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First two members of the $K^\pi = 0^-$ band in ^{20}Ne

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In an alpha capture experiment on an ^{16}O gas target, the 3^-, 7.156 MeV state in ^{20}Ne has been observed to decay to the 1^-, 5.782 MeV and the 4^+, 4.248 MeV states with gamma ray branches of $45 \pm 5\%$ and $55 \pm 5\%$, respectively. The strengths of the 1374 and 2908 keV transitions were deduced to be $B(E2) = 51 \pm 8$ W.u. and $B(E1) = 79 \pm 9$ μW.u., respectively. The strongly enhanced $E2$ rate for the 3^- to 1^- transition is convincing evidence for these two states being the first members of this $K^\pi = 0^-$ band in ^{20}Ne. From resonance scattering experiments, the alpha widths for these two states were determined to be 28 ± 3 eV and 8.1 ± 0.3 keV, respectively; values in agreement with cluster calculations of alpha widths in ^{20}Ne.

[NUCLEAR REACTIONS Measured $\sigma(E,\theta)$ for $^{16}O(\alpha,\alpha)^{16}O$ and $\sigma(E_R)$ for $^{16}O(\alpha,\gamma)^{20}Ne$; deduced Γ_α for $E_x = 5.782$ and 7.156 MeV and radiative transition rates from $E_x = 7.156$ MeV.]

INTRODUCTION

A $K^\pi = 0^-$ band, beginning with the state at 5.782 MeV is one of the many bands proposed empirically and theoretically in ^{20}Ne. Experimental evidence for a state to be a member of this particular band comes mostly from alpha transfer reactions[1] which selectively excite certain levels whose energies follow a rotationlike $J(J+1)$ dependence. These reactions also excite the ground state band which is well established on the basis of the level energies which follow, at least to first order, a $J(J+1)$ dependence and the enhanced $E2$ rates for transitions between the levels.[2] In the $K^\pi = 0^-$ band, no rates are known for in-band transitions and as has been pointed out by Buck *et al.*,[3] a measurement of such a rate would be very useful in establishing the nature of this band.

The high cross sections in the transfer reactions to states in the $K^\pi = 0^-$ band suggest that the reduced alpha widths for these states are large. In fact, although the spectroscopic factors derived from experiment are not always consistent[4] between reactions using different projectiles, they are large and approach one in some cases. Most confidence is placed in the results using relatively heavy projectiles, e.g., ^{11}B and ^{13}C, and high energies since these conditions favor the direct reaction mechanism. Unfortunately, under these conditions, states of lower angular momentum are not as readily excited and the spectroscopic factors for the 1^- and 3^- states are not well established.[1,4] Complementary to the cluster transfer reactions is the elastic scattering experiment which measures the width of the state. Such an experiment has been performed for the 3^- state[5] of this band but not the 1^- band head.

The most successful theories to account for the large reduced widths of this $K^\pi = 0^-$ band are the cluster models of Brink as discussed in Horiuchi and Suzuki,[6] and of Buck *et al.*[3] Furthermore, their predictions for the in-band $E2$ transitions, at least for the ground state band, can be brought into agreement with experiment with an effective charge considerably less than normally used in shell model calculations.[3] To deduce an effective charge for the $K^\pi = 0^-$ band requires a measurement of an $E2$ rate within the band. Unfortunately, such an experiment involves the observation of low energy gamma rays between unbound states with large particle decays. This together with the high background associated with a solid target defeated Toppel *et al.*[7] in their attempt to measure, in an alpha capture experiment, the radiative decay of the 3^- state. In this paper we report on a successful investigation of the gamma ray decay of this 3^- state and of the resonance scattering measurement of the 1^- and 3^- states.

THE EXPERIMENTS

For both the alpha capture and elastic scattering experiments, oxygen gas was contained in a windowless gas cell (Fig. 1) 8.0 cm in diameter and bombarded by $^4He^+$ ions entering and leaving the cell through two pairs of canals. The inner canals were 3 mm in diameter and 4 cm long while the outer ones were 6.4 mm in diameter and 6.4 cm long. The region between the pairs of canals was cryogenically pumped by a 10 cm diameter plate,

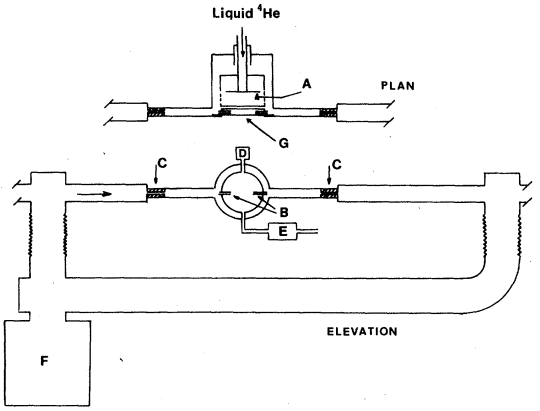

FIG. 1. Schematic drawing of the differentially cryopumped gas target equipped for gamma ray work. The components are *A*—cryogenic pumping surface, 10 cm diameter; *B*—primary gas flow restrictions; *C*—secondary gas flow restrictions; *D*—capacitance manometer; *E*—gas flow regulating valve; *F*—fast turbo pump; *G*—thin metal plate used when gamma rays are observed.

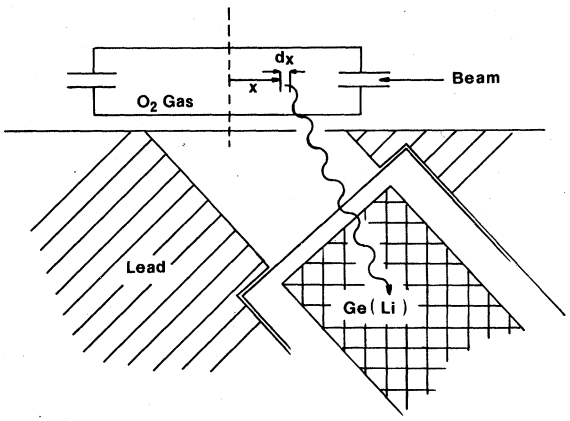

FIG. 2. Extended gas target used for the alpha capture experiment. At a pressure of 1.5 Torr reactions can occur throughout the beam path between the entrance and exit canals. The Ge(Li) detector is housed in a lead collimator to shield it from background radiation produced by the beam hitting the canals and chamber walls.

cooled with liquid helium. No difficulty was experienced in maintaining a pressure of 1.5 Torr in the gas cell and the normal operating pressure of 10^{-6} Torr in the beam line. In this situation, the oxygen gas flow to the cell was about 4 l/h and the liquid helium consumption 1.2 l/h. Without gas in the cell 30 μA beams of $^4He^+$ were routinely focused through the entrance and exit canals with less than 0.05% of the beam on either canal. The beam current was monitored in a Faraday cup, some 3 m past the gas cell. For the measurement of the number of alpha particles incident on the target gas, a correction for gas scattering and changes in the charge state of the beam as it passed through the cell was determined by measuring the current with and without gas in the cell. The gas pressure in the cell was measured with a capacitance manometer and maintained constant to ~0.2% by means of the gas-flow regulating valve.

In the elastic scattering experiments, four Si(Li) detectors of ~20 keV resolution were mounted on a plate which replaced the thin metal covering (item *G* in Fig. 1) in an arrangement similar to that of Mak *et al.*[8] Alpha particles reached the detectors through two rectangular apertures 1.6×3.2 mm^2 separated by 2.5 cm with the second aperture 1.0 cm from the counter, covered by an ~2 μg/cm^2 hydrocarbon foil which sealed the gas cell. For normalization purposes, Xe gas in an amount providing a counting rate comparable to that from the oxygen was introduced into the gas reservoir. With apertures of equal size in front of each counter, different lengths of gas, varying from ~0.24 cm for a counter at 90° to 0.94 cm for a counter near 161°, served as the reaction region. This meant that the angle subtended by a counter could be as large as 8° and that the effective angle of observation could be slightly different from the value determined by geometry. The effect of this uncertainty in angular position was investigated by fitting the resonance curves obtained with different values of the angle and incorporating the variation of the results into the errors in the final results. The best fit, in the sense of a minimum in the chi-squared statistic as a function of angle, was obtained with an angle within 1° of the nominal value determined from geometry.

For the gamma ray measurements, with a 17% Ge(Li) detector, oxygen gas, depleted by a factor of 6 in ^{17}O below its natural abundance, was used because the $^{17}O(\alpha,n\gamma)^{20}Ne$ reaction proved to be the principal source of background, especially in the low energy region. In order to increase the counting rate from the relatively wide 3^- level (~8 keV), the target was made as thick as possible by maintaining a gas pressure of 1.5 Torr in the cell. This meant that ~95% of the resonance was "compressed" into the 6.25 cm long region between tips of the entrance and exit canals. For this extended source (Fig. 2) the cross section at a position x from the center of the cell can be written as

$$\sigma(x) = (2J+1)\,\frac{\pi\lambda^2\Gamma_\alpha\Gamma_\gamma}{[E(x)-E_0]^2+(\Gamma/2)^2}\ ,$$

where $E(x)$ is the center-of-mass energy at the position x and E_0 is the resonance energy. Since the energies are measured in the laboratory this can be rewritten as

$$\sigma(x) = (2J+1)\,\frac{\pi\lambda^2\Gamma_\alpha\Gamma_\gamma}{\left[\left(\frac{M_0}{M_0+M_\alpha}\right)\left(\frac{dE}{dx}\right)x\right]^2 + (\Gamma/2)^2},$$

where dE/dx is the laboratory stopping power in the gas, provided the beam has the resonance energy at the center of the cell. In the actual experiments, the resonance curve for elastically scattered alpha particles was used to arrange that this condition was satisfied.

The total counting rate from the gas in the cell is then

$$N_{\alpha\gamma} = N_\alpha n_0 \frac{(2J+1)\pi\lambda^2\Gamma_\alpha\Gamma_\gamma}{\left[\left(\frac{M_0}{M_0+M_\alpha}\right)\left(\frac{dE}{dx}\right)\right]^2} \int_{x_1}^{x_2} \frac{\epsilon(x)W(x)dx}{x^2\left[\frac{\Gamma}{2\left(\frac{M_0}{M_0+M_\alpha}\right)\frac{dE}{dx}}\right]^2},$$

where n_0 is the number density of target atoms, $\epsilon(x)$ is the detection efficiency, and $W(x)$ reflects the angular distribution for the gamma rays from the position x. The integral was evaluated numerically from a knowledge of $\epsilon(x)$, determined by moving a point ^{56}Co source along the reaction region and from a calculation of $W(x)$ assuming that all interactions of the gamma rays occur 2.5 cm inside of the front face of the Ge(Li) detector. The importance of this assumption was tested by varying the assumed point of the interactions. It was found to contribute considerably less error to the final result than, for example, uncertainties in the source to detector distance or in the position of the resonance in the cell.

The number density of oxygen atoms n_0 was determined in three independent ways: (1) from the total gas pressure in the cell, (2) from the Rutherford scattering of 2 MeV alpha particles at $\theta_L = 120°$, and (3) from the difference in energy loss of 3.045 MeV alpha particles traversing the gas cell for a very low gas pressure (0.05 Torr) and the pressure used in the experiment. Although the first method should be the most reliable, it suffers from the criticism that the pressure is not measured where the reactions occur. In the second type of measurement, the solid angle of the detector is needed. Again there is an extended source of about 1 cm in length. Consequently a Monte Carlo procedure, in which the direction of emission for a particle leaving a small volume of the extended source was chosen randomly, was used to determine the solid angle of the detector. In the third type of measurement, the resonance yield curve at 120° was determined for pressures of 0.05 and 1.5 Torr with a beam of ~2 μA. The gas density was considered uniform in the reaction region of the gas cell and to drop exponentially by a factor of 1000 along the total length of the entrance canal. Then, from the value of the stopping power per oxygen atom,[9] the number density was obtained. All these determinations agreed with each other within statistical uncertainties and gave an atomic oxygen number density of $n_0 = (1.14 \pm 0.09) \times 10^{17}$ cm^{-3} at 1.5 Torr.

In order to investigate the influence of the beam intensity on the number density, the variation of the elastic scattering counting rate was determined as a function of beam current at a fixed gas pressure of 1 Torr. It was found that the counting rate per unit charge dropped at a rate of 0.3% per μA of beam. This drop was interpreted as a decrease in target concentration due to an increase in temperature. Thus a correction of 10% was applied to the gamma ray counting rates since these were determined with beam currents of 35 μA, which remained constant to 5% for the duration of the experiment.

THE RESULTS

The yield curves for alpha particles elastically scattered at $\theta_{c.m.} = 160°$ from ^{16}O for both the 1^- and 3^- resonances are shown in Figs. 3 and 4. The solid lines are fits to the data based on an R-matrix calculation.[10] At the 1^- resonance a single level was used in the fitting, while at the 3^- resonance three additional levels with parameters J, E, $\Gamma_\alpha = \Gamma$, of 0^+, 3.0801 MeV, 2.1 keV (Ref. 11); 0^+, 4.46 MeV, 0.8 MeV; and 2^+, 5.09 MeV, 0.8 MeV (Ref. 2) were used. Within reasonable limits none of the parameters of these levels influence the fits obtained. Fits similar to the ones shown in Figs. 3 and 4 were obtained at the other scattering angles; they confirm the spin assignments of 1^- and 3^- since the resonance shapes at all angles are only consistent with $l = 1$ and $l = 3$ transfers, respectively. A grid search technique was

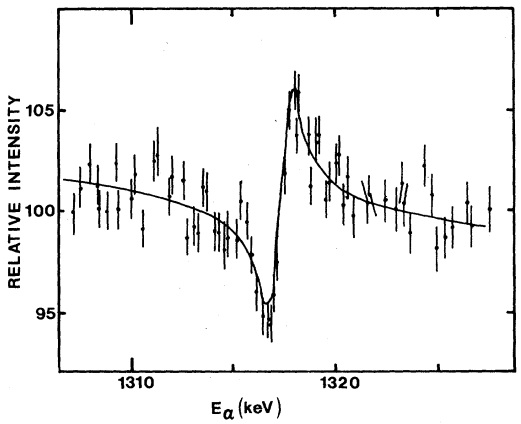

FIG. 3. Elastic scattering of α particles at $\theta_{c.m.} = 160°$ near the 1^- resonance in ^{20}Ne. The fitting procedure yields $\Gamma_\alpha = 28$ eV and $E_\alpha = 1317.4$ keV.

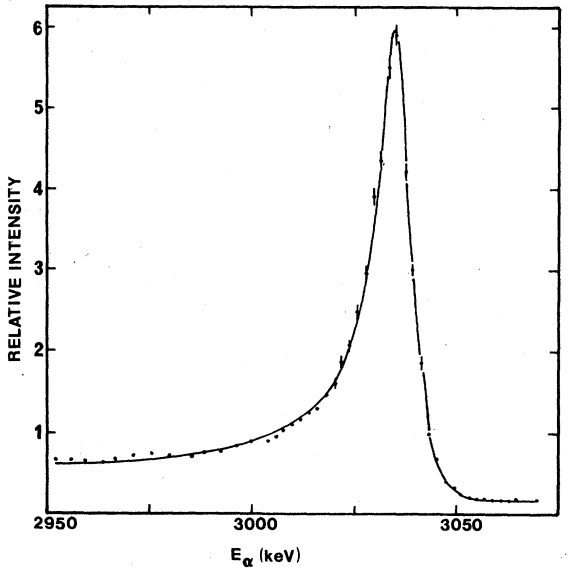

FIG. 4. Elastic scattering of α particles at $\theta_{c.m.} = 160°$ near the 3^- resonance in ^{20}Ne. The fitting procedure yields $\Gamma_\alpha = 8.1$ keV and $E_\alpha = 3036.1$ keV.

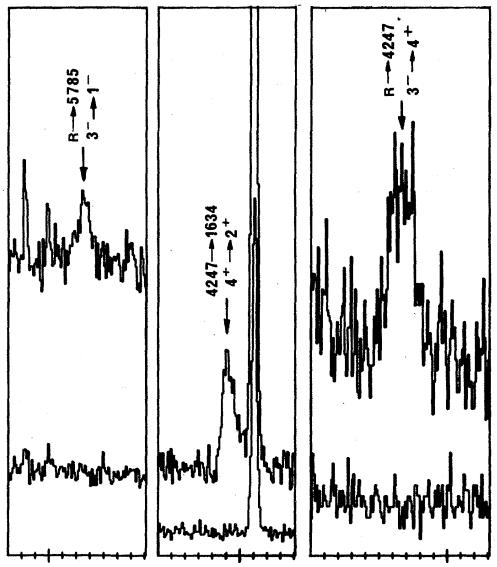

FIG. 5. Sections of the γ-ray spectrum from $^{16}O(\alpha,\gamma)^{20}$Ne. The upper curves were obtained on the resonance at $E_\alpha = 3.036$ MeV and the lower curves, off the resonance at 3.020 MeV. The latter have been reduced by a factor of 2 for clarity. The three regions are at 1.37, 2.60, and 2.90 MeV. The very strong line in the middle region is due to $Pb(n,n')Pb$ exciting the 2.614 MeV state in ^{208}Pb.

performed for each fit, using as parameters the energy and alpha (total) width of the resonances. Within statistics, the fits at all angles gave the same energies; the average values are 1317.4 ±0.2 and 3035.9 ±0.3 keV for the two resonances (the errors do not include a calibration error which is estimated to be 2.0 keV). Similarly, the widths measured at the different angles agreed with each other giving average values of 28 ±3 eV and 8.1 ±0.3 keV. In the case of the lower resonance, because it is narrow, the energy spread in the beam ΔE, influences significantly the value of Γ obtained. This energy spread was determined to be 1.2 ±0.2 keV from the gamma ray yield for the 1^+ doublet in the $^{14}N(\alpha,\gamma)^{18}F$ reaction at $E_\alpha = 1.53$ MeV.[8] The contribution of the uncertainty in ΔE to the error in Γ was detemined by fitting the data with ΔE as a third parameter in the grid search. Besides indicating that this uncertainty contributes ~50% of the error in Γ, the best fits were obtained with $\Delta E = 1.1$ keV, confirming the value determined from the alpha capture experiment on ^{14}N. The value of 8.1 ±0.3 keV for the 3^- resonance agrees with the value obtained by Cameron[5] (when his value is converted to the center of mass), while the value of Γ for the 1^- resonance is consistent with the limit deduced from the $\omega\gamma$ value of Van der Leun *et al.*[12] and the gamma ray branching of Almquist and Kuehner.[13]

The gamma rays were observed both on and off resonance with a Ge(Li) detector at 130° to the beam and on resonance with it at 50°. For on-resonance experiments, the beam energy as determined by the elastically scattered alpha particles was adjusted until the energy of the alpha particles at the center of the gas cell corresponded to the resonance energy. Three lines associated with the decay of the 3^- level were clearly seen in the spectra taken on resonance. The spectral region for each of these is shown in Fig. 5 where the lower curve is the spectrum taken off resonance reduced by a factor of 2 for the sake of clarity, while the upper curve is the spectrum taken on resonance at 130°. With the counter at 50°, all three lines were Doppler shifted to a higher energy as expected. From the energy of the lines, determined from a calibration based on several background lines due to Fe, Al, and Pb, the gamma rays were readily identified. As expected, no transition was observed from the particle unstable 1^- level at 5.782 MeV. The gamma ray energies establish the energy of the 3^- state as 7156.3 ±0.5 keV which agrees with the (d,p) work of Middleton *et al.*[14] (7159 ±4 keV) but not the $^{12}C(^{12}C,\alpha)$ work of Medsker *et al.*[15] (7166 ±6 keV). It should be noted that the gamma ray energy of 1374.3 ±0.4 keV for the transition between the 3^- and 1^- levels is consistent with the difference in the center-of-mass energies of the resonances, 1374.5 ±0.4 keV, determined from the scattering experiments.

A search of the spectra was made for lines of

other transitions from the resonance state especially the one to the 2^+, 1.634 MeV state; no evidence was found for any other line. In order to make a quantitative estimate for any such transition, a gaussian shaped peak of variable intensity but expected width was added to the background at the position expected for the line. The intensity at the 95% confidence level of this possible peak, determined as suggested by Rogers,[16] was taken as the upper limit for the strength of the transition. The results are presented in Table I. The intensity of the three observed lines was obtained in a similar fashion except that the errors on the measurements were taken at the 68% confidence limits. As expected the intensities of the 2614 and 2908 keV transitions were observed to be equal.

In calculating the transition strengths, pure multipoles of the lowest possible order have been assumed. This assumption is easily justified; for example, the presence of $M2$ and $E3$ admixtures in the 3^- to 4^+ transition at the recommended upper limit[17] would constitute only 0.23 and 0.16% of the transition strength and therefore not change the $E1$ strength measurement.

DISCUSSION

The measured widths for the 1^- and 3^- states are reasonably close to the values 21 eV and 6.7 keV, respectively, calculated by Buck *et al.*,[3] who maintain that the large reduced alpha widths predicted by their model or other cluster models, in comparison with these quantities calculated in the shell model, are due to the localization of the cluster outside the core. Since the localization depends on the exact shape of the potential used, specifically the diffuseness, potentials which increase slightly the separation of the cluster and core would increase the predicted alpha width. We have calculated the widths for these states as 29 eV and 9.0 keV using the cosh potential of Bradlow *et al.*[18] This potential is an analytical approximation to the folded potential and has a slightly larger spatial extent than the latter. Consequently the somewhat larger values for the alpha widths are consistent with the view that the diffuseness of the potential does influence the localization of the alpha particle.

The large enhancement in the strength of the 1374 keV transition is convincing evidence for the collective nature of the 1^- and 3^- states of this $K^\pi = 0^-$ band.

Buck *et al.*[3] have calculated the strengths for transitions within this and other bands, treating the alpha cluster as a single particle. Consequently, from our experimental value, an effective charge of $e_{\text{eff}} = (1.28 \pm 0.10)e$ may be deduced. It is seen that this value is essentially the same as the one needed to reproduce the observed transition rates within the ground state band[3] and is considerably smaller than that used in shell model calculations.[19]

For the rotational model, the transition rate may be used to deduce an intrinsic quadrupole moment of $Q_0 = (80 \pm 7)$ fm^2. This is significantly larger than that deduced for the ground state band and for the $K^\pi = 2^-$ band which both[20] have $Q_0 = 55$ fm^2. In the cluster model, the quadrupole moment[21] is proportional to the square of the relative separation of the cluster and core in a specific state. From the wave function[3] for the lower members of the $K^\pi = 0^-$ and ground state band, the ratio of the quadrupole moments is deduced to be 1.45, which is just observed experimentally.

With all the success of the cluster model in accounting for the alpha widths of the 3^- and 1^- states and the enhanced $E2$ rate between the two states, it fails to predict the observed strength for the 3^- to 4^+, $E1$ transition. Although weak, this transition is some ten times stronger than other $\Delta T = 0$, $E1$ rates in ^{20}Ne with the exception of the $E1$, 5.782 to 2^+, 1.634 MeV transition. There are two aspects to this problem: One, the actual strength is much larger than expected

TABLE I. Transitions from the 3^- state at $E_x = 7.156$ MeV excited in the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction at $E_\alpha = 3.036$ MeV. Energies with errors are for gamma rays actually observed. The strengths are deduced assuming pure transitions.

Final state E_x (keV)	J^π	E_γ (keV)	Γ_γ (meV)	Strength
0	0^+	7156	<0.05	<5.0 W.u. $E3$
1634	2^+	5523	<0.08	<0.9 μW.u. $E1$
4248	4^+	2908.4 ± 0.4	0.97 ± 0.11	79 ± 9 μW.u. $E1$
4968	2^-	2188	<0.05	<0.23 mW.u. $M1$
5621	3^-	1535	<0.05	<0.66 mW.u. $M1$
5782	1^-	1374.3 ± 0.4	0.64 ± 0.10	51 ± 8 W.u. $E2$

from the cluster model which predicts a strength of zero, a value also expected from isospin selection rules, and two, the mode of decay of the 3^- state.

We make no comment on the actual value of the strength but note that both the 3^- and 1^- states show the same behavior in that they prefer to decay to the higher of two J values allowed for electric dipole transitions. Pilt[22] has drawn attention to the similar situation in the odd-A nuclei ^{21}Ne and ^{23}Na, where he derived an empirical relationship to account for the observed $E1$ rates based on the mixing into the ground state band of other bands built on Nilsson orbits. Unfortunately, he was not able to explain the magnitude of the mixing on the basis of a microscopic description of the phenomenon. In ^{20}Ne, even the qualitative idea of band mixing is very difficult to imagine. Consequently, the explanation for this tendency of $E1$ $J \rightarrow J+1$ transitions remains obscure.

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