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$E0$ decay of the first excited 0^+ state in ^{32}S

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The $E0$ branching ratio Γ_π/Γ of the ^{32}S (3.78-MeV, 0^+) state to the ground state was measured to be $(3.54 \pm 0.62) \times 10^{-4}$. When combined with the lifetime $\tau_m = (0.90 \pm 0.15)$ psec of this state one obtains the value $\langle M \rangle_\pi = (2.22 \pm 0.27)$ fm^2 for the $E0$ matrix element.

[NUCLEAR REACTION $^{31}P(^3He, d)$, E=8.5 MeV; ^{32}S measured $E0$ branching ratio. Deduced $E0$ matrix element.]

I. INTRODUCTION

In recent years a number of $E0$ matrix elements have been measured for $4n$ pair-pair light nuclei for $A \leq 40$. Most of these measurements as, for example on ^4He (Ref. 1), ^{12}C (Ref. 2), ^{16}O (Ref. 3), ^{24}Mg (Ref. 2), and ^{28}Si (Ref. 2), were made by electron inelastic scattering. Some of them are new measurements of particularly important cases like in ^{16}O (Ref. 4) and ^{40}Ca (Ref. 5). Table I summarizes the existing data on $E0$ decays in $4n$ nuclei for $A \leq 40$. As can be seen from the table there are still some nuclei (^8Be, ^{20}Ne, ^{36}Ar) for which no monopole decay is known. Most of the

TABLE I. Compilation of properties for $J^\pi = 0^+$ excited states in $4n$ nuclei of the s, p, and s-d shells.

Nucleus	E_x (MeV)	τ_m or Γ	Ref.	$\langle M\rangle_\pi$ (fm^2) [a]	Ref.
^4He	20.1	(270 ± 50) keV	21	2.02 ± 0.32	1
^{12}C	7.65	(8.7 ± 2.8) eV [b]		5.00 ± 1.25	13
				5.46 ± 0.29	14
		(9.7 ± 3.3) eV	26	5.57 ± 0.50	15
				5.33 ± 0.26	16
				5.37 ± 0.22	2
				5.39 ± 0.26 [c]	
^{16}O	6.05	(72 ± 7) psec	22	3.66 ± 0.55	3
		(96 ± 7) psec	4		
		(84 ± 12) psec [c]		3.55 ± 0.25 [d]	
	12.05	(1.5 ± 0.5) keV	23	4.40 ± 0.44	17
				4.39 ± 0.28	18
	14.00	(170 ± 50) keV	19	3.3 ± 0.7	19
^{24}Mg	6.43	(190 ± 60) fsec	12	6.23 ± 0.62	20
				6.33 ± 0.29	2
^{28}Si	4.98	(45 ± 10) fsec	12	6.8 ± 0.4	2
	6.69	(120 ± 30) fsec	12	≤3.0(2.0 ± 1.0)	2
^{32}S	3.78	(900 ± 150) fsec	12	11.8 ± 1.5	9
				10 ± 1	8
				≤3.5(2.2 ± 1.3)	2
^{40}Ca	3.35	(3.4 ± 0.2) nsec	24	3.6 ± 1.1	2
		(3.04 ± 0.11) nsec	25		
		(3.03 ± 0.14) nsec	5		
		(3.12 ± 0.22) nsec [c]		2.71 ± 0.10 [e]	

[a] For ground-state decays.
[b] Width deduced from $\langle M\rangle_\pi = (5.39 \pm 0.26)$ fm^2 listed in column 5 and from $\Gamma_\pi/\Gamma = (6.9 \pm 2.1)$ 10^{-6} (Ref. 27). In deducing $\Gamma_\pi = (60 \pm 6)$ μeV from the value of $\langle M\rangle_\pi$ the formulas of Dalitz (Ref. 28) for $Z \neq 0$ (Ref. 29) were used rather than the Oppenheimer-Schwinger one.
[c] Weighted average value.
[d] Deduced from $\tau_m = (84 \pm 12)$ psec (column 3).
[e] Deduced from $\tau_m = (3.12 \pm 0.22)$ nsec (column 3).

$E0$ decays are given for the first excited 0^+ state. $E0$ decays of higher excited states are reported only for ^{16}O and ^{28}Si. Such $E0$ measurements on higher excited 0^+ states are of particular interest in determining how much of the sum rule strength these levels account for. For example in ^{16}O the three reported $E0$ matrix elements take almost 20% of the isoscalar energy weighted sum rule.[6]

In this paper we give the results of measurements on the $E0$ branching ratio of the ^{32}S (3.78-MeV, 0^+) state to the ground state obtained by the experimental method described in Ref. 7. Strehl[2] has recently reported an upper limit to the value of the matrix element for this transition which is $\langle M\rangle_\pi \leq 3.5$ fm^2 or possibly a value of (2.2 ± 1.3) fm^2. An older measurement of Lombard, Kossanyi-Demay, and Bishop[8] yields (10 ± 1) fm^2. Bishop[9] reported (11 ± 1.5) fm^2. As the discrepancy in these results represents about a factor 10 in the $E0$ branching ratio, we undertook a measurement of the π-branching ratio for the $E0$ decay of this state by an independent method.

II. EXPERIMENTAL RESULTS

The $^{31}P(^3He,d)^{32}S$ reaction was used to populate the first excited 0^+ state in ^{32}S. It has been shown that this reaction proceeds mostly through a stripping mechanism and that the deuterons populating the 0^+ state are strongly forward peaked.[10] For this reason we detect the heavy particles at 0° to the beam axis instead of at 180° as in Ref. 7. Phosphorus targets of ~200 μg/cm^2 on 250-μg/cm^2-thick gold backings were prepared following the method given in Ref. 11.

The 8.5-MeV $^3He^{++}$ beam was stopped in a 50-μm-thick tantalum foil which was placed on a 6.3-mm-diam collimator 3 cm in front of a detector. Deuterons from the reaction passed through the foil and were detected in a 150-mm$^2\times$150-μm-thick surface barrier detector placed 4 cm downstream from the target. With a proton background from the $^{31}P(^3He,p)$ reaction the bias voltage on the solid state detector was chosen so as to have a depletion depth sufficient to fully detect the deuterons feeding the 3.78-MeV state. This depletion depth is also just enough to fully detect the protons from the prolific $^1H(^3He,p)$ reaction (hydrogen is a target contaminant). The procedure described in the next paragraph provided a check on the identification and purity of the particle group detected in the single surface barrier detector.

In a test run the particle spectrum from the $^{31}P+{}^3He$ reaction at 0° was taken after replacing the 150-μm-thick surface barrier detector by a ΔE-E telescope consisting of a 56-μm ΔE counter followed by a 1000-μm E counter. The ΔE counter was collimated to a diameter of 4 mm. Two-dimensional ΔE versus $\Delta E+E$ energies particle spectra were taken for full and partial bias voltage of the E counter. The partial bias was chosen so as to detect fully only the deuterons feeding the 3.78-MeV state. The yield of this deuteron group for full and partial bias was checked to be the same for the same integrated total charge. Figure 1 shows the resulting deuteron and proton spectra taken simultaneously at $E(^3He)=8.5$ MeV for full bias on the E counter. As could be seen in the figure the deuterons feeding the three first states in ^{32}S stand out clearly in the deuteron spectrum.

For the $e^\pm$ pair decay measurements the plastic scintillator telescopes, with 0.4-mm-thick ΔE counters as described in Ref. 7, were used. The test run for the 3.35-MeV $E0$ decay in ^{40}Ca gave (6.0 ± 0.3)% for the pair efficiency of this decay for a 400-keV electronic discrimination in the E counters.

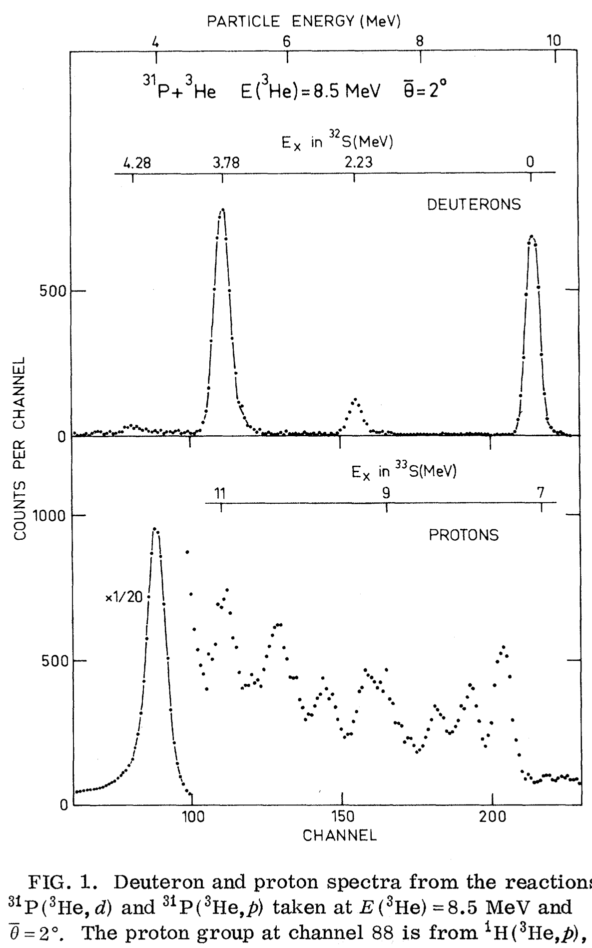

FIG. 1. Deuteron and proton spectra from the reactions $^{31}P(^3He,d)$ and $^{31}P(^3He,p)$ taken at $E(^3He)=8.5$ MeV and $\bar{\theta}=2°$. The proton group at channel 88 is from $^1H(^3He,p)$, hydrogen being a target contaminant. The particles passed through a 50-μm-thick tantalum foil before being detected.

Figures 2(b) and 3 show projections of the nonrepresented two-dimensional particle energy versus pair energy spectrum which was obtained for a 30-h measurement with a $^3He^{++}$ beam of 30 nA. The ^{32}S (3.78-MeV, 0^+) state was populated by $(4.89\pm0.17)\times10^6$ deuterons detected in the solid state detector as shown in the $\frac{1}{8}$ sampled direct particle spectrum of Fig. 2(a) stored in the $X=0$ channels of the two-dimensional spectrum. The background under the deuteron group relevant to the 3.78-MeV state (around channel 74) which extends until channel ~110 is from the $^{31}P(^3He,p)$-$^{33}S(p)^{32}P$ reaction when the two protons are detected simultaneously in the solid state detector.

Figure 3 represents the π spectrum from the 3.78 MeV → g.s. decay. It is the projection onto the π-energy axis of heavy particle channels 70–78 (see Fig. 2). The π yield was extracted from the

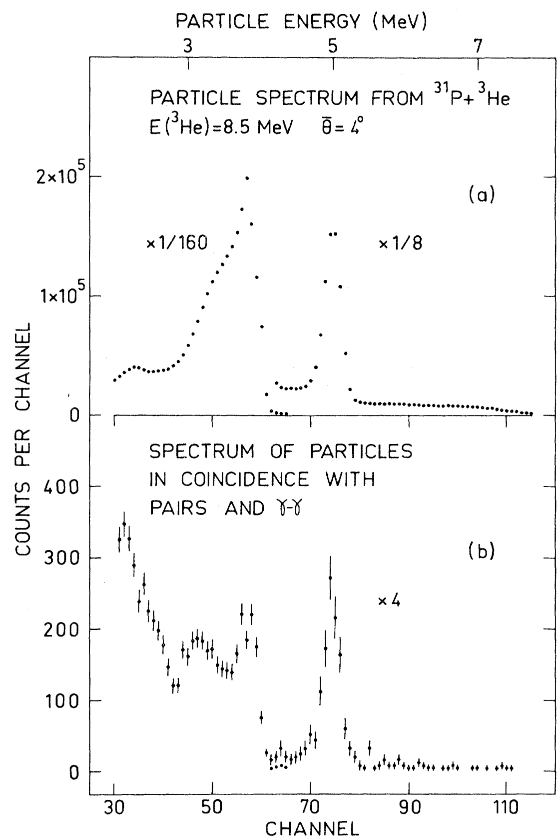

FIG. 2. (a) $\frac{1}{8}$ sampled direct particle spectrum from $^{31}P+{}^3He$ (a part of the spectrum is represented × 1/160) taken simultaneously with the nonrepresented particle energy vs pair energy spectrum. The peak around channel 74 is from $^{31}P(^3He,d)^{32}S$ (3.78 MeV). The heavily populated proton group at channel 57 is from $^1H(^3He,p)$. The bias of the particle detector was chosen as explained in Sec. II. (b) Projection onto the particle energy axis of the two-dimensional spectrum.

TABLE II. Properties of the first excited $J^\pi=0^+$ state in ^{32}S.

E_x (MeV)	τ_m (psec)	Γ_π/Γ	$\langle M\rangle_\pi$ (fm^2)	s.p.u. strength [a]
3.78	0.90 ± 0.15 [b]	$(3.54\pm0.62)10^{-4}$	2.22 ± 0.27	0.11 ± 0.03

[a] Reference 29.
[b] Reference 12.

spectrum either by taking $(2.3\pm0.5)\times10^{-5}$ γ-γ interactions per detected deuterons[7] or by analyzing the spectrum by a least squares fit with the known shapes for the γ-γ interactions and for the π spectra. The latter are represented in Fig. 3 by the dashed curves. A good agreement was obtained between the two methods and 150 ± 21 π were deduced in the spectrum.

Combining these numbers with the calculated pair efficiency for the 3.78-MeV π decay, $(8.65\pm0.86)\%$, one finds $\Gamma_\pi/\Gamma=(3.54\pm0.62)\times10^{-4}$. By taking $\tau_m=(0.90\pm0.15)$ psec (Ref. 12) for the mean lifetime of the 3.78-MeV state, the π partial mean

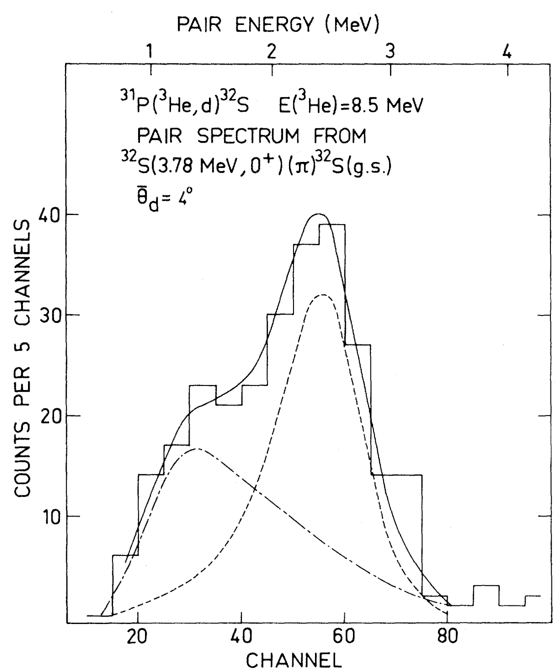

FIG. 3. Pair spectrum obtained from the projection of the events for channels 70–78 of Fig. 2(b) onto the pair energy axis of the relevant particle energy vs pair energy spectrum. The long-short dashed line is the shape of the γ-γ interactions from the 3.78 MeV → 2.23 MeV → g.s. γ cascade deduced from Ref. 7. The dashed line is the shape of the π spectrum from the 3.78 MeV → g.s. π decay deduced from the ^{40}Ca(3.35 MeV) → g.s. π decay. The weighting of these two curves was obtained by a least squares fit.

lifetime is found to be (2.54 ± 0.61) nsec. This yields $\langle M \rangle_\pi = (2.22 \pm 0.27)$ fm^2 for the $E0$ matrix element. These results are summarized in Table II.

III. DISCUSSION

The discrepancy between the (e, e') results of Lombard *et al.*[8] and Strehl[2] has already been discussed in Ref. 2. The present measurement which yields a matrix element of (2.22 ± 0.27) fm^2 is consistent with the upper limit of 3.5 fm^2 reported by Strehl[2] and in agreement with his possible value of (2.2 ± 1.3) fm^2. One should notice that a matrix element of the order of 10 fm^2 such as reported in Refs. 8 and 9 implies a π-branching ratio a factor of 20 bigger than that found in the present determination (Table II).

The $E0$ strength in single particle units (s.p.u.)[29] of the 3.78-MeV state in ^{32}S is 0.11 ± 0.03. It is interesting to compare this value with the $E0$ strength of the first excited 0^+ state in neighboring $4n$ nuclei. For A less than 32, one can deduce from the matrix element values of Table I the following strengths (in s.p.u.): 1.28 ± 0.15 (^{28}Si), 1.36 ± 0.20 (^{24}Mg), 0.74 ± 0.11 (^{16}O), 2.50 ± 0.24 (^{12}C), and 1.5 ± 0.5 (^{4}He). For ^{40}Ca one finds 0.127 ± 0.009 which is of the same order of magnitude as the ^{32}S value and about a factor of 10 lower than the strengths in lighter nuclei. An $E0$ measurement in ^{36}Ar would be interesting in view of that sudden drop in the $E0$ strength after ^{28}Si.

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