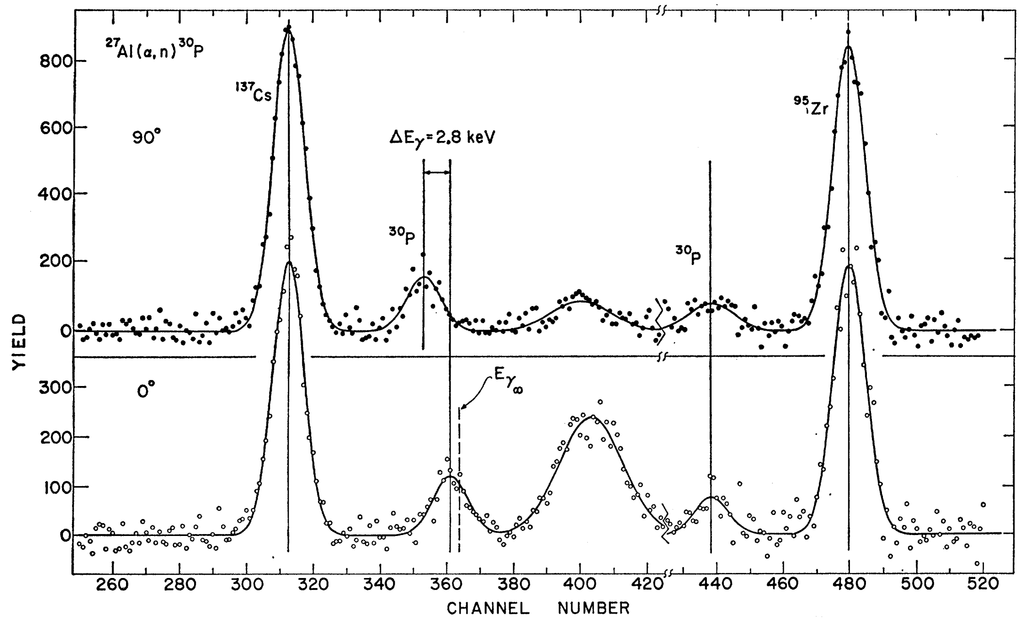

FIG. 1. Typical spectra obtained at 0° and 90° for the recoil ^{30}P stopping in carbon. Background has been subtracted. The lines through the data are Gaussian fits used to determine the peak positions (indicated by a vertical line through each peak). The ^{137}Cs and ^{95}Zr peaks are in alignment, while a 2.8-keV shift is apparent for the lower of the ^{30}P lines. The peak position of the unattenuated fully-shifted line is indicated by E_{γ_∞}. No shift is seen in the upper ^{30}P line.

line was chosen as a reference rather than the well-known ^{54}Mn line because the Compton tail of the ^{54}Mn line extends under the ^{30}P lines under investigation. Also, the 0.7240-MeV ^{95}Zr line is much closer to the ^{30}P lines and hence drifts in gain and bias are of less importance in determining shifts of the ^{30}P lines.

RESULTS

Sample spectra obtained are shown in Fig. 1. After background subtraction, the peaks in the pulse-height spectra were fitted by Gaussian curves by means of the Argonne variable-metric program.[5] The energies of the ^{30}P lines were then calculated by linear interpolation from the calibration peaks. Although the Doppler-shifted lines are not Gaussian, the energies determined in this way are only negligibly different from the true centroids.[6] The energies obtained for the two transitions observed in ^{30}P were 0.677±0.001 MeV and 0.709±0.002 MeV. The rather broad center peak at 0.694 MeV is due[7] to the reaction $^{72}Ge(nn')^{72}Ge$.

The fact that the lines at 0.677 and 0.709 MeV disappeared at bombarding energies below the threshold for their production in the $^{27}Al(\alpha,n)$ reaction indicated that they do indeed come from ^{30}P. However, the two known ^{30}P states in this region were reported[3] at 0.684 ±0.003 and 0.705±0.003 MeV. Further investigation was therefore undertaken to explain the energy discrepancy in the lower of the two observed lines. The energy of 684 keV was assigned by Endt and Van der Leun[3] to the first excited state in ^{30}P on the basis of data obtained by several investigators using the $^{29}Si(p,\gamma)^{30}P$ reaction. Different resonances in this reaction produce different population ratios of the two lowest levels. Since the NaI(Tl) spectrometers used in these experiments were unable to resolve the two lines, the energy determination depended on the knowledge of the intensity ratio of the two lines. Van der Leun and Endt[8] assumed that the resonance at 414-keV proton energy populated only the lowest level, whereas only the second level was populated by the 700-keV

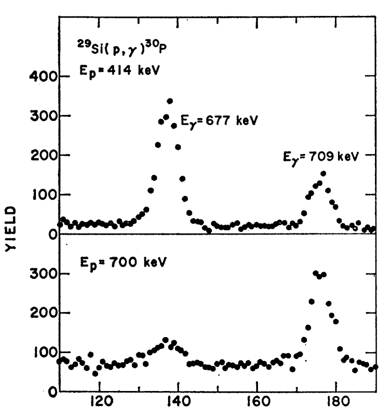

FIG. 2. Gamma spectra from the $^{29}Si(p,\gamma)^{30}P$ reaction in the neighborhood of the lines from the first two states of ^{30}P. Note that both levels are populated at each of the proton resonances used, in contrast to the assumptions of Ref. 8.

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TABLE I. Transition energies and shifts observed for the first two levels in ^{30}P. A correction has been applied to all shifts to take account of the finite solid angle subtended by the detector at 0°. A meaningful energy for the weak upper state could not be obtained with the thinner targets.

	Target thickness		First level			Second level	
Run	Al (μg/cm^2)	C (μg/cm^2)	E_γ (keV)	$\Delta E_{\gamma\alpha}$ (keV)	τ (10^{-13} sec)	E_γ (keV)	$\Delta E_{\gamma\alpha}$ (keV)
1	50	50	677.1	2.77 ± 0.23		709.5	-0.59 ± 0.57
2	50	50	676.8	3.11 ± 0.23	1.58	708.9	-0.45 ± 0.53
3	50	50	677.1	2.92 ± 0.45		708.4	0.81 ± 1.01
4	25	125	676.7	3.06 ± 0.40	1.42	...	...
5	10	125	677.1	2.92 ± 0.60	1.68	...	...
	Vacuum recoil			3.93 ± 0.33			3.6 ± 0.7
			τ(677 keV) = $(1.55\pm0.30)\times10^{-13}$ sec			τ(709 keV) $\geq 3.0\times10^{-12}$ sec	

resonance. In this way they arrived at energies of 684 ± 3 and 705 ± 3 keV.

In order to definitely establish that the 677-keV transition reported here is in fact from the state referred to by Endt and Van der Leun, the γ-ray spectra at the above two ^{29}Si$(p,\gamma)^{30}$P resonances were remeasured taking advantage of the much better resolution now available with the lithium-drifted germanium γ-ray detector. A 50-μg/cm^2 ^{29}SiO target (enriched to 95% ^{29}Si) was bombarded with 414- and 700-keV protons from the Argonne 2-MeV Van de Graaff accelerator. The spectra obtained are shown in Fig. 2. It is obvious from Fig. 2 that the assumptions made by Endt and Van der Leun were erroneous. At the 414-keV resonance, the upper state is populated with about one-third the intensity of the lower state and hence their assumption that only the lower level is populated leads to an error in its assigned energy. At the 700-keV resonance, the lower state is populated with about one-fourth the intensity of the upper. This also implies that the decay of the 709-keV level includes not more than a 20% branch through the 677-keV level. The present measurements yielded 677.0 ± 1.0 and 709.0 ± 1.0 keV for the energies of these two states. In addition, we also observed these same two lines (677 and 709 keV) while investigating the ^{30}Si$(p,n)^{30}$P reaction above the threshold for formation of these levels but found them to be absent below this threshold ($E_p=5.9$ MeV). This further confirmed their assignment to ^{30}P.

The results of the ^{27}Al$(\alpha,n)^{30}$P Doppler-shift experiment are shown in Table I, where the energies of the γ rays at 90° and the observed Doppler shifts at 0° are listed. The values in this table have been corrected for the finite solid angle subtended at 0° (a correction of 2% of the shift). The slowing down of the recoils while traversing the thin Al layer has a negligible effect on the measured vacuum shift. As can be seen from Table I, the effects of changing target thickness were considerably smaller than the statistical error in peak location. This result is in agreement with the close similarity of the effective slowing-down times of aluminum and carbon.

The expressions used to evaluate the nuclear lifetimes from the attenuated Doppler shifts were derived by Blaugrund[9] and are discussed in the preceding paper.[2] These expressions are based on the theory of atomic collisions developed by Lindhard, Scharff, and Schiott.[10] Values of $\Delta E_{\gamma\alpha}/\Delta E_{\gamma\infty}$, the ratio of the attenuated Doppler shift to the full shift, were calculated by numerical integration of the stopping equations [Eqs. (5a), (15a), and (19) of Ref. 9] for various possible nuclear lifetimes τ, and the results were compared with the experimental ratios. The path length traversed by the particles was monitored as a function of time, and the change in stopping material as the recoils passed from the aluminum layer to the carbon layer was explicitly taken into account during the integration. The full shift, calculated from the kinematics of the reaction on the assumption of isotropic emission of the neutrons in the center-of-mass system, is 4.03 and 4.22 keV for the two transitions. This is in agreement with the measured values. Because of the low energy of the neutrons, the neutron emission has a relatively small effect on the ^{30}P recoil energy (and hence on the full energy shift).

Electronic stopping cross sections for ^{31}P ions in carbon have been measured recently by Fastrup *et al.*[11] In the energy region of interest here, the measured electronic stopping power is approximately 14% higher than predicted by Lindhard *et al.*[10] Unfortunately there are no experimental data on the slowing down of phosphorus ions in aluminum. In evaluating here the slowing down of ^{30}P ions, Lindhard's theoretical electronic and atomic stopping cross sections were used, corrected in the same way as discussed in the preceding paper[2] (i.e., $f_n=1.0_{-0.4}^{+0.1}$ and $f_e=1.16\pm0.20$ both for carbon and aluminum). The density of carbon evaporated onto a cold substrate was measured by immersing fragments of the foils in different mixtures of carbon tetrachloride ($\rho=1.59$ g/cm^3) and bromoform ($\rho=2.98$ g/cm^3). Our result for the carbon film was $\rho=1.82\pm0.10$ g/cm^3; the fragments remained suspended in mixtures with this density but sank or floated in lighter or heavier mixtures.

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The mean lives of the 677-keV level obtained from measurements with various targets are summarized in Table I. The average of all these measurements is

$$\tau(677\text{ keV}) = (1.55 \pm 0.30) \times 10^{-13}\text{ sec.}$$

About half of the error arises from uncertainties in the stopping power and in the thicknesses of different target layers.

For the 709-keV level only a lower limit for the lifetime could be established. Assuming an experimental error equal to two standard deviations, this lower limit is

$$\tau(709\text{ keV}) \gtrsim 3.0 \times 10^{-12}\text{ sec.}$$

The energies of the first two levels in ^{30}P adopted from our measurements with various reactions are 677.0±1.0 and 709.0±1.0 keV.

DISCUSSION

The strength of the 677-keV $M1$ transition is related to the transition probability for the β decay $^{30}S \rightarrow {}^{30}$P by the formula given by Kurath.[1,2]

$$\tau = (4.0 \pm 0.4 \times 10^{-13}) \left[1 + 0.2125 \frac{\langle J_f T_f \| l\tau \| J_i T_i \rangle}{\langle J_f T_f \| \sigma\tau \| J_i T_i \rangle} \right]^{-2} \text{ sec}$$

for[12] $\log ft = 4.39 \pm 0.03$. As this is a rather slow transition, the lifetime obtained by ignoring the orbital interaction is much too slow. The ratio of the reduced matrix elements representing the orbital- and spin-dependent interaction, obtained from the above expression by substituting the measured lifetime for τ, might have either of two values: $+2.8 \pm 0.8$ or -12.2 ± 0.8.

Wiechers and Brussaard[13] have calculated the $M1$ transition probabilities for the first two states in ^{30}P using the shell-model wave functions of Glaudemans *et al.*[14] The lifetimes derived from their results are 1.6×10^{-13} sec for the lower state, in excellent agreement with our measurement, and 6.5×10^{-12} sec for the upper state, consistent with our experimental limit.

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Two-Nucleon Emission Process in π^--Meson Absorption

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The purpose of the paper is to investigate the effects of the short-range N-N correlations on the branching ratio $W(pn \rightarrow nn)/W(pp \rightarrow np)$, on the distribution of the absorption rate with respect to the projection of the openintg angle between the emitted nucleons, and on the total absorption rate in negative-pion absorption by C^{12} nuclei.

1. INTRODUCTION

As a useful method of getting some interesting information on nuclear structure, the absorption of stopped negative π mesons has attracted the attention of many theorists and experimentalists.[1–3] The information obtained from a study of the pion-capture process is as follows:

(1) The negative-pion absorption at rest occurs preferentially on a proton in a strongly correlated nucleon pair, and this ejects two nucleons out of the nucleus, leaving a two-hole excitation behind. Since the transition rate to a shell-model state of two holes has a sensitive state dependence, appreciable information about the two-hole states, in particular their spins and orbital angular momenta, is obtainable from an investigation of this transition process.

(2) Since the pion is absorbed at rest, the momentum distribution of the nucleons in the nucleus can be obtained by measuring the momenta of the ejected nucleons.

(3) From the energy and momentum conservation law, in the case of the π^- absorption by a single nucleon in the nucleus, the elementary processes $\pi^- + p \rightarrow n + \gamma$ and $\pi^- + p \rightarrow n + \pi^0$ are possible. However, in the case of nucleonic absorption (nonradiative and nonmesonic capture) the π^- mesons are dominantly absorbed by a strongly correlated nucleon pair in the nucleus, i.e., $\pi^- + p + n \rightarrow n + n$ or $\pi^- + p + p \rightarrow n + p$. This is con-

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