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Lifetime Measurements of Low-Lying States of ^{33}P

P. Wagner, J. P. Coffin, M. A. Ali, D. E. Alburger,* and A. Gallmann
Laboratoire de Physique Nucléaire et d'Instrumentation Nucléaire, Centre de Recherches Nucléaires et Université Louis Pasteur, Strasbourg, France

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Proton-γ coincidence techniques have been used to measure, by the Doppler-shift attenuation method, the lifetimes of the nine bound states of ^{33}P below 4.3-MeV excitation energy, via the ^{31}P$(t, p\gamma)^{33}$P reaction, at triton bombarding energies of 2.5 and 3.1 MeV. More accurate excitation energies have also been obtained for these states. For the first nine excited states in ^{33}P the measurements lead to the following energies (keV) and lifetimes (psec): 1431.5 ± 0.3 (0.60 ± 0.10), 1847.3 ± 0.3 (0.80 ± 0.15), 2537.6 ± 0.5 (0.070 ± 0.012), 3275.5 ± 1.0 (0.21 ± 0.04), 3490.2 ± 1.0 (0.11 ± 0.02), 3626.6 ± 1.0 (0.17 ± 0.08), 4048 ± 1 (0.085 ± 0.030), 4194 ± 3 (0.15 ± 0.05), and 4225 ± 1 (0.39 ± 0.10). The decay modes and branching ratios for these states have also been measured. These results restrict the spin and parity of the listed states (MeV) to the following assignments (J^{π}): 3.28 ($\frac{3}{2}, \frac{5}{2}^{+}$), 3.63 ($\frac{7}{2}^{+}$), 4.05 ($\frac{5}{2}^{(+)}$), 4.19 ($\frac{5}{2}^{+}$). For some transitions better limits have been set on the δ mixing ratios previously measured. The ^{33}P spectrum obtained is compared to other results and to applicable shell-model calculations.

I. INTRODUCTION

Considerable work has been devoted to the study of ^{33}P and a fairly good body of experimental information concerning the 10 existing states of ^{33}P below an excitation energy of 4.3 MeV is available. The most recent and complete work is due to Harris, Nagatani, and Olness,[1] who studied the ^{31}P$(t, p\gamma)^{33}$P reaction. A good summary of the theoretical and experimental studies on ^{33}P prior to their publication can be found in their paper. Harris, Nagatani, and Olness have measured p-γ angular correlations and their results, in conjunction with lifetime restrictions, led them to assign the following spins and parities for the first 10 levels [MeV (J^{π})] in ^{33}P: 0.0 ($\frac{1}{2}^{+}$), 1.43 ($\frac{3}{2}^{+}$), 1.85 ($\frac{5}{2}^{+}$), 2.54 ($\frac{3}{2}^{+}$), 3.28 ($\frac{3}{2}, \frac{5}{2}$), 3.49 ($\frac{3}{2}$ or $\frac{5}{2}$), 3.63 ($\frac{7}{2}^{+}$), 4.05 ($\frac{3}{2}, \frac{5}{2}$), 4.19 ($\frac{5}{2}, \frac{7}{2}$), and 4.22 ($\frac{7}{2}^{-}$). They also have measured energies and values or limits for branching and multipole mixing ratios of the transitions. The detailed experimental spectrum obtained was compared with shell-model calculations from Glaudemans, Wiechers, and Brussaard,[2] and Wildenthal *et al.*,[3] and serious discrepancies appear.

Since then, the only experimental work published on ^{33}P is due to Goosman and Alburger,[4] who have measured more accurately the excitation energies of the first two excited states of ^{33}P, and new calculations were done by Glaudemans, Endt, and Dieperink[5] and Wildenthal *et al.*[6] Since a good test of the wave functions is provided by electromagnetic transition rates, it is important to compare such quantities to absolute γ-ray transition probabilities, which can be deduced from lifetime measurements.

The present work was initiated because of an obvious lack of information concerning the lifetimes of the low-lying states of ^{33}P. The only measurements available are due to Currie and Evans[7] and concern the 1.43- and 1.85-MeV levels. We have measured the lifetimes of the first nine low-lying excited states of ^{33}P. These measurements should also elucidate some open questions from previous experimental work. We have also measured accurate excitation energies and branching ratios for the same nine states of ^{33}P, in order to establish, or clarify, unknown or controversial decay modes.

II. EXPERIMENTAL METHODS

All of the present work has been done using the ^{31}P$(t, p\gamma)^{33}$P reaction, initiated from a triton beam, delivered by the 3-MV Van de Graaff of the Centre de Recherches Nucléaires de Strasbourg-Cronenbourg. The lifetime measurements made use of the Doppler-shift attenuation method (DSAM) in studying the γ-ray spectra in coincidence with proton groups. Excitation energies of the ^{33}P levels and branching ratios have been extracted from the same measurements. In view of the complexity of the direct γ-ray spectra no information could be easily obtained from such measurements and moreover the coincidence technique insures first a well-defined direction of recoil for the recoiling nuclei and secondly a selective feeding of the levels under study.

The experiments were done at bombarding energies of 2.5 and 3.1 MeV. The reason for running at two different energies was because the "doublet" of states at 4.19 and 4.22 MeV in ^{33}P could not be resolved in the proton channel and, according to

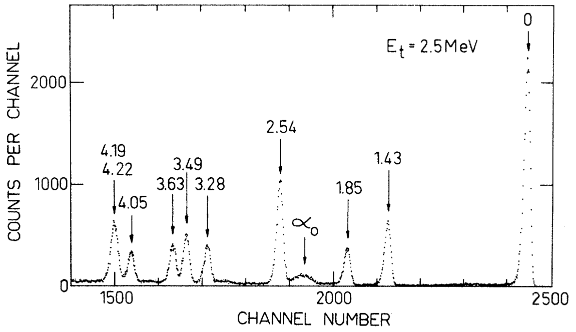

FIG. 1. Particle spectrum resulting from 2.5-MeV triton bombardment of a Zn_3P_2 target, measured with an annular surface-barrier detector at θ_{lab} =155°. A Mylar foil, 50 μm thick, was placed in front of the counter. Proton groups from the $^{31}P(t,p)^{33}P$ reaction are labeled by the excitation energies (in MeV) of the states populated. The α_0 group corresponds to the $^{31}P(t,\alpha)^{30}Si$ reaction.

Harris, Nagatani, and Olness,[1] the 4.22-MeV level should be almost exclusively populated at 2.5 MeV. On the other hand the "doublet" of states was easily resolved in the γ channel because of the high energy resolution of the detector, but we thought that it was worth having two independent sets of lifetime measurements as a check.

The targets were prepared by evaporating zinc phosphide (Zn_3P_2) onto molybdenum backings 0.03 mm thick. The measurements were done using a 300-μg/cm^2 target placed perpendicular to the beam direction. An additional set of measurements was done at E_t = 3.1 MeV with a 100-μg/cm^2 Zn_3P_2 target positioned at 45° with respect to the beam axis.

The protons were detected by means of an annular silicon surface-barrier counter of 1500-μm thickness and having a 150-mm^2 sensitive area. This counter located at θ_{lab} = 180° and 12 mm away from the target could detect protons emitted between 147 and 163° in the laboratory. A Mylar absorber (50 and 75 μm thick for the 2.5- and 3.1-MeV runs, respectively) was placed in front of the detector to stop the scattered tritons and slow down the α particles from the reaction $^{31}P(t,\alpha)^{30}Si$. Figure 1 shows a typical proton spectrum obtained at E_t = 2.5 MeV.

The γ rays were detected using a 100-cm^3 Ge(Li) detector, having a measured resolution of 3 keV full width at half maximum for the 1.33-MeV γ rays of ^{60}Co, and placed at 4.5 cm from the target. A curve of γ-ray efficiency versus energy was measured *in situ* using a ^{56}Co source.

A typical method of measurements consisted of storing, in four distinct parts of a multichannel analyzer, γ rays in coincidence with the proton groups on which four windows were set. Measurements were alternated between θ_{lab} = 0 and 90° for the Ge(Li) detector with additional measurements

TABLE I. Excitation energies for levels of ^{33}P. Columns 1 and 2 list the initial and final levels between which the major transitions occur. The energies of the corresponding transitions are reported in column 3. These values, corrected for recoil and relativistic effects, give the excitation energies reported in column 4. Column 5 lists the excitation energies from Harris, Nagatani, and Olness (Ref. 1) except the two first states for which the reported values are transition energies from Goosman and Alburger (Ref. 4).

		Present work		Previous work[a]
E_i (MeV)	E_f (MeV)	Transition energy (keV)	Excitation energy E_i (keV)	Excitation energy (keV)
1.43	0	1431.4 ± 0.3	1431.5 ± 0.3	1431.4 ± 0.3 [b]
1.85	0	1847.2 ± 0.3	1847.3 ± 0.3	1847.60 ± 0.15 [b]
1.85	1.43	416.3 ± 0.3		
2.54	0	2537.1 ± 0.5	2537.6 ± 0.5	2540 ± 3 [a,b]
2.54	1.43	1106.8 ± 0.3		
2.54	1.85	691.0 ± 0.4		
3.28	0	3275.1 ± 1.0	3275.5 ± 1.0	3279 ± 4
3.28	1.85	1428.6 ± 0.4		
3.49	1.43	2058.8 ± 0.4	3490.2 ± 1.0	3494 ± 4
3.49	1.85	1642.6 ± 0.3		
3.63	1.43	2195.1 ± 1.0	3626.6 ± 1.0	3631 ± 4
3.63	1.85	1779.1 ± 0.8		
4.05	1.43	2616.6 ± 0.8	4048 ± 1	4053 ± 4
4.05	2.54	1509.5 ± 0.6		
4.19	0	4193.9 ± 3.0	4194 ± 3	4189 ± 12
4.22	1.85	2377.3 ± 0.6	4225 ± 1	4225 ± 4

[a] Reference 1.

[b] Transition energy from Ref. 4.

at $\theta_{\mathrm{lab}} = 55°$ in some cases. Spectra from a set of ^{60}Co, ^{88}Y, and ^{208}Tl (ThC'') sources were taken after each run as a check of gain stability, and every spectrum exhibiting a gain shift greater than 0.5 keV was rejected.

III. METHOD OF ANALYSIS

The experimental attenuation factors $F(\tau)$ were deduced from the energy shifts ΔE in the following way:

$$\Delta E = E_0 \beta_0 \langle \cos\theta \rangle_{\mathrm{av}} F(\tau) ;$$

$\beta_0 = v_0/c$, where v_0 is the initial velocity of the recoiling nucleus; $\langle \cos\theta \rangle_{\mathrm{av}} = Q_1(P) \cos\theta \, Q_1(\gamma)$; θ is the mean angle between the recoil direction and γ counter axis; $Q_1(P)$ and $Q_1(\gamma)$ are the finite solid-angle correction factors for the particle and γ-ray detector, respectively.

The curves $F(\tau)$ versus the lifetime τ were calculated by the method of Blaugrund,[8] considering the slowing down of ^{33}P in ^{31}P, Zn, and Mo. The following values for electronic stopping powers were used: $k_e = 0.164$ (in ^{31}P), $k_e = 0.218$ (in zinc), and $k_e = 0.325$ (in molybdenum). These values were deduced using the ranges and stopping powers tabulated by Northcliffe and Schilling.[9] The specific energy loss due to atomic collisions was calculated using the Lindhard, Scharff, and Schiøtt[10] method.

The factors $F(\tau)$ were calculated by the usual method taking into account the target thickness by dividing it into 10 slices and averaging over the corresponding values. As to the question of errors we know of no direct experimental data on the slowing down of ^{33}P ions in ^{31}P, Zn, and Mo to compare with the theory. We therefore decided to set errors of ±20% on the extrapolated values for the electronic and nuclear stoppings powers k_e and k_n. The error on the target thickness is also ±20%. These errors actually result in a smaller overall theoretical error. Thus, in one example (that of the first excited state of ^{33}P to be discussed later) the ±20% errors due to the target thickness, electronic stopping power, and nuclear stopping power correspond to errors of ±2.8%, ±10.2%, and ±6.9%, respectively, on τ, or to an over-all theoretical error of ±12.6%. When this is combined with the ±11.9% experimental error of the measurement the final error on τ is ±17.3%.

The excitation energies reported in Table I correspond to the energies of the transitions as deduced from the 90° runs corrected for nuclear recoil and relativistic effects.

γ-ray branching ratios were deduced from the intensity ratios measured at 0 and 90°, and using the angular-correlation coefficients given by Harris, Nagatani, Olness.[1] When no coefficient was available, we have assumed that a_4 could be neglected, so that for each branch the net number of counts is given, with usual notation, by

$$N(\theta) = \mathcal{E} I \left[1 + a_2 Q_2 P_2(\cos\theta) \right] ,$$

where $\mathcal{E}$ is the relative efficiency of the Ge(Li) counter measured as explained before. For each branch we then had two equations from which it was possible to obtain I and a_2 and deduce the branching ratios. The normalization factor between the 0 and 90° runs was taken as the collected charge ratio. In the case where 55° runs were available they were used as a check.

IV. RESULTS AND DISCUSSION

All the excitation energies of the ^{33}P levels measured in this work are reported in Table I. The γ-ray branching ratios for the decay of the levels are listed in Table II, and our lifetime measure-

TABLE II. Branching ratios for the transitions from the decay of levels in ^{33}P. Columns 1 and 2 list the initial and final levels between which the transitions occur.

E_i (MeV)	E_f (MeV)	Branching ratios (%)	
		Present work	Previous work[a]
1.43	0	100	100
1.85	0	93 ± 4	92 ± 3
	1.43	7 ± 4	8 ± 3
2.54	0	82 ± 3	88 ± 8
	1.43	10 ± 3	8 ± 4
	1.85	8 ± 3	4 ± 4
3.28	0	47 ± 4	49 ± 8
	1.85	53 ± 4	51 ± 8[b]
3.49	0	<4	<25
	1.43	38 ± 4	38 ± 15
	1.85	62 ± 4	62 ± 15
3.63	0	<3	<6
	1.43	72 ± 3	69 ± 6
	1.85	28 ± 3	31 ± 6
4.05	0	5 ± 3	<10
	1.43	77 ± 4	100
	1.85	<4	<9
	2.54	11 ± 4	<15
	3.28	7 ± 3	
4.19	0	100	100
	1.43	<4	
	1.85	<5	<50
4.22	0	<4	<9
	1.43	<4	
	1.85	100	100

[a] From Ref. 1.

[b] The authors of Ref. 1 could not establish the final state to which this branch connected.

ments are summarized in Table III. In each table, comparisons with previous work are shown. In Fig. 2 we show the γ-ray spectra in coincidence with proton groups to the states at 1.85 MeV and higher. We now discuss the results on the various levels.

1.43-MeV Level

The excitation energy of this state is found to be equal to 1431.5 ± 0.3 keV, in very good agreement with the value of 1431.4 ± 0.3 keV, previously reported by Goosman and Alburger.[4] The lifetime that we have measured, $\tau = 0.60 \pm 0.10$ psec, is also in good agreement with the value given by Currie and Evans[7] as $\tau = 0.79 \pm 0.23$ psec.

The 1.43-MeV level has been shown[1, 11, 12] to be $J = \frac{3}{2}$. It decays to the $\frac{1}{2}^{+}$ ground state by an $L = 1$ and $L = 2$ mixed transition for which an averaged value (from Refs. 1, 11, and 12) of the mixing ratio is $\delta = 0.59 \pm 0.10$. If the 1.43 MeV → 0 transition were of an $M2/E1$ character, with our τ value the $M2$ strength would then be $|M_{M2}|^2 > 140$ W.u., which is unlikely. Thus this transition must be an $M1/E2$ transition, and we confirm the even parity of the 1.43-MeV level as established by Davies, Hardy, and Darcey.[13]

1.85-MeV Level

The excitation energy of the 1.85-MeV level has been measured as 1847.3 ± 0.3 keV, a value in good agreement with the 1847.6 ± 0.15-keV value reported in Ref. 4, and the branching ratio measured in this work is very similar to the one obtained in Refs. 1 and 11. The lifetime is equal to 0.80 ± 0.15 psec and has to be compared with the value of 1.36 ± 0.17 psec quoted from Ref. 7. The agreement is not particularly good, but it should be pointed out that this is a relatively long lifetime with respect to the DSAM, and the results are very dependent on the determination of the parameters.

From previous work,[14] the 1.85-MeV level has been shown to be a $J = \frac{5}{2}$ state decaying to the ground state with an $L = 2$ and $L = 3$ mixed transition, for which $\delta = -(0.02 \pm 0.03)$ (see Ref. 1). Our lifetime value allows us to retain only an $E2/M3$ character because an $M2/E3$ mixing would lead to an $M2$ strength greater than 200 W.u., which is unlikely. Thus we confirm the even parity of the 1.85-MeV level previously established by Davies, Hardy, and Darcey.[13]

2.54-MeV Level

Within the errors, the excitation energy and the branching ratios measured in this work for the 2.54-MeV level are in good agreement with previous measurements.[1, 4, 13] This state has been shown to have $J^{\pi} = \frac{3}{2}^{+}$ and to decay to the ground state with an $E2/M1$ mixed transition. The values for the mixing ratio are $\delta = -(0.16 \pm 0.04)$ or 2.6 ± 0.3. The lifetime that we have measured as equal to 0.070 ± 0.012 psec does not allow us to choose between either of the two possible solutions for δ, since for $\delta = -0.16$ one finds $|M_{M1}|^2 = 2.2 \times 10^{-2}$ W.u. and $|M_{E2}|^2 = 0.35$ W.u. and $\delta = 2.6$ leads to $|M_{M1}|^2 = 2.9 \times 10^{-3}$ W.u. and $|M_{E2}|^2 = 12.6$ W.u.

TABLE III. Summary of lifetime measurements on the excited states of ^{33}P. Unless otherwise specified, the beam energy was 3.1 MeV and the effective target thickness 140 μg/cm^2.

E_i (MeV)	E_f (MeV)	$F(\tau)$	$F(\tau)$ averaged	Present work τ (psec)	Previous work[a] τ (psec)
1.43	0	0.27 ± 0.03	0.27 ± 0.03	0.60 ± 0.10	0.79 ± 0.23
1.85	0	0.21 ± 0.02	0.21 ± 0.02	0.80 ± 0.15	1.36 ± 0.17
2.54	0	0.83 ± 0.02	0.82 ± 0.02	0.070 ± 0.012	
	1.43	0.78 ± 0.08			
	1.85	0.73 ± 0.12			
3.28	0	0.53 ± 0.06		0.21 ± 0.04	
	1.85	0.60 ± 0.09[b]			
3.49	1.43	0.79 ± 0.06	0.72 ± 0.03	0.11 ± 0.02	
	1.85	0.69 ± 0.04			
3.63	1.43	0.73 ± 0.17[c]	0.64 ± 0.12	0.17 ± 0.08	
	1.85	0.54 ± 0.19[c]			
4.05	1.43	0.79 ± 0.07[b]	0.80 ± 0.06[b]	0.085 ± 0.030	
	1.43	0.79 ± 0.15[c]			
	2.54	0.86 ± 0.15[b]			
4.19	0	0.67 ± 0.08[b]	0.67 ± 0.08	0.15 ± 0.05	
4.22	1.85	0.40 ± 0.06[b]	0.40 ± 0.06	0.39 ± 0.10	

[a] From Ref. 7.

[b] $E_t = 3.1$ MeV. Target thickness of 300 μg/cm^2.

[c] $E_t = 2.5$ MeV. Target thickness of 300 μg/cm^2.

3.28-MeV Level

All the previous studies failed to establish whether it was the 1.43- or the 1.85-MeV level that the 3.28-MeV level was cascading through, because of the closeness of the transition energies which would be 1844 and 1431 keV in the former case and 1428 and 1847 keV in the latter case. Our measurements indicate that the 3.28-MeV level decays to the 1.85-MeV level. Figure 3 shows spectra for the 1.43- and 1.85-MeV energy regions of the γ-ray spectra measured in coincidence with proton groups leading to the 1.85-, 3.28-, 4.05-, and 4.19-MeV + 4.22-MeV levels. We know that all these levels except the one at 3.28 MeV, decay directly or indirectly to the 1.43- and 1.85-MeV levels. In this figure it is clear that the transition of 1.85-MeV energy, observed in the decay of the

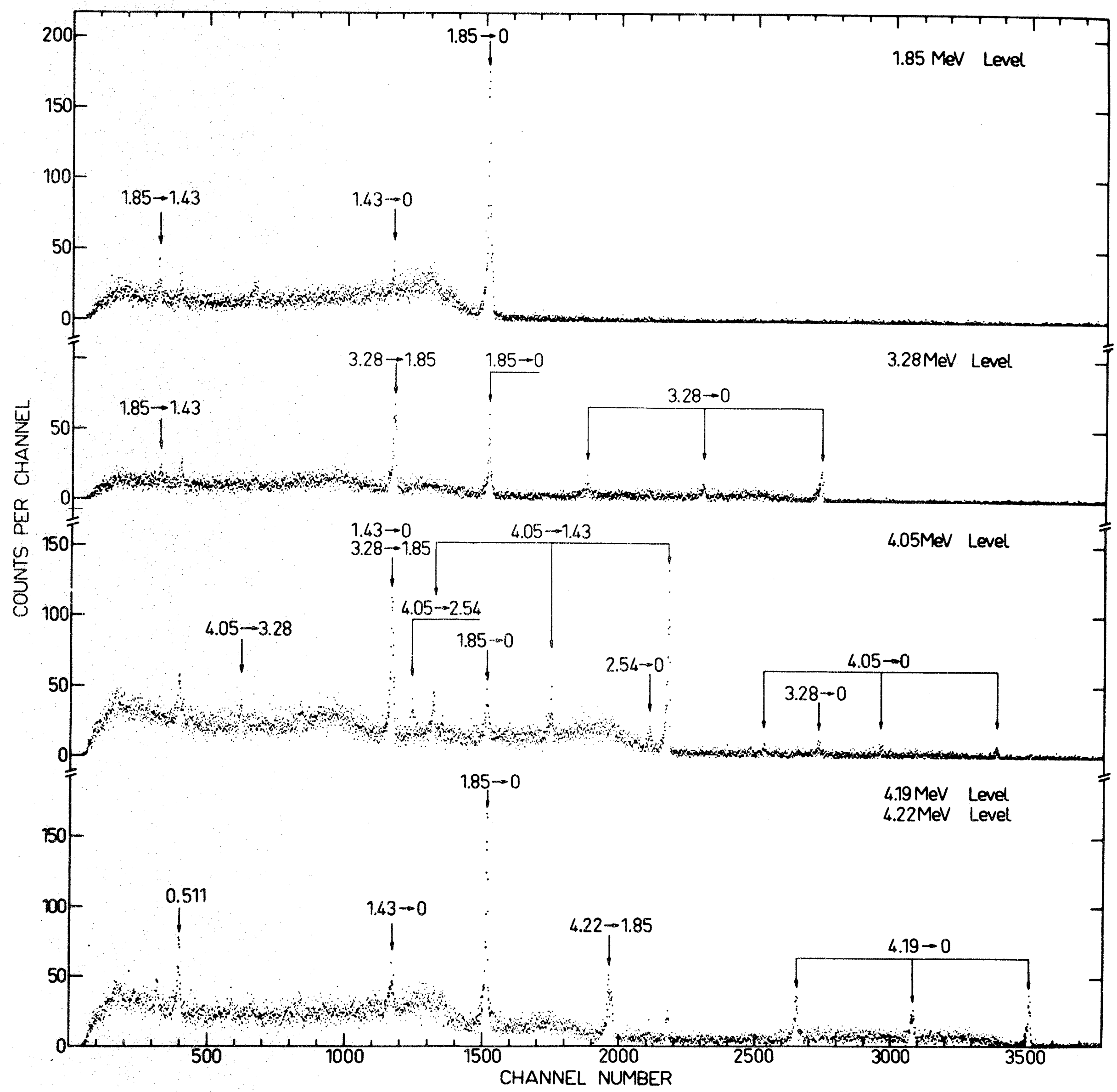

FIG. 2. Spectra of γ rays from the $^{31}P(t, p\gamma)^{33}P$ reaction measured in coincidence with the proton groups leading to the 1.85-, 3.28-, 4.05-, 4.19-, and 4.22-MeV levels in ^{33}P – illustrating the γ-ray deexcitation of these levels. γ-ray peaks are identified according to the levels between which the transitions occur. The triton bombarding energy was $E_t = 3.1$ MeV, and the Ge(Li) γ-ray counter was placed at $\theta_{lab} = 0°$.

3.28-MeV level, corresponds to the "true" 1.85 → 0 transition, whereas the transition of 1428.6 keV is lower than the energy of the "true" 1.43 MeV → 0 transition by 2.8 ± 0.5 keV. Moreover, if one adds the energies of the members of the cascade, as they were measured in this particular spectrum, one obtains $1428.6 \pm 0.4 + 1846.8 \pm 0.4 = 3275.4 \pm 0.6$ keV, a value in very good agreement with the energy of 3275.1 ± 1.0 keV for the crossover transition.

Another argument is based on the fact that the $F(\tau)$ values measured for the 3.28 → 0 transition and the presumed 3.28 → 1.85 transition are in good agreement and lead to a lifetime $\tau = 0.21 \pm 0.04$ psec (see Table III). If this latter transition were in fact 1.43 → 0, then the $F(\tau)$ would have to be such that the lifetime would be longer than 0.6 psec, which is obviously not the case.

We have, therefore, established that the 3.28-MeV level decays to the second excited state with a branch of $(53 \pm 4)\%$, the other branch equal to $(47 \pm 4)\%$ going to the ground state. Such a branching ratio is consistent with the one measured by Harris, Nagatani, and Olness.[1] Both results are in contradiction to the 12% limit on a ground-state branch set by Hardie *et al.*[12] and allow us to rule out this possibility. Knowing, now, the decay mode of the 3.28-MeV level the results of Harris, Nagatani, and Olness[1] from the p-γ angular correlations have been reanalyzed.[15] The data can still be fitted with $J = \frac{3}{2}$ and $\frac{5}{2}$. If $J = \frac{3}{2}$, the 3.28 → 0 (A) and 3.28 → 1.85 (B) transitions are essentially pure dipole transitions. In the $\frac{5}{2}$ assumption, the correlations are consistent with a pure quadrupole character (i.e., no $L = 3$) for the crossover transition and a mixed transition $\delta[(L=2)/(L=1)] \simeq 0.5$ for the branch to the 1.85-MeV level. We have calculated the strength of the A and B transitions for all the possible multipolar characters allowed by $J^\pi = \frac{3}{2}^\pm$ and $\frac{5}{2}^\pm$ for the 3.28-MeV level. In case where $J^\pi = \frac{3}{2}^\pm$ and $\delta = 0$ we find $|M_{M1}|^2 = 0.2 \times 10^{-2}$ W.u. or $|M_{E1}|^2 = 6 \times 10^{-5}$ W.u. for A and $|M_{M1}|^2 = 2.7 \times 10^{-2}$ W.u. or $|M_{E1}|^2 = 8 \times 10^{-4}$ W.u. for B. All these values are acceptable with respect to the compilation of Skorka, Hertel, and Retz-Schmidt.[16] It is therefore impossible to exclude any of the possibilities. If $J^\pi = \frac{5}{2}^\pm$, then assuming $\delta = [L = 3/L = 2] = 0.10$ for the transition A, one would obtain $|M_{E2}|^2 = 0.8$ W.u. and $|M_{M3}|^2 = 4960$ W.u. or $|M_{M2}|^2 = 26$ W.u. and $|M_{E3}|^2 = 148$ W.u. This result indicates clearly that $\delta = 0$ and that the 3.28-MeV level decays to the ground state by a pure quadrupole transition. Similar calculations for transition B shows that with $\delta \simeq 0.5$, $|M_{M1}|^2 = 2.2 \times 10^{-2}$ W.u., and $|M_{E2}|^2 = 11$ W.u. for positive parity of the 3.28-MeV state and $|M_{E1}|^2 = 6.5 \times 10^{-4}$ W.u. and $|M_{M2}|^2 = 369$ W.u. for negative parity. The latter value excludes a negative parity in the assumption of a $\frac{5}{2}$ spin.

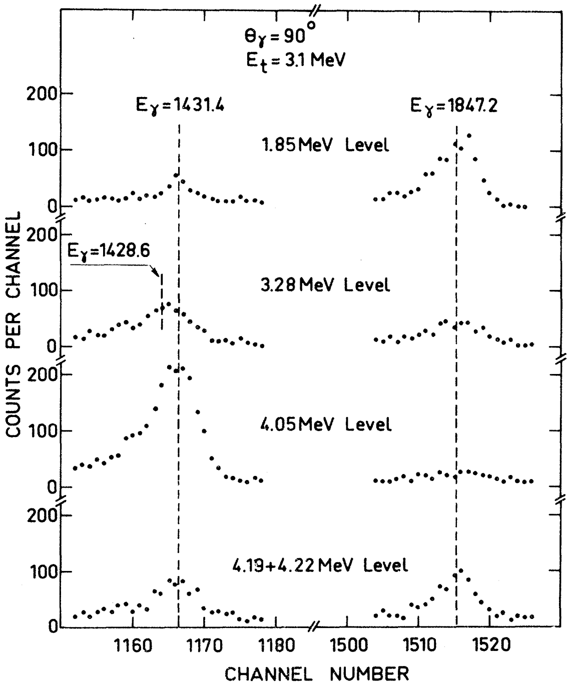

FIG. 3. Partial spectra of γ rays from the ^{31}P$(t, p\gamma)$-^{33}P reaction measured at $\theta_\gamma = 90°$, in coincidence with the proton groups leading to the 1.85-, 3.28-, 4.05-, 4.19-, and 4.22-MeV levels in ^{33}P. The positions of the 1.43 MeV → 0 and 1.85 MeV → 0 transitions, labeled as $E_\gamma = 1431.4$ keV and $E_\gamma = 1847.2$ keV, respectively, are indicated by dotted lines. In the spectrum corresponding to the decay of the 3.28-MeV level the peak in the region of 1.43-MeV energy is clearly displaced. It corresponds to the transition 3.28 MeV → 1.85 MeV for which the energy is 1428.6 keV.

To summarize, our results, in conjunction with previous work, restrict the spin and parity of the 3.28-MeV level to $J^\pi = \frac{3}{2}$ or $\frac{5}{2}^+$.

3.49-MeV Level

From previous work[1, 12] this state has been found to be $J = \frac{3}{2}$ or $\frac{5}{2}$, and decays to the first two excited states with mixings of dipole and quadrupole transitions. The lifetime is $\tau = 0.11 \pm 0.02$ psec.

If $J = \frac{3}{2}$, considering that $\delta = 1.35 \pm 0.2$ for the 3.49 → 1.43 transition as indicated in Ref. 1, it is then possible to restrict the parity assignment to positive because negative parity would imply a strong $M2$ transition of 255 W.u., which is very unlikely. Nevertheless, this value of δ is a weighted average of two different results[1, 12] from which the possible value $-3.8 \leq \delta \leq 0$ has been removed. This latter value does not exclude a negative parity so that an even parity assignment may still be regarded as questionable.

In conclusion, our results support the character $J^\pi = \frac{3}{2}^{(+)}$ or $\frac{5}{2}$ for the 3.49-MeV level.

3.63-MeV Level

This state has been shown[1, 12] to be $J = \frac{7}{2}$ and to decay to the first excited state by an almost pure quadrupole transition ($\delta = 0.06 \pm 0.07$) and to the second excited state also with an essentially pure dipole transition ($\delta = 0.1 \pm 0.1$). The lifetime that we have measured for this state is $\tau = 0.17 \pm 0.08$ psec and leads to an $M2$ strength of 357 W.u. for the $3.63 \rightarrow 1.43$ transition in the case where the initial state would be $J^\pi = \frac{7}{2}^-$. This is clearly improbable and indicates a positive parity for the 3.63-MeV level. Even a small $M3$ admixture of $\delta = 0.01$ would correspond to an $M3$ strength of 1560 W.u., which is obviously impossible. Therefore the value δ for the $3.63 \rightarrow 1.43$ transition can certainly be reduced to $\delta = 0 \pm 0.01$. Our results establish that the 3.63-MeV level has a positive parity as suspected by Harris, Nagatani, and Olness[1] by lifetime restrictions.

4.05-MeV Level

As may be seen in Fig. 2 the main γ-ray line in coincidence with protons to the 4.05-MeV level corresponds to the transition to the first excited state, but weaker transitions are also observed to the ground state and to the states at 2.54 and 3.28 MeV. The excitation energy of this state is 4048 ± 1 keV and Doppler-shift measurements, performed for the transitions to the 1.43- and 2.54-MeV states, lead to the lifetime result $\tau = 0.085 \pm 0.030$ psec.

The existence of a transition to the ground state ($J^\pi = \frac{1}{2}^+$) allows us to exclude the possibility $J = \frac{7}{2}$ for the 4.05-MeV state, in agreement with the results of Harris, Nagatani, and Olness.[1] Such a transition, taking our lifetime measurement into account, would require prohibitively large strengths $|M_{E3}|^2 = 890$ W.u. or $|M_{M3}| = 3 \times 10^4$ W.u. Harris, Nagatani, and Olness have restricted the spin to $\frac{3}{2}$ or $\frac{5}{2}$, and set limits on the value of the mixing parameter δ of the transition to the first excited state. For $J = \frac{3}{2}$ they have found $|\delta| > 8.1$. Such a value, combined with the lifetime, allows us to exclude the $\frac{3}{2}^-$ possibility corresponding to a strength $|M_{M2}|^2 > 300$ W.u., as well as the $\frac{3}{2}^+$ possibility, for which the strength $|M_{M1}|^2 < 2 \times 10^{-4}$ W.u. For $J = \frac{5}{2}$, Harris, Nagatani, and Olness have measured $\delta = -(0.19^{+0.05}_{-0.02})$. Assuming a negative parity, we find then a strength $|M_{M2}|^2 = 13 \pm 4$ W.u. Such a large enhancement leads us to conclude that the parity is more probably positive so that $J^\pi = \frac{5}{2}^{(+)}$.

4.19-MeV Level

As may be seen in Fig. 2 the only observed decay mode for the 4.19-MeV level is a γ transition to the ground state. The excitation energy deduced from the 90° spectrum is 4194 ± 3 keV, and the lifetime measurement yields the following result: $\tau = 0.15 \pm 0.05$ psec.

The angular-correlation measurements[1] indicate that the spin of this level may either be $\frac{5}{2}$ or $\frac{7}{2}$. The $\frac{7}{2}$ value can be excluded because the short value of the lifetime would imply an enhancement of several orders of magnitude for the $L = 3$ transition to the ground state. Thus, we conclude that the spin is $\frac{5}{2}$. A negative-parity assignment to this level, combined with our lifetime result, would correspond to an $M2$ strength of 20 W.u., so that the parity is more probably positive.

4.22-MeV Level

This level decays predominantly to the 1.85-MeV level; by inspection of Fig. 2 no evidence is seen for a ground-state transition. The excitation energy has been measured as 4225 ± 1 keV, and the life-

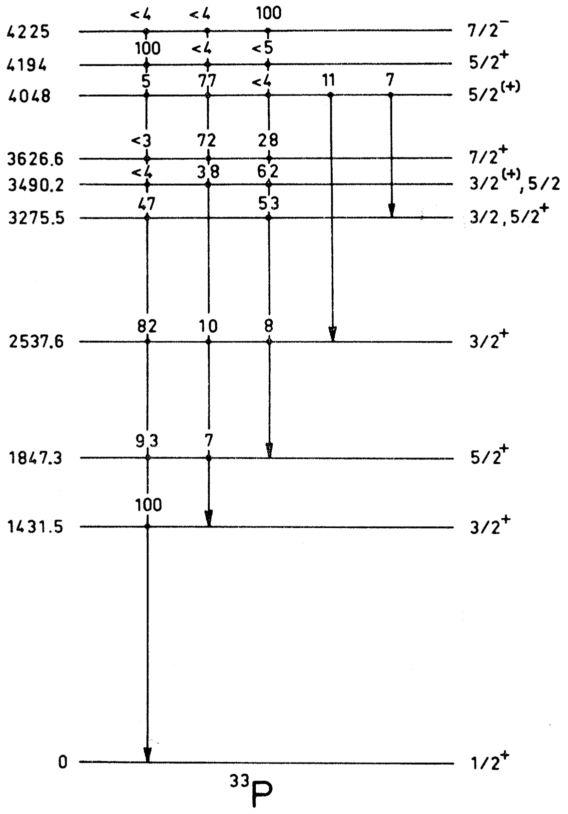

FIG. 4. ^{33}P level scheme summarizing information obtained in the present work on excitation energies, branching ratios, spins and parities for levels of $E_{\text{ex}} < 4.3$ MeV.

TABLE IV. Comparisons between experimental and theoretical values of $B(M1)$ and $B(E2)$. The experimental values are calculated from the lifetimes and branching ratios measured in the present work and from δ mixing ratios of Ref. 1. The theoretical values are taken from calculations of Wildenthal *et al.* (Ref. 6) and Glaudemans, Endt, and Dieperink (Ref. 5).

					Theory					
Initial state (MeV)	Final state (MeV)	$\delta(E2/M1)$	Experimental $100\times B(M1)(\mu_N^2)$	Experimental $B(E2)$ (e^2 fm^4)	$100\times B(M1)(\mu_N^2)$ Ref. a	$100\times B(M1)(\mu_N^2)$ Ref. b	$100\times B(M1)(\mu_N^2)$ Ref. c	$B(E2)$ (e^2 fm^4) Ref. a	$B(E2)$ (e^2 fm^4) Ref. b	$B(E2)$ (e^2 fm^4) Ref. c
1.43	0	(0.59 ± 0.10)	2.3	60	0.2	3.4	2	40	27	28
1.85	0	∞		44				29	25	27
2.54	0	$-(0.16\pm0.04)$	4	2.1	15	10	8.1	0.1	13	16
		(2.6 ± 0.3)	0.5	79	15	10	8.1	0.1	13	16
3.63	1.43	∞		67						47
3.63	1.85	(0.1 ± 0.1)	1.6	0.75			0.0			43

[a] From Ref. 6 with FPSDI.
[b] From Ref. 6 with MSDI.
[c] From Ref. 5.

time measurement result is $\tau=0.39\pm0.10$ psec.

Previous angular distribution measurements of protons from the ^{31}P$(t,p)^{33}$P reaction have shown that the parity of this state is negative (Ref. 13) and the angular-correlation analysis of Harris, Nagatani, and Olness[1] has further restricted the spin to be $J^\pi=\frac{7}{2}^-$. Our lifetime measurement indicates then that the strength of the $E1$ transition to the second excited state is $|M_{E1}|^2=1.8\times10^{-4}$ W.u. A small admixture of $M2$ component to the transition cannot be excluded, but the mixing parameter is probably small: $|\delta|<0.25$ corresponding to $|M_{M2}|^2<9$ W.u. in agreement with the results of Harris, Nagatani, and Olness,[1] $|\delta|<0.1$.

V. SUMMARY AND DISCUSSION

The main interest of this work was to measure the lifetimes of the nine bound states of ^{33}P below an excitation energy of 4.3 MeV and the results are summarized in Table III. The experimental technique used has allowed us to measure also simultaneously accurate excitation energies, decay modes, and branching ratios for these levels. We have set more restrictive limits on weak branches and have observed transitions not seen before. We have also shown that the 3.28-MeV level decays to the 1.85-MeV level with a branch of 53%, the remaining strength going to the ground state. These results are listed in Tables I and II and are summarized in Fig. 4. Our results, in conjunction with previous particle-γ angular-correlation and mixing-ratio measurements, enable us to establish the following sequence, indicated in Fig. 4, of spin and parity for the nine first excited states [MeV (J^π)] of ^{33}P: 1.43 $(\frac{3}{2}^+)$, 1.85 $(\frac{5}{2}^+)$, 2.54 $(\frac{3}{2}^+)$, 3.28 $(\frac{3}{2},\frac{5}{2}^+)$, 3.49 $(\frac{3}{2}^+,\frac{5}{2})$, 3.63 $(\frac{7}{2}^+)$, 4.05 $(\frac{5}{2}^{(+)})$, 4.19 $(\frac{5}{2}^+)$, and 4.22 $(\frac{7}{2}^-)$.

We shall now compare our results to recent shell-model calculations of Wildenthal *et al.*[6] and Glaudemans, Endt, and Dieperink[5] for $A=33$. In these calculations the model space was chosen such that all $2s_{1/2}$ and $1d_{3/2}$ states and up to two holes in the $1d_{5/2}$ shell were taken into account, the $1s$ and $1p$ shells being filled at all times. For one of the Hamiltonians, Wildenthal *et al.*[6] use an effective surface δ interaction modified with isospin-dependent monopole terms (MSDI). These authors have also developed an alternative effective Hamiltonian (FPSDI) starting with an MSDI Hamiltonian and then treating the two-body matrix elements which do not involve the $d_{5/2}$ orbit as independent free parameters, adjusted to fit experimental level energies. Glaudemans, Endt, and Dieperink[5] have used an MSDI Hamiltonian with empirically modified $M1$ and $E2$ operators.

The reduced transition probabilities calculated by Wildenthal *et al.* and Galudemans, Endt, and Dieperink are reported in Table IV, together with the corresponding experimental values deduced from the present results. One can see that in all but one case the strong $E2$ transitions are calculated to be strong, and for those strong transitions the relative strength is well reproduced by the calculations. The qualitative features of $M1$ transitions are also reproduced by the calculation, since moderately weak transitions are calculated to be fairly weak. These conclusions fit well into the framework of the general remarks which can be made about the predictions relative to the transition strengths in the nuclei $A=30$ to 35.

Note added in proof: Similar lifetime measurements on ^{33}P levels have been carried out by Poletti, Bardin, Pronko, and McDonald.[17] In general the present results are in excellent agreement with those of Poletti *et al.*

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*Visitor from Brookhaven National Laboratory, Upton, New York 11973

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Distorted-Wave Born-Approximation Analysis of ^{36,38}Ar(d,p) to Neutron Resonances in ^{37,39}Ar

W. R. Coker

Center for Nuclear Studies, University of Texas, Austin, Texas 78712*

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^{36,38}Ar (d,p) angular distributions at 9- and 10-MeV incident energy, for 13 neutron-unbound states in ^{37,39}Ar, are described in terms of conventional distorted-wave Born-approximation theory using complex-energy eigenstates as form factors, and spectroscopic information is extracted which is consistent with previous studies of the bound neutron states of ^{37,39}Ar.

I. INTRODUCTION

In studies of the reaction ^{36}Ar$(d,p)^{37}$Ar at 9.16 MeV,[1] and ^{38}Ar$(d,p)^{39}$Ar at 10.06 MeV[2] it has been found that a number of neutron unbound states in ^{37}Ar and ^{39}Ar are populated. Sen *et al.*[1,2] were able to obtain angular distributions for these states in 5° steps over c.m. angles from 26 to 146°; specifically, data are available for states at 8.89 and 9.01 MeV in ^{37}Ar, and at 6.79, 7.00, 7.06, 7.14, 7.22, 7.34, 7.40, 7.50, 7.56, 7.63, and 7.73 MeV in ^{39}Ar.

Presented here are distorted-wave Born-approximation (DWBA) analyses of these 13 angular distributions, making use of complex-energy eigenstates to described the resonance states. It is shown that use of complex-energy eigenstates permits extraction of spectroscopic factors consistent with the usual bound-state single-particle spectroscopic factors.

II. COMPLEX-ENERGY EIGENSTATES

The complex-energy eigenstate, often called a Gamow state, is either of two equivalent facto. making up the residue of the Green's function of the system, at the pole corresponding to a given resonance.[3-5] Thus it is closely analogous to the bound-state function, which is again either factor of the residue of the Green's function of the system at the pole corresponding to a given bound state. It is straightforward to show that complex-energy eigenfunctions have normalization and orthogonality properties analogous to bound states,[6] and can form part of a basis for eigenstate expansion, in the sense that a quantum mechanical state Ψ can, under weak restrictions, be expanded as a sum over discrete bound and Gamow states, plus a contour integral over continuum states.[7] The choice of contour determines the number of Gamow states included in the discrete sum, and also the set of functions Ψ which may be so expanded. The situation is quite reminiscent of Regge-type representations of the scattering amplitude, in many ways.

Some confusion has resulted over the connection of Gamow states to the familiar Hilbert spaces of scattering theory. Berggren[8] has shown that norms can be introduced for Gamow states such that many analogous mathematical properties,