Experimental evidence against the proposed band based on a shape isomer in ^{32}S

J. D. MacArthur, S.-P. Kwan, H.-B. Mak, W. McLatchie, S. A. Page, and S.-S. Wang
Department of Physics, Queen's University, Kingston, Canada K7L 3N6

T. K. Alexander
Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories,
Chalk River, Canada K0J 1J0
(Received 8 Februrary 1985)

The spin and parity of the 9.065 MeV state in ^{32}S, populated in the $^{28}Si(\alpha,\gamma)^{32}S$ reaction, has been found to be 4^+. Therefore, this state cannot be the second member of a band based on the proposed 0^+ shape isomer at 8.507 MeV in ^{32}S. In the same reaction, no evidence for the 0^+ and 4^+ states at 8.507 and 10.276 MeV was found.

The existence of shape isomers has been predicted by several models and identified in many nuclei with $Z > 92$. However, for light nuclei, although they are predicted, no convincing evidence for such structures has been observed. Recently, interest in the existence of shape isomers in light nuclei has increased because of the fact that these shape isomers have been suggested as a possible explanation of anomalous projectile fragments,[1] excited nuclear species produced in high energy collisions. They are conjectured to have relatively long lifetimes ($\sim 10^{-10}$ s) and anomalously short mean free paths, indicative of very large reaction cross sections.

Schultheis and Schultheis[2] have examined the experimental information on the levels and spins in the light $A = 4N$ nuclei, and concluded that many of these nuclei have sequences of states that are good candidates for bands based on shape isomers.

An especially favorable case is ^{32}S, for which two calculations[3,4] have suggested that a band could exist with its 0^+ isomeric band head at $E_x \simeq 8$ MeV, and with an intrinsic quadrupole moment of 2.08–2.19 e b. Furthermore, very enhanced $E2$ transitions are expected between the levels. The identification of candidates for such bands rests on the location and lifetime of the band head and the energy spacing and spin sequence of the levels based on the shape isomer.[3] Schultheis and Schultheis[4] have used these criteria to identify from the known levels of ^{32}S the states at 8.507, 9.065, and 10.276 MeV, which have spins and parity of $0^+, 2^+$, and 4^+, respectively, as an exceptionally favorable set for such a band.

Experimentally, the 0^+ 8.507 and 4^+ 10.276 MeV states have only been seen in the $^{34}S(p,t)^{32}S$ reaction.[5] The 9.065 MeV state was not observed in the (p,t) reaction but has been observed in the $^{28}Si(\alpha,\gamma)^{32}S$ reaction, and a spin and parity of 2^+, 3^-, or 4^+ has been assigned.[6] To be in agreement with the model calculations,[3,4] the spin and parity of the 9.065 MeV level has to be 2^+. Since the predictions of the shape-isomer states are based on alpha or cluster models for ^{32}S, it seemed probable that the $^{28}Si(\alpha,\gamma)^{32}S$ reaction would excite these states. In the present experiment, the spin of the 9.065 MeV state was determined and the radiative decays of the 8.507 and 10.276 MeV states were sought using the reaction $^{28}Si(\alpha,\gamma)^{32}S$. The spin and parity of the 9.065 MeV level is 4^+, in contradiction to the model prediction, and no evidence for the 0^+ band head or the 4^+ member was found.

Targets a few keV thick were prepared by vacuum evaporation of natural Si or $^{28}SiO_2$ onto thick gold blanks. In the preparation of targets for the measurements of the strength of a resonance, thin (~ 2 μg/cm^2) C foils were also placed near the gold blanks during the evaporation. In a Rutherford backscattering experiment with a 2.0 MeV ^{4}He beam, this deposit was found to have a composition of 31% O and 69% Si by weight, i.e., to be mostly SiO.

The γ rays from the reaction were detected with 18% and 22% Ge(Li) detectors, each with a resolution of 2.2 keV full width at half maximum (FWHM) at 1.332 MeV. In the angular distribution experiments, the smaller detector was positioned at 90° to the beam direction, while the large detector was used to measure the γ-ray yield at each of five angles between 0° and 90°. The efficiency of each detector was determined with a ^{56}Co source of known strength placed at the position of the beam spot that was visible on the targets after bombardment.

The targets were placed inside a liquid N_2 cooled shroud, to which a negative voltage could be applied in order to suppress secondary electrons. Consequently, a true measure of the incident current was obtained and hence the absolute yield of the γ rays could be deduced. The shroud also helped maintain a pressure $< 1.3\times 10^{-7}$ kPa (10^{-6} Torr) in the target chamber.

The results of the angular distribution for two of the γ rays from the resonance state are shown in Fig. 1. These angular distributions of the γ rays to the 3^+ 5.413 and 4^+ 4.459 MeV levels clearly establish the spin of the 9.065 MeV state as 4^+. The branching ratios for all three transitions from this state were determined from this angular distribution experiment and are presented in Table I. The present branching ratios are not in agreement with those deduced from the data of Rogers *et al.*,[6] who measured the yield of γ rays at 55° only. To obtain branching ratios, Rogers *et al.* assumed that the transitions were pure dipole, which is not the case. When allowance is made for the angular distributions of the γ rays, the results of Rogers *et al.* are in agreement with the present results. Consequently, it is clear that the state excited in this experiment is that reported in the literature as the 9.065 MeV state. The resonance strength[7] of the reaction, $\omega\gamma = (2J+1)\Gamma_\alpha\Gamma_\gamma/\Gamma$, was measured as 67 ± 6 meV. On the assumption that $\Gamma_\alpha >> \Gamma_\gamma$, the reduced transition probabilities[8] shown in Table I were deduced. Figure 2 shows the Doppler shift for two of the transitions from this level; both measurements

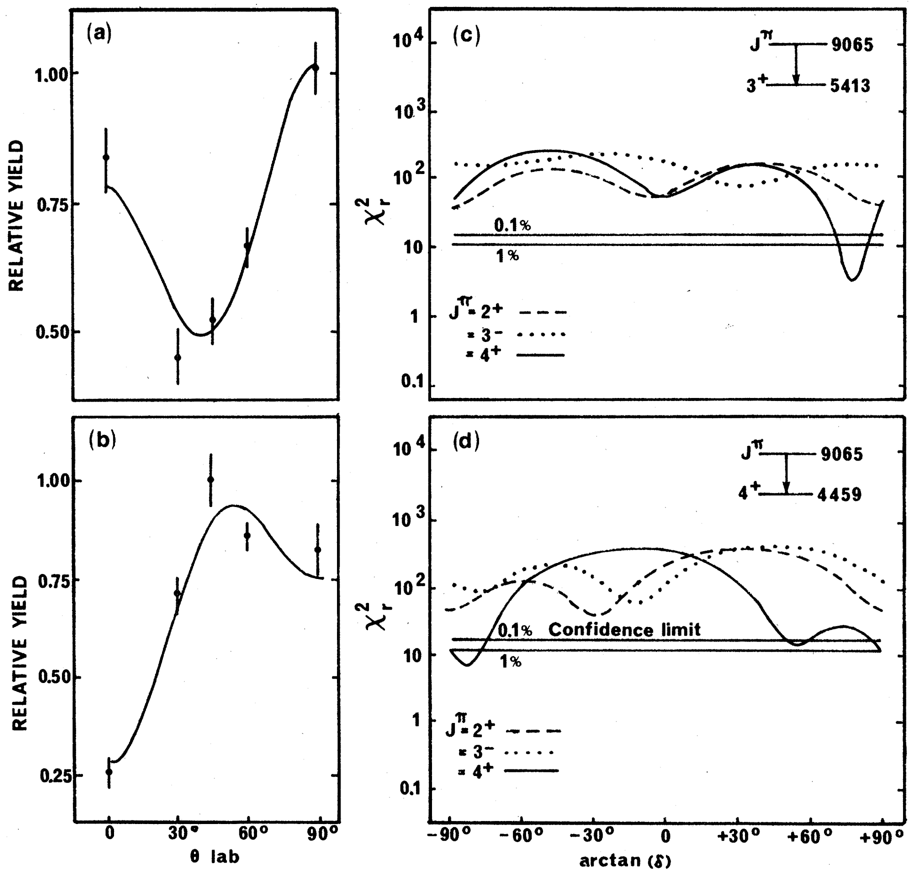

FIG. 1. Angular distributions, panels (a) and (b), and mixing ratio analyses showing χ^2 vs $\tan^{-1}\delta$ in panels (c) and (d) for two of the transitions from the 9.065 MeV state in ^{32}S. These data establish the spin of the state as 4^+ and both of the γ rays as $E2$ transitions.

are consistent with a full Doppler shift. Therefore, the lifetime of the state is less than 20 fs (i.e., $\Gamma > 30$ meV), and the assumption that $\Gamma_\alpha >> \Gamma_\gamma$ is justified.

Figure 3 shows the yield curve at 90° from two regions of the γ-ray spectrum for α-particle energies near that expected to excite the 0^+ resonance (the region spanned by the bar). Both yield curves show a resonance, and a γ-ray spectrum was taken at the peak of the yield curve. The energies of the γ rays from this resonance established the energy of the excited state as 8493 ± 2 keV, and identified it as the 1^- state for which the resonance strength[6] is 16 ± 3 meV. This identification served as the energy calibration for the α particles. The $J^\pi = 0^+$ resonance would only be seen in the yield curve with the 4.0–6.5 MeV window because a ground state transition is forbidden. No evidence for such a resonance is observed and an upper limit on any possible strength for the transition to the first-excited state, considered to be the most likely, can be made from a comparison of the two yield curves.

Away from the observed 1^- resonance, 30 counts (considered the minimum detectable above the background) corresponds to a strength of 2.0 meV when allowance is made for the difference in detection efficiency between γ rays of 6.3 and 8.5 MeV and the angular distribution of the 1^- to 0^+ transition. For a 0^+ resonance unresolved from the 1^- resonance the limit on the resonance strength is less certain. However, the counting rate in the 4.0–6.5 MeV window can be completely accounted for by the Compton distribution of the 8.5 MeV γ ray and the known branch[6] from the 1^- to the 2^+ first-excited state. Therefore any masked resonance

TABLE I. Radiative decay of the 4^+ 9.065 MeV state.

E_f (MeV)	J_f^π	br (%)	Γ_γ (meV)	$\tan^{-1}\delta$ (°)	$B(M1)$ (μW.u.)	$B(E2)$ (W.u.)
4.282	2^+	12 ± 1	0.85 ± 0.11	0 ± 3	· · ·	0.074
4.459	4^+	30 ± 3	2.24 ± 0.32	-85^{+6}_{-2}	8.4	0.22
5.413	3^+	58 ± 4	4.30 ± 0.53	76 ± 2	250	1.28
2.230	2^+	< 1	< 0.05	0		< 0.0007

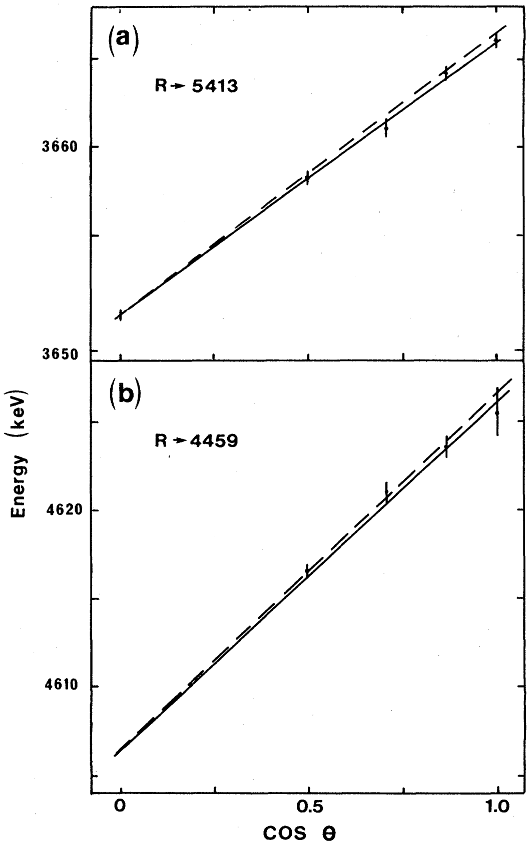

FIG. 2. The γ-ray energy vs angle for two transitions from the 9.065 MeV resonance state (R) to the 5413 keV level [panel (a)] and to the 4459 keV level (b). The solid lines are the best fits to the data, while the dashed lines indicate the expected full Doppler shifts. Both transitions have essentially full shifts and, therefore, the lifetime of the resonance state is < 20 fs.

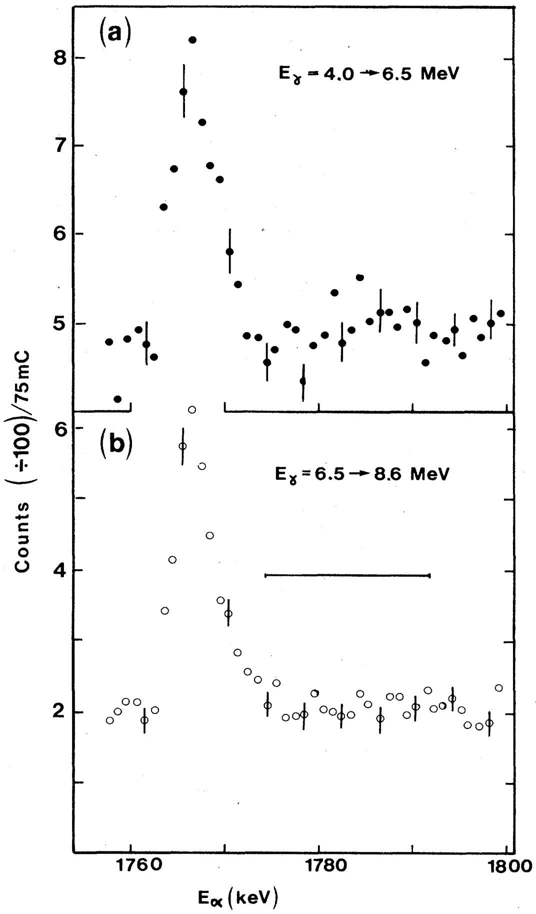

FIG. 3. The yield curve for γ-ray counts between 4–6.5 MeV (a) and 6.5–8.6 MeV (b) in the $^{28}Si(\alpha,\gamma)^{32}S$ reaction. The 0^+ 8.507 ±0.008 MeV state, observed in the $^{34}S(p,t)^{32}S$ reaction is expected in the 16 keV region spanned by the bar. The resonance observed at $E_\alpha = 1.766$ MeV excites a known 1^- state in ^{32}S at 8493 ±2 keV.

cannot contribute more than 60 counts in it, which would correspond to a strength of 4 meV.

The search for the 4^+ resonance at an excitation energy of 10.276 MeV was undertaken with a target of natural Si. Consequently, yield curves for wide regions, e.g., 4–6.5 and 6.5–8.5 MeV of the γ-ray spectra showed resonances in both the $^{28}Si(\alpha,\gamma)^{32}S$ and the $^{30}Si(\alpha,\gamma)^{34}S$ reactions. Therefore, for a positive identification of the former reaction, the 2.230 MeV γ ray from the transition between the first excited and ground states was used. This procedure is justified because, for any reasonable decay of the 4^+ state, the first excited state will be excited directly or indirectly. (A large majority of the excited states in ^{32}S decay through the first excited state.[9]) Figure 4 shows the yield curve, observed at 90° for this γ ray. The measured γ-ray energies and the decay schemes constructed from the spectra obtained at the unresolved peaks in the yield curve identified these resonances as corresponding to the 10 288 ±2 keV $J^\pi = 3^-$ and 10 294 ±2 keV $J^\pi = 2^+$ states[9] in ^{32}S, respectively, and hence provided the energy calibration for the α particles. The resonance strength, $\omega\gamma$, for the 3.816 MeV reaonance to the 10.288 MeV $J^\pi = 3^-$ level is 2.3 ±0.5 eV.[6] Since this resonance decays directly or indirectly[10] through the first excited state, the resonance strength for a possible

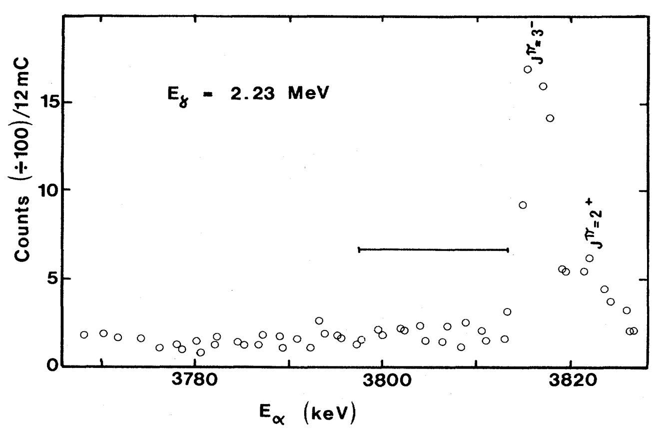

FIG. 4. The yield curve for the first-excited to ground state transition in the region where the resonance to the 4^+ state is expected. The bar spans the energy within ±8 keV of the expected position. The resonances at $E_\alpha = 3.816$ and 3.821 MeV excite states at 10 288 ±2 keV, $J^\pi = 3^-$, and 10 294 ±2 keV, $J^\pi = 2^+$ in ^{32}S.

4^+ resonance can be estimated. In the bombarding energy region between 3.770 and 3.813 MeV, an upper limit of 50 counts for an undetected resonance corresponds to a strength of 70 meV. For a resonance corresponding to the 4^+ level, unresolved from these known resonances, nothing can be deduced because the γ-ray spectra taken at the two resonances revealed only γ rays that could be fitted into decay schemes for the established 3^- and 2^+ states.

Since only limits have been established on the resonance strengths for the reaction to the 0^+ and 4^+ states seen in the (p,t) reaction, it is necessary to comment on whether or not this is evidence for these states being candidates for members of a band based on a shape isomer. A shape isomer is not expected to have a strong radiative decay to the 2^+ first-excited level. If it is assumed that the α width is the dominant width for both resonance states, i.e., $\Gamma_\alpha \simeq \Gamma$, the γ-ray transitions to the first-excited state from the 0^+ and 4^+ resonances have $B(E2)$ values < 0.04 and < 0.05 W.u., respectively. These are relatively weak and therefore are consistent with transitions from a band based on a shape isomer. For comparison it may be noted that in ^{28}Si, the strengths of similar transitions from 0^+ and 4^+ members of the proposed band based on a shape isomer have $B(E2)$ values of 0.25 Weisskopf unit (W.u.)[9] and 0.09 W.u.,[11] respectively.

Since the calculations of Schultheis and Schultheis are based on an alpha cluster model and their density distribution shows distinctive maxima, relatively large reduced widths might be expected. The maximum Γ_α values for the 0^+ and 4^+ states, assuming Wigner limits for the reduced widths, are 40 and 106 meV, respectively. These numbers are much larger than the limits of 2 and 8 meV for the quantity $\Gamma_\alpha \Gamma_\gamma / \Gamma$ associated with the possible resonances; hence, the assumption $\Gamma_\alpha >> \Gamma$ seems justified. It is interesting to note that, if the total width of the 0^+ state is 40 meV or less, its lifetime is > 17 fs, which is in the range of existing techniques for observation of the decay of the state.

Our search for the 0^+ and 4^+ levels does not allow a definite conclusion to be drawn about the structure of these states. However, it does suggest that to further pursue the investigation of a shape isomer in ^{32}S at ~ 8 MeV, the existence of a 0^+ state at 8.507 MeV, seen only in the (p,t) reaction, must be more firmly established, or a search for a new 2^+ state initiated.

The choice of the 8.507, 9.065, and 10.276 MeV states in ^{32}S as a unique group of states forming a rotational band based on an isomeric state rests heavily on the spacing of levels with the correct spin sequence. The present experiment firmly establishes the spin of the 9.065 MeV state as 4^+, rather than 2^+, and means that the energy spacing characteristic of such a band is destroyed. Since there is no other 2^+ state known at this excitation energy in ^{32}S, the present result is strong evidence against the proposed band.

This work was supported by the Natural Sciences and Engineering Research Council of Canada.

[1]B. F. Bayman, P. J. Ellis, and Y. C. Tang, Phys. Rev. Lett. **49**, 532 (1982).
[2]H. Schultheis and R. Schultheis, Phys. Rev. C **27**, 1367 (1983).
[3]Karlheinz Langanke, Phys. Rev. C **28**, 1574 (1983).
[4]H. Schultheis and R. Schultheis, Phys. Rev. C **25**, 2126 (1982).
[5]H. Nann and B. H. Wildenthal, Phys. Rev. C **13**, 1009 (1976).
[6]D. W. O. Rogers, W. R. Dixon, and R. S. Storey, Nucl. Phys. **A281**, 345 (1977).
[7]H. E. Gove, *Nuclear Reactions,* edited by P. M. Endt and M. DeMeur (North-Holland, Amsterdam, 1959), Chap. VI.
[8]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), p. 382.
[9]P. M. Endt and C. van der Leun, Nucl. Phys. **A310**, 1 (1978).
[10]J. Vernotte, M. Langevin, S. Fortier, E. Bozek, A. Chevallier, A. J. Pape, and J. C. Sens, Nucl. Phys. **A124**, 350 (1969).
[11]G. Glatz, P. Betz, J. Siefert, F. Heidinger, and H. Röpke, Phys. Rev. Lett. **46**, 1559 (1981).