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Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Level structure and $E2$ strength from the $^{31}P(n,\gamma)^{32}P$ reaction

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An investigation of the thermal neutron radiative capture reaction $^{31}P(n,\gamma)^{32}P$ has yielded data with high statistical precision. Ninety-eight transitions have been assigned to a derived decay scheme and the neutron separation energy was found to be 7935.70(4) keV. Three $E2$ transitions have been identified with average strength $\overline{B(E2)\downarrow}=4.2^{+1.6}_{-2.5}\ e^2\mathrm{fm}^4/\mathrm{MeV}$. This value is consistent with the Axel-Brink hypothesis.

An investigation of the electric quadrupole strength throughout the entire mass region has been underway here for some time. A favorable case, in which three such transitions can arise, is the $^{31}P(n,\gamma)^{32}P$ reaction, a reaction that has not been studied in detail since the early work of Lycklama and Kennett[1] and Van Middelkoop.[2] The observation of $E2$ transitions requires spectra with high statistical precision; consequently, such measurements afford an opportunity to obtain high quality level structure information. Here we report upon markedly improved level data for ^{32}P and examine the significance of the $E2$ strengths observed.

The measurements were conducted at the McMaster University reactor[3] using a pair spectrometer[4] with a resolution of 3.8 keV for 5 MeV photons. A 0.5 g phosphorus sample was counted for a period of 300 h, which yielded a spectrum in which a 1 percent transition at 5 MeV had an area of 17 000 counts. The energy and relative intensity calibration was obtained through the mixed source technique in which the extensively studied $^{14}N(n,\gamma)^{15}N$ reaction was used.[5,6] More complete details of the experimental procedures used and the spectral analysis methods employed have been previously reported.[7,8] The system used precluded examination of the low energy portion of the spectrum, and hence only transitions above 1.7 MeV are reported. Sample hydroscopy combined with the excitation via inelastic neutron scattering of the 2233 keV state in ^{31}P resulted in strong and masking interference from 2215 to 2240 keV. The former problem made it necessary to obtain the absolute calibration of intensity through the use of a mixture of melamine ($C_3H_6N_6$) and $AlPO_4$.

Table I presents the 98 transitions observed with intensity greater than 0.05% and placed within a derived level scheme, a number double that observed previously.[1,2] (Some 45 transitions remain unassigned, accounting for 2 percent of the strength.) Photon energies have been corrected for recoil and the error includes that from both scale calibration and the ^{15}N separation energy.[9] Based upon the 172(6) mb ^{31}P (Ref. 10) and 77(2) mb ^{14}N (Ref. 11) cross sections and the efficiency calibration, the intensity uncertainty is 5 percent, in addition to the spectral statistical factors.

The level energies were obtained through an iterative procedure based upon the method of maximum likelihood. In this treatment, a level must have at least two transitions coupling it with other states to be considered. The results obtained are given in Table II, along with associated information. Based upon the mixed source calibration, the intensity leaving the compound state appears to be completely accounted for, and if the low lying levels are examined most of the intensity required to feed the ground state is seen to be present. The quantity $\sum_i E_i I_i / Q$ yields a value of 98% when corrected for the low energy cutoff, well within error of the expected value of 100%. The recommended level energies[12] are also tabulated. The present results are seen to have a precision increase of almost an order of magnitude over the previous level energies,[12] with the former showing a trend to lower values. The neutron separation energy of 7935.70(4) keV is slightly lower than the earlier value of 7936.7(6) keV (Ref. 12) and the recent estimate of 7936.5(5) given by Wapstra and Audi.[13]

The target spin of $J_f=\frac{1}{2}^+$ coupled to an s-wave neutron leads to spins of 0^+ or 1^+ for the capture state.[10] Transitions leading to final states characterized by $J=3^+$ can be interpreted as being $E2$ in nature, provided that the spin assignment is certain and the p-wave capture contribution is negligible. Levels that have been identified as 3^+ on the basis of a critical assessment of reported data for ^{32}P (Ref. 12) are given in Table III, along with the observed primary γ-ray energy and intensity. The fractional contribution from p-wave capture in the region of neutron energies extending over the area of peak integration is calculated to be 1.6×10^{-7}. This contribution may therefore be neglected. The strongest of these $E2$ transitions, that at 6181 keV which populates the 1755 keV state, is shown in the spectral region illustrated in Fig. 1.

Macklin and Mughabghab[14] estimate a 103 mb direct capture contribution to the 172 mb cross section. Estimates of the direct capture $E2$ contribution[15] show this to be negligible in this case because of the very small d-wave spectroscopic factors.[12] We therefore interpret these transitions as arising from resonance capture, which we attribute to the remaining 69 mb. An estimate of the $J=1^+$ channel con-

TABLE I. Transitions assigned to the ^{31}P(n,γ)^{32}P reaction. Photon energies have been corrected for nuclear recoil.

Energy (keV)	Intensity (%)	Assignment	Energy (keV)	Intensity (%)	Assignment
1739.53(6)	1.37(7)	7936 − 6196	4026.84(22)	0.06(1)	5350 − 1323
1778.94(7)	1.10(6)	4009 − 2230	4035.21(15)	0.09(1)	4548 − 513
1806.21(18)	0.40(2)	7936 − 6130	4200.24(9)	3.4(2)	5350 − 1149
1873.44(4)	1.9(1)	7936 − 6062	4359.98(3)	1.09(6)	5509 − 1149
1941.13(3)	2.6(1)	3264 − 1323	4364.74(2)	4.7(2)	4877 − 513
2099.37(12)	0.36(2)	2177 − 78	4455.68(7)	0.21(1)	5779 − 1323
2114.55(2)	7.5(4)	3264 − 1149	4491.36(2)	2.2(1)	7936 − 3444
2151.54(2)	7.3(4)	2230 − 78	4552.45(22)	0.05(1)	5701 − 1149
2156.83(2)	8.6(4)	7936 − 5779	4580.43(12)	0.10(1)	5093 − 513
2426.40(3)	1.83(9)	7936 − 5509	4629.56(4)	0.50(3)	5779 − 1149
2431.62(10)	0.30(2)	4661 − 2230	4632.36(9)	0.15(1)	4711 − 78
2514.95(4)	1.05(5)	4692 − 2177	4661.49(2)	3.7(2)	4661 − 0
2579.34(6)	0.45(2)	2657 − 78	4671.73(2)	12.8(6)	7936 − 3264
2586.13(2)	6.0(3)	7936 − 5350	4691.97(15)	0.08(1)	4692 − 0
2609.13(13)	0.19(1)	5350 − 2740	4739.44(7)	0.19(1)	6062 − 1323
2657.49(3)	1.79(9)	2657 − 0	4799.36(7)	0.21(1)	4877 − 78
2686.28(12)	0.19(1)	4009 − 1323	4877.16(3)	0.70(4)	4877 − 0
2712.73(8)	0.31(2)	4036 − 1323	4912.85(3)	0.77(4)	6062 − 1149
2740.41(4)	0.63(3)	2740 − 0	4932.0(15)[a]	0.03(2)	7936 − 3005
2842.90(11)	0.19(1)	7936 − 5093	5072.33(13)	0.09(1)	5072 − 0
2860.01(9)	0.23(1)	4009 − 1149	5182.91(13)	0.09(1)	5696 − 513
2863.33(2)	2.4(1)	7936 − 5072	5195.43(2)	1.37(7)	7936 − 2740
2886.25(2)	4.3(2)	4036 − 1149	5266.00(2)	3.2(2)	5779 − 513
2931.20(15)	0.14(1)	3444 − 513	5278.25(2)	1.25(6)	7936 − 2657
3058.38(2)	7.2(4)	7936 − 4877	5349.57(7)	0.19(1)	5350 − 0
3120.07(7)	0.30(2)	5350 − 2230	5432.67(11)	0.10(1)	6582 − 1149
3122.77(23)	0.08(1)	4877 − 1755	5509.08(27)	0.04(1)	5509 − 0
3132.31(9)	0.20(1)	5350 − 2218	5549.51(9)	0.14(1)	6062 − 513
3186.05(2)	2.1(1)	3264 − 78	5617.99(21)	0.05(1)	6130 − 513
3224.90(6)	0.32(2)	7936 − 4711	5623.31(9)	0.13(1)	5701 − 78
3243.67(9)	0.19(1)	7936 − 4692	5683.65(4)	0.40(2)	6196 − 513
3264.30(7)	0.26(1)	3264 − 0	5700.79(3)	0.67(3)	5779 − 78
3274.32(2)	5.4(3)	7936 − 4661	5706.03(2)	2.7(1)	7936 − 2230
3338.49(11)	0.15(1)	4661 − 1323	5717.58(4)	0.42(2)	7936 − 2218
3366.33(3)	0.75(4)	3444 − 78	5758.9(5)[a]	0.014(3)	7936 − 2177
3387.94(10)	0.16(1)	7936 − 4548	5778.76(3)	0.93(5)	5779 − 0
3444.34(3)	0.77(4)	3444 − 0	5983.90(24)	0.05(1)	6062 − 78
3483.55(9)	0.18(1)	5701 − 2218	6062.27(4)	0.44(2)	6062 − 0
3512.15(4)	0.45(2)	4661 − 1149	6118.24(8)	0.14(1)	6196 − 78
3518.75(4)	0.46(2)	5696 − 2177	6129.66(8)	0.12(1)	6130 − 0
3522.92(2)	14.4(7)	4036 − 513	6181.07(19)	0.05(1)	7936 − 1755
3549.15(3)	0.92(5)	5779 − 2230	6196.38(4)	0.37(2)	6196 − 0
3554.69(4)	0.52(3)	4877 − 1323	6503.95(5)	0.28(1)	6582 − 78
3561.02(13)	0.12(1)	4711 − 1149	6581.86(6)	0.21(1)	6582 − 0
3900.16(2)	19.2(10)	7936 − 4036	6613.21(14)	0.08(1)	7936 − 1323
3923.13(2)	1.75(9)	5072 − 1149	6786.27(2)	15.5(8)	7936 − 1149
3926.75(2)	2.5(1)	7936 − 4009	7422.97(2)	4.9(3)	7936 − 513
3930.80(3)	0.70(4)	4009 − 78	7857.68(3)	0.91(5)	7936 − 78
3957.59(3)	0.56(3)	4036 − 78	7935.75(4)	0.40(2)	7936 − 0
4008.86(3)	0.81(4)	4009 − 0			

[a] These transitions, which have intensities below the 0.05% intensity cutoff imposed when constructing this table, have been included since they have been identified as having an *E*2 nature.

TABLE II. Levels deduced in ^{32}P from thermal neutron capture on ^{31}P. Previous level energies are from Ref. 12.

No.	Energy (keV)	Intensity (%) In	Out	Previous value (keV)
1	0.00	11	· · ·	0.0
2	78.02(5)	15	· · ·	78.1(1)
3	512.69(5)	28	· · ·	513.0(2)
4	1149.35(5)	36	· · ·	1149.7(2)
5	1322.81(6)	4.3	· · ·	1323.2(2)
6	1754.61(15)	0.13	· · ·	1754.5(2)
7	2177.10(6)	1.5	0.4	2177.8(3)
8	2217.98(19)	0.8	· · ·	2218.9(3)
9	2229.63(6)	5.3	7.3	2229.8(6)
10	2657.46(5)	1.3	2.2	2657.8(6)
11	2740.31(6)	1.6	0.6	2744.7(14)
12	3263.98(6)	13	13	3264.0(4)
13	3444.34(5)	2.2	1.7	3445.0(3)
14	4008.89(7)	2.5	3	4007.1(9)
15	4035.58(5)	19	19	4036.2(5)
16	4547.80(9)	0.16	0.01	
17	4661.43(5)	5.4	4.7	4662.8(4)
18	4692.04(5)	0.2	1.1	
19	4710.62(15)	0.3	0.3	
20	4877.35(6)	7.2	6.2	4877.6(5)
21	5072.42(6)	2.4	1.8	5073.1(9)
22	5092.94(17)	0.2	0.1	
23	5349.61(7)	6.0	4.4	5349.8(6)
24	5509.31(5)	1.8	1.1	5509(2)
25	5695.83(8)	· · ·	0.5	
26	5701.46(10)	· · ·	0.4	5700(3)
27	5778.78(5)	8.5	6.5	5779.5(6)
28	6062.23(5)	1.9	1.6	6062.6(13)
29	6129.75(24)	0.4	0.2	6131(8)
30	6196.32(6)	1.4	0.9	6197(2)
31	6581.94(6)	· · ·	0.6	6582(3)
32	7935.70(4)	· · ·	100.0	7936.7(6)

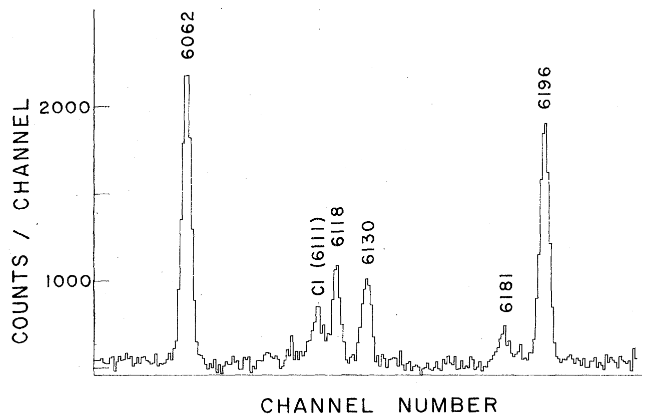

FIG. 1. A 240 channel segment of the 8192 ^{31}P$(n,\gamma)^{32}$P spectrum is shown. Here the 6062 keV transition has an intensity of 0.44%, while that at 6181 keV, which is an $E2$ transition, exhibits an intensity of about 1 in 2000 capture events. The contaminant chlorine is indicated by the presence of its very intense (20%) 6111 keV transition. This, along with the other contaminants, iron, titanium, and aluminum were identified by their strong transitions and corrections were made for their spectral contributions. The gain is 0.85 keV/channel.

tribution to this component may be obtained from consideration of the intensity distribution of the magnetic dipole transitions. Six transitions populate 0^+ or 2^+ states which can only have as their genesis the 1^+ state. The average strength of this class will be denoted by $\langle \Gamma_\gamma / E^3 \rangle_+$ while transitions to final states with $J=1^+$, which may be populated by either reaction channel, will have average strength given by $\langle \Gamma_\gamma / E^3 \rangle$. The ratio $F = \langle \Gamma_\gamma / E^3 \rangle_+ / \langle \Gamma_\gamma / E^3 \rangle$ is then a direct measure of the $J=1^+$ channel contribution. The observed value $F=1.1$ is consistent with the hypothesis that resonance capture proceeds entirely through the $J=1^+$ channel. The influence of Porter-Thomas[16] fluctuations renders this value imprecise; however, because of the low level density in this mass region, it is highly likely that only one state contributes to the thermal neutron capture cross section. We therefore conclude that the resonance capture is primarily due to a $J=1^+$ bound state.

To calculate the strength function, estimates of the radiative width and level spacing must be available. Only one $J=1^+$ resonance, that at 156.9 keV, has been identified.[12] The latest measurements[14] give a width of 3.3 eV, implying 3.2 eV at thermal energy. An analysis of four resonances in ^{28}Si and five in ^{32}S yields an average width of 2.9 eV. We have adopted 3.1 eV as the width estimate for the following calculation. The spacing of $J=1^+$ levels at the separation energy was calculated to be 124 keV, using the level density formula of Gilbert and Cameron.[17] Table III summarizes the results of the analysis, wher the estimates of $\overline{B(E2)\downarrow}$ are obtained directly from the partial widths, the level density and the transition energy as described on Lone.[18]

These results may be tested for consistency with the Axel-Brink hypothesis.[19] As described in more detail elsewhere,[20] the $E2$ strength function is derived from the systematic properties of the isoscalar and isovector giant quad-

TABLE III. Electric quadrupole strengths in ^{32}P.

Level energy (keV)	Photon energy Expected (keV)	Observed (keV)	Intensity (%)	$B(E2)$ (e^2fm^4/MeV) Expt.	Calc.
1754.6	6181.09(15)	6181.07(15)	0.052(5)	4.9(5)	3.6
2177.1	5758.60(6)	5758.9(5)	0.014(3)	1.9(4)	3.8
3004.8	4930.9(5)	4932.0(15)	0.03(2)	9(6)	4.3
			Average	$4.2^{+1.6}_{-2.5}$	

rupole resonances, taking into account exchange effects on the energy-weighted sum rule for the isovector component. The average transition probability calulated in this way is given by $\overline{B(E2)\downarrow}=3.9\ e^2\mathrm{fm}^4/\mathrm{MeV}$. This value is consistent with the observation of $4.2^{+1.6}_{-2.5}\ e^2\mathrm{fm}^4/\mathrm{MeV}$. The quoted average is midway between the unweighted mean, the estimate for error-free Porter-Thomas samples, and the weighted average reflecting experimental uncertainties. The uncertainty reflects the 50% confidence limits for a χ^2 distribution with three degrees of freedom.

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