selection rules transitions, which are average values for nuclei with $A<20$. It is expected that the inhibition factors should be less for Ca^{40}, so that estimates are conservative. There are many other possible branches with comparable expected widths. From the above, we conclude that if this were a 3^- state, the ground-state branch would be expected to be less than 0.5%. It is measured to be at least 50%, thus making a 3^- assignment unlikely.

All existing data favor, or do not exclude, 1^- as the spin and parity for a state at 6.94 MeV. The ground-state branch observed in coincidence with a strong inelastic α group is not from a spin-2 state, is, with very high probability, not from a spin-3 state, and with little doubt is from a spin-1 state.

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Lifetime of the First Excited State of P^{32}

R. A. Mendelson, Jr., and R. T. Carpenter
Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa

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The mean life of the first excited state of P^{32}(77 keV, 2^+) has been measured to be $(5.2_{+0.9}^{-0.5})\times10^{-10}$ sec. The state was formed by the $P^{31}(d,p)P^{32}$ reaction. The time differences between the detection of a proton in a solid-state detector and a 77-keV γ ray in a NaI(Tl) crystal were measured. The prompt time distribution was obtained in a similar way using the transition between the second and first excited states of Na^{24} excited by the $Na^{23}(d,p)Na^{24}$ reaction. The data were analyzed using the third-moment method. An upper limit of 5×10^{-10} sec was obtained for the mean life of the second excited state of Na^{24}. The result obtained for P^{32} indicates that pure j-j coupling is not an adequate description for the two lowest states in this nucleus.

I. INTRODUCTION

The spins of the ground and 77-keV first excited state of P^{32} have been established through numerous experiments as being 1^+ and 2^+, respectively.[1] Since nuclei in this mass region are thought to be nearly spherical,[2] these states have been interpreted as arising from the j-j coupling configuration $(2s_{1/2},d_{3/2})$. $P^{31}(d,p)P^{32}$ stripping results indicate that these states are rather pure.[1] The experimental $l=2$ reduced width for the ground state is 20 times the $l=0$ value.[3] Further, the weighted ratio of reduced widths,

$$\frac{[(2J+1)\theta^2]_{0.077\text{ MeV}}}{[(2J+1)\theta^2]_{\text{g.s.}}},$$

has the experimental value of 4.4/3, while for pure states the predicted value is 5/3, since the relative reduced widths are then equal.[3]

A further and somewhat more stringent test of the purity of these states is provided by a measurement of the radiative transition probability between them. For $M1$ transitions, this quantity is independent of the radial nuclear wave functions involved so that the theoretical expression is exact and thus directly comparable to experiments to the extent that pure j-j coupling is a good approximation.[4] Because of the small energy difference between the states involved, it is expected that the transition should have very little $E2$ admixture. The present work, then, was undertaken to provide this transition probability and thus yield further evidence of the character of nuclei in this mass region.

The experimental technique to be described in the next section is a very powerful one for measuring the lifetimes of short-lived states that decay with γ-ray energies on the order of 100 keV. However, the method does require the auxilliary measurement of a comparatively prompt radiation of nearly the same energy. We have been unable to find a previous report of such a transition. However, the 0.564-MeV level of Na^{24}, which decays chiefly to the first excited 0.472-MeV, $J=1^+$ level, has a spin tentatively set at $J=2^+$.[1] Daum has considered Na^{24} in terms of the band-mixed collective model.[5] The 2^+ (0.564-MeV) level is treated as the head of a $K=2^+$ band while the 1^+ (0.472-MeV) level

[1] P. M. Endt and C. Van de Leun, Nucl. Phys. **34**, 324 (1962).
[2] V. K. Thankappan and S. P. Pandya, Nucl. Phys. **37**, 394 (1962).
[3] M. H. MacFarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).
[4] A. M. Lane and L. A. Radicati, Proc. Phys. Soc. (London) **A67**, 167 (1954).
[5] C. Daum, Nucl. Phys. **51**, 244 (1964).

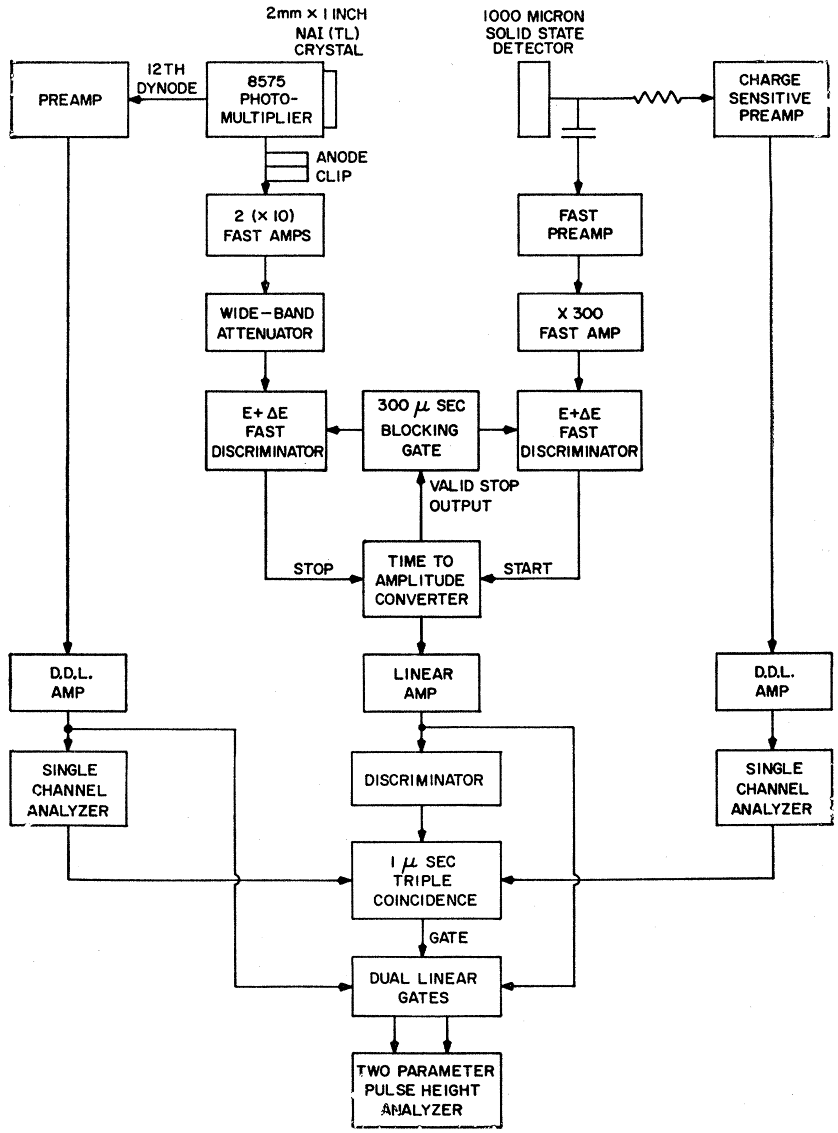

FIG. 1. Block diagram of electronics.

is treated as the head of a $K=1^+$ band. In this model there are no selection rules which would slow or inhibit this transition; hence, it is expected that this $M1$ transition will have a lifetime within a factor of 10 of the single-particle estimate as is typical for $M1$ transitions in this region. A previous experiment set an upper limit of 7×10^{-10} sec on the mean lifetime of this state.[6] It was hoped that the lifetime of this level was sufficiently short so it could be used as a prompt time distribution for the P^{32} data.

The technique consisted of measuring the time differences between the protons signifiying the formation of the state and the decaying γ rays from the state. A solid-state detector was used to determine the proton's energy as well as to produce a timing signal. The γ ray was detected by a thin NaI(Tl) crystal mounted on a fast photomultiplier.

II. EXPERIMENTAL

The experiment was performed using deuterons, accelerated to 2.5 MeV by the University of Iowa type-CN Van de Graaff accelerator, incident on a GaP [7] target. The target was prepared by evaporation of GaP onto a carbon backing approximately 20 μg/cm^2 thick. The target thickness was observed to be less than 150 keV thick to the deuteron beam. The solid-state proton detector was placed at 60° to the beam at a distance of 1.25 in. from the target. The beam was stopped by a polished tantalum sheet 2.5 in. behind the

[6] S. J. du Toit and L. M. Bollinger, Phys. Rev. 123, 629 (1962).

[7] Available from Semi-Elements, Inc., Saxonburg, Pa.

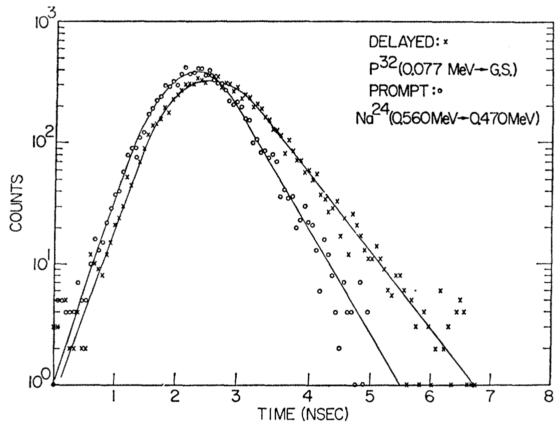

FIG. 2. Lifetime data.

target. The γ-ray detector was placed 0.75 in. from center of the target which was inclined 45° to the reaction plane. The detector itself was at an angle of 90° to the reaction plane.

The solid-state detector used was a 10 000 Ω cm silicon surface-barrier type of 1000 μ thickness and 100-mm^2 area. The detector was totally depleted in order to minimize the charge collection time arising from series resistance of undepleted silicon and the detector capacitance. The solid-state detector pulses were amplified by a conventional charge-sensitive preamplifier which was connected in parallel with a fast high-impedance preamplifier capacitively coupled to the signal. The fast signals were then further amplified and routed to the fast electronics.

Because of the low-energy 77-keV γ ray, a thin NaI(Tl) crystal was used to advantage. The use of a thin (2-mm-thick by 1-in.-diam) crystal of high-Z material provided a relative efficiency of approximately 40:1 for 77 keV compared to 1–10 MeV γ rays. This allowed a great reduction in the high-energy γ-ray background which significantly reduced accidental coincidences and overloading of the electronics. The crystal was viewed by an RCA-8575 photomultiplier. The fast timing signals were taken from the anode and the proportional pulses were taken from the 11th dynode. The anode pulse was clipped to 4.6 nsec by 1.5 ft of shorted RG-174/U 50-Ω coaxial cable in order to prevent damage to the following electronics.

A block diagram of the electronics used is shown in Fig. 1. The clipped anode signal was amplified by cascaded amplifiers (each having a gain of 10) of the UCRL design.[8] A wide-band attenuator was used to adjust the gain. The fast signals were both sent to $(E+\Delta E)$ triggers.[9] These triggers contained both a lower level discriminator E and an upper level discriminator which triggered at $(E+\Delta E)$. By setting $\Delta E \gg E$, it was possible to derive the timing information far down in the photomultiplier noise, yet only obtain an output for large, real signals. This reduced the rate in the following electronics greatly with the net result of better time resolution. The time-to-amplitude converter used was of the start-stop type. A block that turned the triggers off for 30 μsec was generated whenever a coincidence occurred. This eliminated the possibility of multiple pulsing of the triggers on the long tails of the clipped anode pulses and thus prevented the distortion of the data.

The linear signals were processed by conventional slow electronics. A triple slow (1 μsec) coincidence between the linear signals opened the linear gates to pass the γ ray and time signal to the computer-based–two-parameter analyzer. Data were accumulated with 2048-channel detail on the time axis and 30 channels on the γ-ray energy axis.

Calibration of the time axis was obtained by inserting 30-cm lengths of air-dielectric lines which had an absolute accuracy of 0.3%.[10]

A window was set on the particle groups corresponding to the unresolved ground and first excited state of P^{32}. Data were taken for approximately 12 h with 0.5 μA of beam on target. The target was then changed and the Na^{23} $(d,p)Na^{24}$ (0.566 → 0.473 MeV) reaction was run at $E_d = 4.2$ MeV with the same particle window. The sodium target was made by evaporating Na metal on a self-supporting carbon backing and was less than 150 keV thick to 4.2-MeV deuterons. Although the γ-ray energies from the sodium and phosphorus are not the same (0.093 and 0.077 MeV, respectively), there is enough overlap of the tail of the sodium photopeak to provide sufficient counts in the phosphorus γ-ray energy region. The sodium thus is used to provide a prompt response for use with the phosphorus data. The γ-ray window, set after taking the data, was placed on the 77-keV photopeak and was about 15 keV wide.

Possible contamination reactions for the phosphorus data are

$$Ga^{69}(d,p)Ga^{70}+5.42 \text{ MeV},$$
$$Ga^{71}(d,p)Ga^{72}+4.29 \text{ MeV}.$$

No significant amounts (<5% of P^{32} ground state) of these reactions could be observed in either the particle spectrum or the γ-ray coincidence spectrum.

The Na^{24} data did not necessarily provide a true prompt distribution for the P^{32} unless the phosphorus lifetime was quite long. An examination of the data in Fig. 2 shows that this is not the case. Hence, the fact that there was a centroid shift and a difference in slopes of the distributions shows only that there was some measurable lifetime. Note that there is virtually no background from accidental counts.

The problem was further complicated by the fact that NaI(Tl) did not have a Gaussian time response

[8] H. G. Jackson, Nucl. Instr. Methods 33, 161 (1965).

[9] All fast electronics, other than amplifiers, are commercial units produced by E. G. and G., Inc. 35 Congress Street, Salem, Mass.

[10] Manufactured by General Radio Co., Cambridge, Mass.

for low-energy γ rays.[11] This effect was due to an exponential distribution of pulse heights of single-electron events and the fact that the discriminator may not necessarily trigger on the first electron unless the trigger level is at a true zero volts. The result was a time distribution which was of the form of a Gaussian folded into a decaying exponential. Unfortunately, this was of the same form as a delayed curve due to a real lifetime. Thus, the prompt may be truly prompt, yet exhibit the characteristics of a lifetime curve.

In order to resolve these problems, the lifetime was determined by the third-moment method. The procedure was to calculate the third moment of the prompt curve about its centroid. The mean life was then given exactly by[12]

$$\tau=\{\tfrac{1}{2}[M_3'(F)-M_3'(P)]\}^{1/3}, \qquad (3)$$

where $M_3'(F)$ and $M_3'(P)$ were the third moments about their centroids. The principal reason for using this method was that it does not depend on the location of the prompt peak and only weakly on the shape of the prompt time distribution.

The final value for P^{32} 0.077-MeV lifetime was, including a possible 10% systematic error, $\tau_m=5.2_{+0.9}{}^{-0.5}\times10^{-10}$ sec or $\tau_{1/2}=3.6_{+0.6}{}^{-0.4}\times10^{-10}$ sec. If the lifetime of Na^{24} were determined to be short (<100 psec), then the P^{32} lifetime would be $\tau_m=5.2\pm0.5\times10^{-10}$ sec or $\tau_{1/2}=3.6\pm0.4\times10^{-10}$ sec.

A limit of $\tau_m<5.0\times10^{-10}$ sec was placed on the Na^{24} 0.560-MeV state by the fact that the measured P^{32} lifetime was greater than this limit.

III. RESULTS

The experimental mean life for the 0.077-MeV state of P^{32} was determined to be $5.2_{+0.9}{}^{-0.5}\times10^{-10}$ sec. The large uncertainty is primarily due to systematic errors associated with lack of an adequate and accurate prompt time distribution. The Mosokowozi extreme single-particle estimate for the mean life is 66×10^{-12} sec. Thus, the transition strength is retarded by a factor of 13 which is typical for nuclei in this region of the periodic table.

In order to provide a comparison with the shell model, we have calculated the magnetic dipole transition probability by evaluating the matrix elements of the $M1$ operator

$$\mathbf{M}=\left(\frac{3}{4\pi}\right)^{1/2}(g_n\boldsymbol{\sigma}_n+g_p\boldsymbol{\sigma}_p+\mathbf{l}_p),$$

using the j-j coupling states

$$|JM\rangle=\sum_{np}(j_pj_nm_pm_n|JM)|j_pm_p\rangle|j_nm_n\rangle,$$

where the subscripts n and p stand for neutron and proton, respectively. The result for the reduced transition probability, valid for $M1$ transitions in nuclei with a single neutron and a single proton outside closed subshells between states which differ only in the coupling of these two nucleons, is

$$\begin{aligned}B(M1)=\frac{3}{4\pi}(2J_f+1)\{&(2j_p+1)^2[\tfrac{3}{2}g_p{}^2W^2(J_fj_pJ_ij_p;j_n1)\\&\times W^2(j_p\tfrac{1}{2}j_p\tfrac{1}{2};l_p1)+l_p(l_p+1)(2l_p+1)\\&\times W^2(J_fj_pJ_ij_p;j_n1)W^2(j_pl_pj_pl_p;\tfrac{1}{2}1)]\\&+(2j_n+1)^2\tfrac{3}{2}g_n{}^2W^2(J_fj_nJ_ij_n;j_p1)\\&\qquad\times W^2(j_n\tfrac{1}{2}j_n\tfrac{1}{2};l_n1)\},\end{aligned}$$

where the subscripts i and f stand for the initial and final states, respectively. The numerical value of this expression for the first excited state in P^{32} is

$$B(M1)=7.26\times10^{-8}\ \text{erg-F}^3,$$

which gives a mean life of

$$\tau_m=43.9\times10^{-12}\ \text{sec}.$$

The experimental value is in disagreement with this prediction, indicating a significant failure of pure j-j coupling to provide an adequate description of the low-lying states of P^{32}.

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[11] S. H. Maxman, Nucl. Instr. Methods **33**, 161 (1965).
[12] R. S. Weaver and R. E. Bell, Nucl. Instr. Methods **9**, 149 (1960).