and (5)–(7), level-density parameters that reproduce the average cross sections and the compound level densities are consistent with the observed widths. The J dependence of the width can also be calculated, and it is found that Γ_J varies only weakly with J, as indicated in Fig. 8(b).

V. SUMMARY

The odd-even shift required to match the level densities of even-even ^{56}Fe with odd-even ^{55}Mn has been found to be independent of excitation energy up to 23 MeV. The conventional procedure of subtracting pairing-energy corrections for even-even and odd-even nuclei to determine the effective excitation energy has been found to be inadequate. A more satisfactory procedure has been found to be to define the effective excitation energy from a reference surface between the even-even and odd-even ground-state mass surface rather than the odd-odd mass surface. A similar conclusion has recently been reported by Gadioli and Zetta.[17] It is interesting to note that a nuclear level-density model,[18] analogous to that used to describe superconductivity in metals, predicts a reference surface closer to the even-even than the odd-odd ground-state surface. The values of the level-density parameter a obtained using the new pairing-energy corrections are smaller than those obtained by the conventional procedure and are in better agreement with theoretical expectations.

ACKNOWLEDGMENTS

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Mean Lives of Some States in Si^{31} below 3.54 MeV*

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A Ge(Li) detector and the reaction $Si^{30}(d, p)Si^{31}$ with $E_d = 2$–4 MeV are used in the coincidence version of the Doppler-shift attenuation method to obtain the following information concerning the mean lives of some low-lying states in Si^{31}: $\tau(0.75\text{ MeV}) = (7.2_{-1.8}^{+2.6})\times10^{-13}$ sec, $\tau(1.69\text{ MeV}) = (7.4\pm2.3)\times10^{-13}$ sec, $\tau(2.32\text{ MeV}) < 3\times10^{-13}$ sec, $\tau(3.14\text{ MeV}) = (5.0_{-2.6}^{+2.2})\times10^{-13}$ sec, $\tau(3.53\text{ MeV}) < 3.7\times10^{-14}$ sec. From these results, the reduced matrix elements for electromagnetic transitions among some of these states are obtained. A comparison is made between these reduced matrix elements and those predicted by the extreme single-particle model, the Nilsson rotational model, and the shell model with configuration mixing in the $2s_{1/2}$ and $1d_{3/2}$ shells. Our results indicate a value of $|\eta| = 2.8_{-0.4}^{+0.6}$ for the Nilsson deformation parameter for Si^{31}. A value of 752 ± 1 keV was obtained for the excitation energy of the 0.75-MeV state.

INTRODUCTION

RECENTLY, Webb *et al.*[1] have obtained information concerning the spins, γ-ray multipole mixing ratios, and γ-ray branching ratios of the states in Si^{31} up to 3.53 MeV (see Fig. 1). Some of these γ-ray transitions seemed to exhibit large electric quadrupole amplitudes suggesting possible collective behavior in Si^{31} as in other $2s$-$1d$ shell nuclei. Indeed, Webb *et al.*[2] have made a collective model[3,4] interpretation of the low-lying structure in Si^{31} (see Fig. 1) and were reasonably successful in obtaining a consistent explanation of the multipole mixing ratios of the ground-state transitions from the states at 1.69 and 2.79 MeV.

In addition Glaudemans *et al.*[5,6] have used an inert Si^{28} core and considered configuration mixing in the $2s_{1/2}$ and $1d_{3/2}$ shells in order to determine shell-model wave functions for nuclei between Si^{29} and Ca^{40}. Wiechers and Brussaard[7] have used these wave functions to calculate $M1$ transition probabilities among the low-lying levels of some of these nuclei.

Since the electromagnetic matrix elements are relatively very sensitive to the assumed forms of the nuclear wave functions, a measurement of the mean

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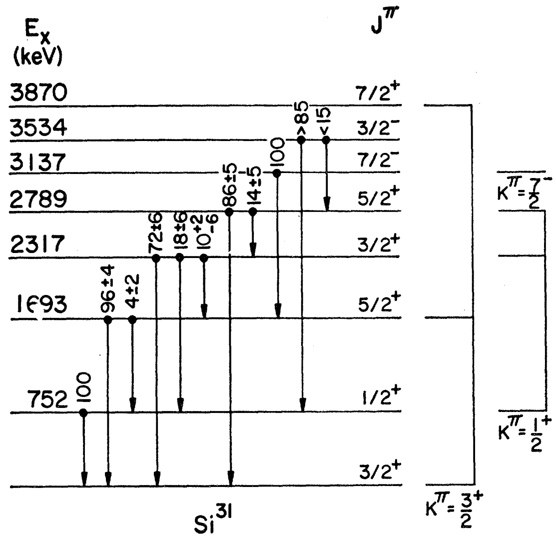

FIG. 1. Energy-level diagram for Si^{31} summarizing the known γ-ray decay schemes, spins, parities, and theoretically determined rotational quantum numbers for the first six excited states.

lives of the states in Si^{31} would be very useful in any detailed evaluation of a particular interpretation of these states. We have used the Doppler-shift attenuation method to obtain information concerning the mean lives of the states in Si^{31} up to 3.54 MeV. The results of this investigation are presented in the following report, and are compared with the predictions of the Nilsson rotational model,[2–4] the shell model,[5,6] and the extreme single-particle model.[8]

EXPERIMENTAL PROCEDURE

Method

Reference 9 contains a complete description of the method we have used to measure Doppler shifts. The ratio of the measured Doppler shift to the measured or calculated unattenuated Doppler shift defines the experimental attenuation factor

$$F_{\text{expt}}=\frac{\langle E_{\gamma 1}\rangle_{s,t}-\langle E_{\gamma 2}\rangle_{s,t}}{(E_0/c)\langle \mathbf{v}_0\rangle_p\cdot[\langle\hat{r}\rangle_{\gamma 1}-\langle\hat{r}\rangle_{\gamma 2}]}, \qquad (1)$$

where $\langle E_{\gamma i}\rangle_{s,t}$ is the space-and-time-averaged energy of γ rays seen by a finite detector at position i, and $\langle \mathbf{v}_0\rangle_p$ is the initial velocity, $\mathbf{v}_0$, of the recoiling ions averaged over all initial velocities allowed by the size of the particle detector. The unit vector $\hat{r}$ is in the direction of an emitted γ ray, and $\langle\hat{r}\rangle_{\gamma i}$ is its average over the dimensions of the γ-ray detector at position i. We have calculated the unattenuated Doppler shift.[9,10]

The mean life was determined from the experimental attenuation factor using essentially the method of Blaugrund.[11] The equations of Lindhard *et al.*[12] were used to calculate the nuclear and electronic stopping powers.[9,13] In addition, slowing down in the target and backing materials are considered as described in detail in Refs. 9 and 10.

We have used two types of experimental arrangements to observe γ rays emitted at two different angles with respect to the initial direction of the recoiling nuclei. The first configuration, discussed in Ref. 9, used one target and one silicon surface-barrier detector, and required the Ge(Li) crystal to be located alternately at two different angles with respect to the recoiling nuclei. The second configuration, an improvement over the first, employs two targets, two particle detectors, and a stationary Ge(Li) crystal located midway between the two targets. This experimental arrangement has been discussed in detail previously.[14] Since γ rays emitted at two different angles with respect to the incident direction of the recoiling nuclei are recorded simultaneously, this arrangement minimizes the systematic errors resulting from gain shifts in the electronics or zero-level drift in the analog-to-digital converter (ADC) of the pulse-height analyzer.

Targets of 100–300 μg/cm^2 of SiO enriched to 95.5% in Si^{30} were evaporated onto thick tantalum strips. The thickness of the targets were determined by weighing them. The targets were mounted horizontally and adjusted so that half of a 50–100-nA beam of 2–4-MeV deuterons hit each target. Recoiling Si^{31} ions were produced in the reaction $Si^{30}(d,p)Si^{31}$. The protons from this reaction were detected in two 1000-μ-thick, 300-mm^2 annular surface-barrier detectors which sub-

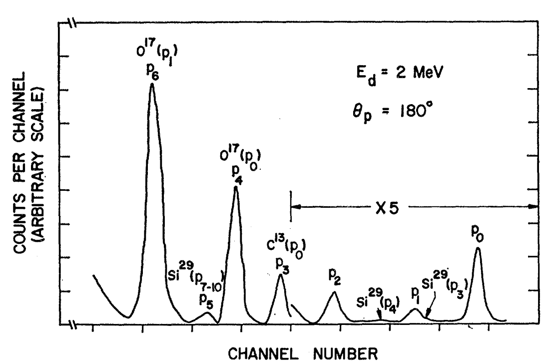

FIG. 2. A proton pulse-height spectrum from the reaction $Si^{30}(d,p)Si^{31}$. Proton groups leading to states in Si^{31} are indicated by the number of the state. Those proton groups resulting from Si^{28}, carbon, and oxygen impurities in the target are also shown.

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tended angles from 140° to 170° with respect to the incident beam direction. These detectors were covered with a 50–200-μ-thick aluminum foil to keep the elastically scattered deuterons from being detected. A typical proton spectrum obtained with one of these detectors is shown in Fig. 2.

Two 20-cm^3 Ge(Li) γ-ray detectors were used during the course of the measurements on Si.[31] These Ge(Li) crystals had 4- and 10-keV resolution full width at half-maximum (FWHM) for 1-MeV γ rays. Gamma rays in coincidence with protons detected by the upstream detector were routed to one-half of a 1024-channel memory and those in coincidence with the downstream detector were routed to the other half. The γ-ray pulses were analyzed with a 4096-channel ADC. The zero-level of the ADC and the gain of all the electronics were digitally stabilized. As a check on the stability of the electronics, the shift of the long-lived[15] [$\tau=(2.587\pm0.042)\times10^{-10}$ sec] 871-keV state in O^{17} was measured simultaneously with the measurements on the states at 0.75, 1.69, and 3.53 MeV in Si^{31}. These measurements were performed with the experimental arrangement of Ref. 9. In all of these cases the shift of the 871-keV γ ray was found to be zero, as it should be, within the statistical uncertainties of the measurements.

Several fast amplifiers and a low-level discriminator were used to obtain timing signals for the γ-ray pulses, and the zero crossover of the proton pulses was used for the proton timing signals. The fast coincidence circuit consisted of a time-to-amplitude converter (TAC) whose output was passed through a single-channel analyzer. The TAC was started by the γ-ray timing pulses and stopped by the proton timing signals. A resolving time of $2\tau=30$ nsec FWHM was obtained with this circuit. The chance rate was measured by comparing the yield of the γ rays of interest to that of the 0.511-MeV γ rays in the coincidence and singles spectra and was less than 3%. Pulse pile-up in the linear γ-ray leg was reduced by rejecting any two γ-ray pulse which were closer together in time than 16 μsec.

Data Reduction and Error Analysis

Average γ-ray energies used in the numerator of Eq. (1) were obtained from pulse-height spectra as described in Refs. 9 and 10. The uncertainty $\delta(\tau)$ in the value of the mean life of a nuclear state determined with the Doppler-shift attenuation method depends on the uncertainties of the following quantities: (a) the experimental attenuation factor F_{expt}; (b) the thickness of the target; and (c) the values of the stopping powers of the target and backing materials. In order to obtain a reasonable estimate of the error $\delta(\tau)$, we have treated the uncertainties in (a) and (b) as random errors; whereas the errors in the calculation of the stopping powers have been assumed to be systematic.[13]

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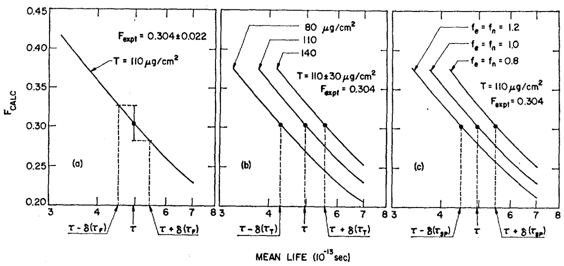

FIG. 3. An illustration of how the errors in the mean life $\delta(\tau_F)$, $\delta(\tau_T)$, and $\delta(\tau_{sp})$ due to the uncertainties in F_{expt}, the target thickness, and the stopping powers, respectively, are obtained for the measurements on the 3.14-MeV state in Si^{31}.

The contributions of (a), (b), and (c) to $\delta(\tau)$ are discussed below.

When a mean life τ is inferred from an attenuation factor F_{expt} there is an uncertainty in the mean life $\delta(\tau_F)$ which results from the statistical uncertainty $\delta(F_{\text{expt}})$ in F_{expt}. The graph in Fig. 3(a) shows how $\delta(\tau_F)$ is obtained from $\delta(F_{\text{expt}})$ for the measurements on the 3.14-MeV state in Si^{31}. If the mean life is read from an F-versus-τ curve corresponding to the target thickness T used in the experiment, there is an error $\delta(\tau_T)$ propagated by the uncertainty $\delta(T)$ in the target thickness. The graph in Fig. 3(b) shows how $\delta(\tau_T)$ is obtained for the measurements on the 3.14-MeV state in Si^{31}. Finally, there is some evidence that stopping powers calculated from the theory of Lindhard *et al.*[12] may disagree with the measured values by 10 to 20%.[13] However, the information is not conclusive and the calculated stopping powers have been used in the present work. Systematic uncertainties of 20% were assigned to these values. Since we are treating these as systematic errors, the error $\delta(\tau_{sp})$ in the mean life due to these errors may be expressed as

$$\delta(\tau_{sp})=\delta(\tau_e)+\delta(\tau_n), \tag{2}$$

where $\delta(\tau_e)$ and $\delta(\tau_n)$ are the errors in the mean life resulting from the errors in the calculated electronic and nuclear stopping powers, respectively. Equation (2) states that the errors $\delta(\tau_e)$ and $\delta(\tau_n)$ are additive. Thus, we have calculated the F-versus-τ curves for various combinations of $(dE/dx)_e=f_e(dE/dx)_{e\,\text{calc}}$ and $(dE/dx)_n=f_n(dE/dx)_{n\,\text{calc}}$, where $(dE/dx)_{e\,\text{calc}}$ and $(dE/dx)_{n\,\text{calc}}$ are the calculated electronic and nuclear stopping powers, respectively, and f_e and f_n are constants[13] equal to 1.0 ± 0.2. The curves yielding the largest variance from the curve calculated for $f_e=f_n=1.0$ were used to determine $\delta(\tau_{sp})$. In the present experiments values of $f_e=f_n=1.2$ and $f_e=f_n=0.8$ yielded the largest differences from the $f_e=f_n=1.0$ curve. The graph in Fig. 3(c) shows how $\delta(\tau_{sp})$ is obtained for the measurements on the 3.14-MeV state in Si^{31}.

The total error $\delta(\tau)$, in the mean life due to all of the sources of error that have been considered here [$\delta(\tau_F)$,

TABLE I. Doppler shifts and mean lives in Si^{31}.[a]

Transition energies (MeV)	Target thickness $Si^{30}O_2$ (μg/cm^2)	$\langle \lvert v_0 \rvert \rangle_p/c$	$\Delta\langle E_\gamma \rangle$ (keV)	F_{expt}	$\tau \pm \delta(\tau_{\mathrm{FT}})$ (10^{-13} sec)	$\tau \pm \delta(\tau)$ (10^{-13} sec)
$0.75 \to 0$	200 ± 30	0.00553	2.11 ± 0.28	0.275 ± 0.038	$7.2_{-1.0}^{+1.4}$	$7.2_{-1.8}^{+2.6}$
$1.69 \to 0$	200 ± 30	0.00525	4.41 ± 0.62	0.270 ± 0.040	$7.4_{-1.3}^{+1.4}$	7.4 ± 2.3
$2.32 \to 0$	310 ± 30	0.00766	32.6 ± 6.5	1.0 ± 0.2	<3	<3
$2.79 \to 0$	310 ± 30	0.00553	no measurement		...	...
$3.14 \to 1.69$	110 ± 30	0.00532	4.01 ± 0.29	0.304 ± 0.024	$5.0_{-2.0}^{+1.7}$	$5.0_{-2.6}^{+2.2}$
$3.53 \to 0.75$	200 ± 30	0.00462	23.05 ± 0.65	0.988 ± 0.033	<0.30	<0.37

[a] The errors in column 6 include only the statistical errors in F_{expt} and target thickness. In addition to these statistical errors the quoted errors in column 7 include a $\pm 20\%$ systematic error assigned to the calculated electronic and nuclear stopping powers.

$\delta(\tau_{\mathrm{T}})$, and $\delta(\tau_{sp})$] is

$$\delta(\tau) = \delta(\tau_{\mathrm{FT}}) + \delta(\tau_{sp}), \tag{3}$$

where

$$\delta(\tau_{\mathrm{FT}}) = \{[\delta(\tau_{\mathrm{F}})]^2 + [\delta(\tau_{\mathrm{T}})]^2\}^{1/2}. \tag{4}$$

Equations (3) and (4) state that $\delta(\tau)$ is obtained from the simple addition of the error $\delta(\tau_{sp})$ due to the systematic errors in the stopping powers to the statistical error $\delta(\tau_{\mathrm{FT}})$ due to the random errors in F_{expt} and the target thickness T.

RESULTS

Doppler shifts have been measured for the states at 0.75, 1.69, 2.32, 3.14, and 3.53 MeV in Si^{31}. Spectra typical of those from which Doppler shifts were obtained are shown in Fig. 4. Results of these measurements are presented in Table I. Column 3 of that table gives calculated average initial speeds of the recoiling nuclei. Column 4 is the measured difference in average energies of γ rays emitted at about 30° and 150° with respect to the recoiling nuclei. On the basis of the results presented in Refs. 9 and 10, we have assigned a 1% uncertainty to the calculation of the unattenuated Doppler shift due to the uncertainties in the positions and solid angles subtended by the particle and γ-ray detectors. In addition, a 0.6% error has been included to account for the proton angular distributions. The experimental results in Table I are statistical averages of several measurements of each Doppler shift. Errors in column 6 only include the statistical errors in the target thickness and F_{expt}, whereas column 7 also includes a 20% systematic error assigned to the calculated electronic and nuclear stopping powers.

The mean life limits for the 2.32- and 3.53-MeV states were determined from attenuation factors which were two standard deviations away from our measured values. A value of 752 ± 1 keV was determined for the γ-ray energy of the $0.75 \to 0$-MeV transition and hence for the excitation energy of the first excited state in Si^{31}.

DISCUSSION

We used the following values of the Nilsson rotational model parameters suggested by Webb *et al.*[2] to calculate the reduced matrix elements for magnetic dipole ($M1$) and electric quadrupole ($E2$) transitions: (a) the deformation parameter $\eta = -2$; (b) the core gyromagnetic ratio $g_R = 0.35$; (c) the spin-orbit coupling parameter $\kappa = 0.10$; and hence (d) $\delta \simeq \eta\kappa = -0.20$, where δ is the spheroidicity parameter. In order to keep the comparisons clear, mixing between bands has not been considered. The shell-model estimates for the reduced matrix elements for $M1$ transitions were calculated from the expressions for $B(M1)$ in Ref. 7, and from the wave functions tabulated in Ref. 6.

0.75-MeV State; $J^\pi = \frac{1}{2}^+$

The shell-model wave function for this state is[6]

$$\Psi^{1/2+}(0.75\text{-MeV}) = [s_{1/2}(d_{3/2}{}^2)^0]^{1/2}. \tag{5}$$

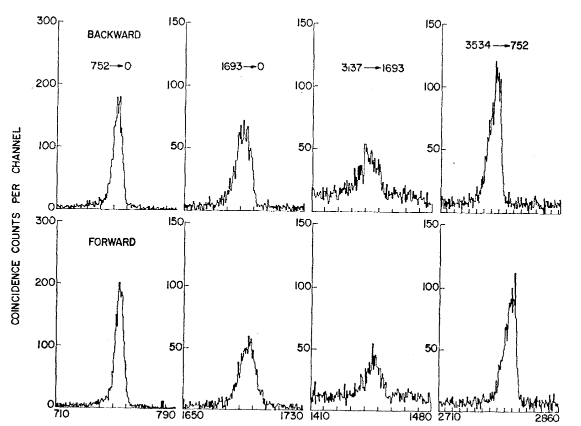

FIG. 4. Pulse-height spectra of γ rays in coincidence with protons associated with the population of the states at 752, 1693, 3137, 3534 keV in Si^{31}. The dispersion in the pulse-height analyzer was 0.539, 0.578, 0.565, and 0.792 keV/channel for the measurements on the states at 752, 1693, 3137, and 3534 keV, respectively.

That is, the 0.75-MeV state is a product wave function of one particle in the $s_{1/2}$ shell and two particles in the $d_{3/2}$ shell. The wave function for the inert Si^{28} core is not included in Eq. (5). Similarly, the ground-state wave function of Si^{31} is[6]

$$\Psi^{3/2+}(0\text{ MeV}) = -(0.871)^{1/2}[(s_{1/2}{}^2)^0 d_{3/2}]^{3/2} + (0.027)^{1/2} \times [s_{1/2}(d_{3/2}{}^2)^2]^{3/2} - (0.102)^{1/2}(d_{3/2}{}^3)^{3/2}. \quad (6)$$

The only $M1$ transition from the 0.75-MeV state which satisfies the $\Delta l=0$ selection rule for $M1$ transitions[16] is the transition to the 2.7% admixture of $[s_{1/2}(d_{3/2}{}^2)^2]^{1/2}$ in the ground-state wave functions. Although this transition satisfies the $\Delta l=0$ selection rule, it does not obey the angular-momentum selection rule which forbids dipole radiation in the transition between the 0^+ and 2^+ configurations of the two $d_{3/2}$ particles,[7] i.e., $|0-2| \leq 1 \leq 0+2$ is not satisfied. Thus, an $M1$ transition between the 0.75- and 0.0-MeV states is forbidden by the shell model.

In the collective model the 0.75→0-MeV transition is a single-particle, *interband* transition between the $K^\pi = \frac{1}{2}^+$ and $K = \frac{3}{2}^+$ band heads (i.e., between Nilsson orbits[4] 9 and 8, respectively) in the Nilsson-model picture of Si^{31} as described by Webb *et al.*[2] Since $\Delta K=1$ satisfies the $\Delta K \leq L$ selection rule[17] for 2^L-pole radiation, this transition is allowed to have a magnetic dipole component.

The present measurement of the mean life of this state permits a check of these predictions. However, the multipole mixture of the 0.75-MeV $(J^\pi=\frac{1}{2}^+)$→0-MeV $(J^\pi=\frac{3}{2}^+)$ transition is not known. In the Nilsson model[2,4] the properties of ${}_{14}Si_{17}{}^{31}$ and ${}_{16}S_{17}{}^{33}$ are similar. Using this model, the fact that the 0.84-MeV $(J^\pi=\frac{1}{2}^+)$→0-MeV $(J^\pi=\frac{3}{2}^+)$ transition in S^{33} is[18] 99% $M1$ indicates that the 0.75→0-MeV transition in Si^{31} is also largely $M1$. Therefore, we will make the reasonable assumption that this transition is pure $M1$. With this assumption, and using our measurement of the mean life of this state, we may calculate the reduced matrix element for this transition and compare it to the estimates of the extreme single-particle model B_W,[8] the shell model,[5–7] and the Nilsson rotational model.[2,4] The results of these comparison are

$$\frac{B_{\text{expt}}(M1\colon 0.75\to 0\text{ MeV})}{B_W(M1\colon 0.75\to 0\text{ MeV})} = 0.12_{-0.03}^{+0.06},$$

$$\frac{B_{\text{expt}}(M1\colon 0.75\to 0\text{ MeV})}{B_{SM}(M1\colon 0.75\to 0\text{ MeV})} = \infty,$$

$$\frac{B_{\text{expt}}(M1\colon 0.75\to 0\text{ MeV})}{B_{NM}(M1\colon 0.75\to 0\text{ MeV})} = 0.94_{-0.23}^{+0.50}.$$

The Nilsson-model estimate is in excellent agreement with the experimental value. The 0.75→0-MeV transition is forbidden in the shell-model description of Si^{31}; whereas Wilkinson[8] concluded that $|M(M1)|^2 \equiv B_{\text{expt}}(M1)/B_W(M1) \approx 0.15$ is the expected *a priori* value for magnetic dipole transitions in light $(A<20)$ nuclei.

1.69-MeV State; $J^\pi = \frac{5}{2}^+$

1.69-MeV $(J^\pi=\frac{5}{2}^+,\ K=\frac{3}{2})$→*0-MeV* $(J^\pi=\frac{3}{2}^+,\ K=\frac{3}{2})$ *Transition*

Webb *et al.*[1] determined two possible values for the $E2/M1$ amplitude ratio in this transition, 4.70 ± 1.00 and (0.49 ± 0.10). The larger value was much more probable, although the 0.49 ± 0.10 value could not be entirely ruled out.[1] Webb *et al.*[2] were also quite successful in using a Nilsson-model interpretation of Si^{31} to calculate the large $E2/M1$ mixing ratio indicated by the 4.70 ± 1.00 value. In addition to predicting the usual enhancement of the $E2$ amplitude in this *intraband* transition, their Nilsson-model calculations also suggest the $M1$ component of this transition is inhibited.[2] The shell model also predicts an inhibition of this magnetic dipole transition rate. The shell-model wave function for this state is[6]

$$\Psi^{5/2+}(1.69\text{ MeV}) = [s_{1/2}(d_{3/2})^2]^{5/2}. \quad (7)$$

Therefore, the only $M1$ transition to the ground state which satisfies the $\Delta l=0$ selection rule[16] is the transition to the 2.7% admixture of $[s_{1/2}(d_{3/2}{}^2)^2]^{3/2}$ in the ground-state wave function.

Again, our measurement of the mean life of this state, together with the previously measured values for the branching ratio and multipole mixture of this transition completely determines the reduced matrix elements. A comparison of these matrix elements with those predicted by the models are as follows: for magnetic dipole radiation, we obtain

$$\frac{B_{\text{expt}}(M1\colon 1.69\to 0\text{ MeV})}{B_W(M1\colon 1.69\to 0\text{ MeV})} = (4_{-2}^{+3}) \times 10^{-4},$$

$$\frac{B_{\text{expt}}(M1\colon 1.69\to 0\text{ MeV})}{B_{SM}(M1\colon 1.69\to 0\text{ MeV})} = 0.71_{-0.33}^{+0.48}$$

$$\frac{B_{\text{expt}}(M1\colon 1.69\to 0\text{ MeV})}{B_{NM}(M1\colon 1.69\to 0\text{ MeV})} = 3_{-1}^{+2}.$$

The Nilsson model and the shell model are in good agreement with the measured value of the reduced matrix element for $M1$ radiation, while the $|M(M1)|^2$ value indicates that this $M1$ transition is inhibited even more than the usual value of 0.15 for light nuclei.[8] For

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[18] J. E. Cummings and D. J. Donahue (to be published).

the electric quadrupole radiation, we have

$$\frac{B_{\mathrm{expt}}(E2\colon 1.69\to 0\ \mathrm{MeV})}{B_{\mathrm{W}}(E2\colon 1.69\to 0\ \mathrm{MeV})}=12_{-3}^{+6},$$

$$\frac{B_{\mathrm{expt}}(E2\colon 1.69\to 0\ \mathrm{MeV})}{B_{\mathrm{NM}}(E2\colon 1.69\to 0\ \mathrm{MeV})}=2.0_{-0.5}^{+1.0}.$$

Again the Nilsson model is in good agreement with the experimental value of the reduced matrix element; whereas the extreme single-particle model comparison indicates this transition is enhanced over the single-particle estimate as is usually the case in the s-d shell and other light nuclei.[8]

Instead of using the Nilsson model to predict the magnitudes of the reduced matrix elements, we may assume the validity of this model and use the measured values of these matrix elements to obtain information concerning the nuclear shape.[17] Using the equations in Kerman[17] and $B_{\mathrm{expt}}(E2\colon 1.69\to 0\ \mathrm{MeV})=(7_{-2}^{+4})\times 10^{-51}$ e^2 cm^4, we obtain

$$|Q_0|=0.45_{-0.06}^{+0.11}\ \mathrm{b}$$

for the magnitude of the intrinsic quadrupole moment of Si^{31}. This value yields[17] a value of $|\beta|=0.30_{-0.04}^{+0.07}$ for the deformation parameter of Si^{31}. Calculations in which β is deduced by minimizing the total energy summed over all Nilsson orbits give a result of[19] $\beta=-0.38$ for the deformation of Si^{31}. If a value of $\kappa=0.10$ is used for the spin-orbit coupling strength, the value of the deformation parameter β corresponds[4] to the following value of the Nilsson-model deformation parameter η: $|\eta|=2.8_{-0.4}^{+0.6}$. This value is in good agreement with the $\eta=-2$ value suggested by Webb *et al.*[2]

1.69-*MeV* ($J^\pi=\frac{5}{2}^+$, $K=\frac{3}{2}$)$\to$0.75-*MeV* ($J^\pi=\frac{1}{2}^+$, $K=\frac{1}{2}$) *Transition*

If the band-mixed[20] Nilsson wave functions determined by Webb *et al.*[2] are used to calculate the expected branching of the 1.69-MeV state the results are[21] 0.997 and 0.003 for the branches to the ground state and first excited state, respectively. The value of 0.003 is not in good agreement with the measured 0.04±0.02 branch, but it is within two standard deviations of this branch.

3.14-MeV State; $J^\pi=\frac{7}{2}^-$

The $M2/E1$ mixing ratio for the 3.14-MeV ($J^\pi=\frac{7}{2}^-$, $K=\frac{7}{2}$)$\to$1.69-MeV ($J^\pi=\frac{5}{2}^+$, $K=\frac{3}{2}$) transition is[1] $x=+0.11\pm0.10$. This multipole mixture and our value for the mean life of this state yield

$$|M(E1)|^2\approx(6_{-2}^{+6})\times10^{-4}.$$

This $|M|^2$ value is in the range of inhibited $E1$ transitions.[8] Since $\Delta K=2$, this large inhibition could be evidence of the $\Delta K\leq 1$ selection rule[17] for dipole transitions. However, the 3.14$\to$1.69-MeV transition is a complicated one involving the rearrangement of at least two particles, so that this transition would be expected to be slow, even from a shell-model viewpoint.

3.53-MeV State; $J^\pi=\frac{3}{2}^-$

If we assume the 3.53-MeV ($J^\pi=\frac{3}{2}^-$)$\to$0.75-MeV ($J^\pi=\frac{1}{2}^+$) transition is pure $E1$, then our upper limit of 3×10^{-14} sec for the mean life of this state leads to $|M(E1)|^2>0.001$, suggesting that this is a single-particle transition, unlike the 3.14$\to$1.69-MeV transition. In addition, there is a strong $l=1$ stripping pattern to this state in the reaction[22,23] Si$^{30}(d,p)$Si^{31}, indicating that this level can be described mainly as a single particle coupled to the Si^{30} ground state.

From the Si$^{30}(d,t)$Si^{29} and Si^{30}(He^3,α)Si^{29} pickup reactions Dehnhard and Yntema[24] concluded that the ground state of Si^{30} is a mixture of about 50% $(s_{1/2}{}^2)^0$ and 50% $(d_{3/2}{}^2)^0$. The shell-model wave function for the ground state of Si^{30} is in reasonable agreement with their conclusions. This wave function is given as[6]

$$\Psi^{0+}(\mathrm{Si}^{30}\colon 0\ \mathrm{MeV})=-(0.726)^{1/2}(s_{1/2}{}^2)^0+(0.274)^{1/2}(d_{3/2}{}^2)^0. \quad (8)$$

Therefore, from the stripping and pickup results, we might expect the shell-model wave function for the 3.53-MeV state to be similar to the wave function composed of a single $p_{3/2}$ neutron coupled to the ground state of Si^{30}. This can be expressed as

$$\Psi^{3/2-}(3.53\ \mathrm{MeV})=a[(s_{1/2}{}^2)^0p_{3/2}]^{3/2}+b[(d_{3/2}{}^2)^0p_{3/2}]^{3/2}, \quad (9)$$

where $|a|^2+|b|^2=1$.

If we use Eq. (9) for the shell-model wave function of the 3.53-MeV state, it is possible to have single-particle $E1$ transitions from this state to the states at 0.75 and 0 MeV. In addition, since $T(L)=(E_\gamma)^{2L+1}$, the ground-state branch would be energetically favored over the branch to the 0.75-MeV state. Therefore, the absence of the 3.53$\to$0-MeV transition, together with our result that the 3.53$\to$0.75-MeV transition is probably a single-particle transition, could mean that the wave function for the 3.53-MeV state is predominantly $[(d_{3/2}{}^2)^0p_{3/2}]^{3/2}$.

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TABLE II. A summary of the comparisons of the $B_{expt}(\sigma L)$ deduced from the results of measurements on Si^{31} with those predicted by the extreme single-particle model, the Nilsson model, and the shell model.

Transition energies (MeV)	Multipole mixing ratio x[a]	Multipole type σL	$B_{expt}(\sigma L)/B_W(\sigma L)$[b]	$B_{expt}(\sigma L)/B_{NM}(\sigma L)$[c]	$B_{expt}(\sigma L)/B_{SM}(\sigma L)$[d]
$0.75 \to 0$	...	$M1$[e]	$0.12_{-0.03}^{+0.06}$	$0.94_{-0.23}^{+0.50}$	∞[f]
$1.69 \to 0$	4.70 ± 1.00	$M1$	$(4_{-2}^{+3}) \times 10^{-4}$	3_{-1}^{+2}	$0.71_{-0.33}^{+0.48}$
		$E2$	12_{-3}^{+6}	$2.0_{-0.5}^{+1.0}$	
$1.69 \to 0.75$	...	$E2$[e]	10_{-6}^{+7}	220_{-120}^{+150}	
$2.32 \to 0$	$0.09 \leq x \leq 2.75$ $-2.75 \leq x \leq -70$	$M1$[e]	>0.006	>0.12	
$3.14 \to 1.69$	0.11 ± 0.10	$E1$	$(6_{-2}^{+6}) \times 10^{-4}$	∞[g]	
$3.53 \to 0.75$	$0.58 \leq x \leq \infty$ $-1.73 \leq x \leq 0.0$	$E1$[e]	>0.001	...	

[a] Reference 1.
[b] Reference 8.
[c] References 4 and 17.
[d] References 6 and 7.
[e] A value of $x=0$ was used to calculate $B_{expt}(\sigma L)$.
[f] $B_{SM}(M1\colon 0.75 \to 0 \text{ MeV})=0$.
[g] $B_{NM}(E1\colon 3.14 \to 1.69 \text{ MeV})=0$.

Finally, we did not see any evidence for a doublet at 0.75 MeV in the γ-ray decay spectrum for the 3.53-MeV state. This is evidence that the branch to the state at 2.79 MeV does not exist, in agreement with the results of Webb *et al.*[1] However, the energy difference between the 3.53- and 2.79-MeV states is 745 ± 6 keV,[25] which overlaps our value of 752 ± 1 keV for the excitation energy of the 0.75-MeV state. Therefore, we might not have been able to resolve the 0.75-MeV γ rays originating in the $3.53 \to 2.79$-MeV transition from those in the $3.53 \to 0.75 \to 0$-MeV transition. The results of cross-section measurements for the formation of the 2.79-MeV state[22,23] by $Si^{30}(d,p)Si^{31}$ indicate a complicated structure for this state. Since we found the 3.53-MeV state to be short-lived, it seems unlikely that a branch to the complicated state at 2.79 MeV would exist.

2.32-MeV ($J^\pi = \frac{3}{2}^+$) and 2.79-MeV ($J^\pi = \frac{5}{2}^+$) States

In the present experiment the yield from these states was very low. Consequently, we have only a poor upper limit for the mean life of the 2.32-MeV state and no measurement on the state at 2.79 MeV.

SUMMARY AND CONCLUSION

Table II summarizes the comparisons of the experimentally determined reduced matrix elements with those predicted by the extreme single-particle model, the Nilsson rotational model, and the shell model with configuration mixing. From the results of Webb *et al.*[1,2] and our mean-life measurements we conclude the Nilsson model provides an excellent description of the electromagnetic properties of the 0.75- and 1.69-MeV states in Si^{31}. The model seems to be particularly successful with the $M1$ transitions from these states. Our results also indicate a value of $|\eta| \approx 2.8_{-0.4}^{+0.6}$ for the Nilsson deformation parameter in reasonable agreement with the $\eta = -2$ value suggested by Webb *et al.*[2]

Our upper limit on the mean life of the 3.53-MeV state in Si^{31} and the absence of the $3.53 \to 0$-MeV branch indicate that this state is predominantly a $[(d_{3/2}{}^2)^0 p_{3/2}]^{3/2}$ configuration. Although the shell model was not very successful in describing the electromagnetic properties of the 0.75-MeV state, it was successful in predicting the $M1$ intensity of the $1.69 \to 0$-MeV transition. In addition it seemed to explain the general electromagnetic properties of the states at 3.14 and 3.53 MeV. Thus, for Si^{31} as for many other nuclei in the $2s$-$1d$ shell, it seems that some transitions are best described by the Nilsson rotational model, and some by the shell model, while a few may be described well by both models.

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