Possible Shape Coexistence and Magnetic Dipole Transitions in $^{17}$C and $^{21}$Ne

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Magnetic dipole(M1) transitions of N=11 nuclei, $^{17}$C and $^{21}$Ne are investigated by using shell model and deformed Skyrme Hartree-Fock+blocked BCS wave functions. Shell model calculations predict well observed energy spectra and magnetic dipole transitions in $^{21}$Ne, while the results are rather poor to predict these observables in $^{17}$C. In the deformed HF calculations, the ground states of two nuclei are shown to have large prolate deformations close to $\beta_2=0.4$. It is also pointed out that the first $K^\pi = 1/2^+$ state in $^{21}$Ne is prolate deformed, while the first $K^\pi = 1/2^+$ state in $^{17}$C is predicted to have a large oblate deformation being close to the ground state in energy. We point out that experimentally observed large hindrance of M1 transition between $I^\pi = 1/2^+$ and $3/2^+$ in $^{17}$C can be attributed to a shape coexistence near the ground state of $^{17}$C.

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I. INTRODUCTION

Recently, many experimental and theoretical efforts have been paid to study structure and reaction mechanism in nuclei near drip lines. It has been known that electromagnetic observables give useful information to study structure of nuclei, not only ground states but also excited states. These observables are expected to pin down precise information of the configuration and the deformation in nuclei. Advanced experimental instruments reveal several unexpected structure of light nuclei with the mass number A~(10-20). One of the current issues is a large quenching of magnetic dipole (M1) transition between the first excited $1/2^+$ state and the ground state with $I^\pi=3/2^+$ in $^{17}$C [1] in comparison with the corresponding transitions in one of N=11 isotones, $^{21}$Ne [2].

The deformation manifests itself in observables like E2 and M1 moments. In ref. [3], deformed Skyrme HF+BCS calculations were performed to study the evolution of deformations in C and Ne isotopes. The calculated electric quadrupole moments and magnetic moments were successfully compared with empirical data. It was pointed out that the shell occupancy gives the crucial effect on the evolution of the deformation of isotope chains. This deformation driving mechanism due to the shell occupancy has been noticed as the nuclear Jahn-Teller effect [10], which gives an intuitive understanding for the evolution of deformation. A possible shape coexistence is pointed out in $^{17}$C because of different deformation driving effects between neutrons and protons. Namely, the first excited $K^\pi = 1/2^+$ state has oblate deformation and almost degenerate with the prolately deformed ground state with $K^\pi = 3/2^+$. On the other hand, there is no sign of shape coexistence in $^{21}$Ne since the shell occupancies are almost the same between protons and neutrons. In theoretical point of view, it is interesting to see how much differences and similarities will appear between the results of standard shell model calculations and those of the mean field theories. To this end, the HF results are compared with shell model results to investigate similarities and differences between two models in such observables like excitation energies and M1 transitions in $^{17}$C and $^{21}$Ne.

In this paper, we extend the previous calculations in ref. [3] and particularly focus on recent experimental data of M1 transitions in $^{17}$C and $^{21}$Ne in order to study possible shape coexistence near the ground states of $^{17}$C. This paper is organized as follows. We study the energy levels, magnetic moments and M1 transitions by using shell model wave functions in Section 2. The deformed HF+blocked BCS results are shown in Section 3. A summary is given in Section 4.

II. SHELL MODEL CALCULATIONS OF $^{17}$C AND $^{21}$NE

In light and medium mass nuclei, the shell model is one of the most successful theories to describe nuclear structure in both the ground states and the excited states. Shell model calculations are performed in (p-sd) model space for $^{17}$C and (sd) model space for $^{21}$Ne with three effective interactions PSDMK2 [4], SFO [5] and WBP [6]. The excitation energies of the first $I^\pi = 3/2^+$, $1/2^+$ and $5/2^+$ states are tabulated in Table I. The SFO interaction is identical to PSDMK2 in (sd) model space so that two results are the same for $^{21}$Ne. The excitation ener-
TABLE I: Shell model calculations of excitation energies in $^{17}$C and $^{21}$Ne. The shell model calculations are performed by using effective interactions PSDMK2, SFO and WBP. For sd shell configurations, the interaction matrices of PSDMK2 and SFO are the same. Experimental data are taken from ref. [1] for $^{17}$C and from ref. [2] for $^{21}$Ne. All units are in MeV.

|        | $^{17}$C |         |         |         |         |         |
|--------|----------|----------|----------|----------|----------|
| int.   | $^{2}_{1}$ | $^{1}_{1}$ | $^{2}_{2}$ | $^{3}_{2}$ | $^{1}_{2}$ |
| MK2    | 0.305    | 0.0      | 0.711    | 1.679    | 5.067    |
| SFO    | 0.304    | 0.0      | 0.654    | 1.678    | 5.039    |
| WBP    | 0.0      | 0.295    | 0.032    | 1.998    | 5.034    |
| exp    | 0.0      | 0.212    | 0.335    |          |          |
|        | $^{2}_{1}$ | $^{1}_{1}$ | $^{2}_{2}$ | $^{3}_{2}$ | $^{1}_{2}$ |
| $^{21}$Ne | MK2 (SFO) | 0.0      | 1.930    | 0.495    | 3.250    | 4.688    |
| WBP    | 0.0      | 2.870    | 0.249    | 3.484    | 5.815    |
| exp    | 0.0      | 2.794    | 0.351    | 3.735    |          |

TABLE II: Magnetic moments in $^{17}$C and $^{21}$Ne in unit of $\mu_N^2$. The shell model calculations are performed by using effective interactions PSDMK2, SFO and WBP with the bare g factors. The values in the brackets for $^{2}_{1}$ in $^{17}$C and $^{1}_{1}$ and $^{2}_{1}$ for $^{21}$Ne are obtained by using the effective g factors for the IV channels, $\delta g_s = -0.2g_s^{IV} \tau_z$, $\delta g_l = -0.15\tau_z$ and $g_p = -1.0\tau_z$ in Eq. (1). Experimental data of magnetic moments are taken from ref. [16] for $^{17}$C and from ref. [17] for $^{21}$Ne.

|        | $^{17}$C |         |         |         |         |         |
|--------|----------|----------|----------|----------|----------|----------|
| int.   | $^{2}_{1}$ | $^{1}_{1}$ | $^{2}_{2}$ | $^{3}_{2}$ | $^{1}_{2}$ |
| MK2    | -0.710   | (-0.686) | -1.548   | -1.453   | -1.447   | 0.250    |
| SFO    | -0.725   | (-0.713) | -1.548   | -1.500   | -1.424   | 0.232    |
| WBP    | -0.858   | (-0.819) | -1.566   | -1.404   | -1.744   | 0.570    |
| exp    | [0.758(38)] |          |          |          |          |          |
| $^{21}$Ne | int. | $^{2}_{1}$ | $^{1}_{1}$ | $^{2}_{2}$ | $^{3}_{2}$ | $^{1}_{2}$ |
| MK2    | -0.887   | (-0.720) | -1.498   | -0.667   | -0.463   | 0.228    |
| WBP    | -0.824   | (-0.674) | -1.548   | -0.643   | -0.692   | 0.127    |
| exp    | -0.661707(5) | [0.49(4)], | [0.70(8)], | [0.88(20)] |          |          |

Magnetic moments and magnetic dipole (M1) transition probabilities B(M1) are given in Tables III and IV respectively. The magnetic operator is defined as

$$\mu_{eff} = (g_s^{bare} + \delta g_s)s + (g_l^{bare} + \delta g_l)l + g_p[Y_s \times s]$$

(1)

where $\delta g_s$ and $\delta g_l$ are the renormalization factors for the spin and the orbital g factors, respectively. The last term of Eq. (1) is the tensor component due to the core polarization effect. The shell model results of magnetic moments are shown in Table III with the bare g factors and the effective g factors for the IV channels, $\delta g_s = -0.2g_s^{IV} \tau_z$, $\delta g_l = -0.15\tau_z$ and $g_p = -1.0\tau_z$. For the magnetic moments, the effect of $\delta g_s$ and $\delta g_l$ cancel each other largely and that of the tensor component $g_p$ is very small. The net effect of the effective operator is less than 5% in $^{17}$C and 20% in $^{21}$Ne. In comparison with experimental data, the optimum quenching factor $\delta g_s$ depends on the model space and the effective interaction. For $^{17}$C, small quenching factors ($\delta g_s/g_s^{IV} \sim 0.0$) at PSDMK2 and SFO, $\delta g_s/g_s^{IV} \sim -0.2\tau_z$ for WBP) give good agreement with the experimental data. Slightly larger values ($\delta g_s/g_s^{IV} \sim -0.25\tau_z$ for PSDMK2 and SFO, $\delta g_s/g_s^{IV} \sim -0.2\tau_z$ for WBP) give reasonable results in the case of $^{21}$Ne.

In Table III two empirical M1 transition probabilities in $^{21}$Ne are reasonably well reproduced by the shell model calculations. The best results among the three interaction are given by WBP interaction with the effective spin g factor $\delta g_s/g_s^{IV} = -0.2\tau_z$. We can see in Tables I, II, and III that the shell model provides good agreement not only for the excitation energies but also for the magnetic moments and M1 transition probabilities in $^{21}$Ne. In $^{17}$C, the M1 transition probability from $I^\pi=5/2^+$ to $3/2^+$ is reproduced well by the shell model with the bare g factors. However, the transition probability from $I^\pi=1/2^+$ to $3/2^+$ is very poorly predicted, i.e., the empirical data is almost one order magnitude smaller than the shell model predictions with the bare g factors. The effective g factors adopted in the magnetic moments in Table III decrease substantially the B(M1) values in $^{17}$C. However, these effective g factors do not give any satisfactory results for the measured two transitions between ($I^\pi=5/2^+ \rightarrow 3/2^+$) and ($I^\pi=1/2^+ \rightarrow 3/2^+$) as shown inside of the brackets in Table III. Recently, the description of M1 transitions in $^{17}$C has been considerably improved with the use of a modified SFO Hamiltonian [2].
III. DEFORMATIONS AND MAGNETIC DIOPOLE TRANSITIONS IN $^{17}$C AND $^{21}$NE

The neutron number dependence of deformations was studied along the chain of C and Ne isotopes in ref. 3 by performing deformed HF+blocked BCS calculations with Skyrme interactions SGII and SIII. In this study, we perform the same deformed HF calculations of two N=11 isotones $^{17}$C and $^{21}$Ne with a different Skyrme interaction SkO'. We found that the results of SkO' are very close to those of SGII and SIII. One advantage of SkO' is to give an oblate deformed ground state for $^{12}$C with the original spin–orbit interaction, while the spin–orbit interaction was reduced in SIII and SGII to obtain the oblate deformation. In numerical calculations, the axial symmetry is assumed for the HF deformed potential. The pairing interaction is taken to be a density dependent pairing interaction in BCS approximation. For numerical details about the pairing calculations, see refs. 8, 9.

Deformed Skyrme HF+ blocked BCS results are shown in Fig. 1(a) for $^{17}$C and Fig. 1(b) for $^{21}$Ne. The deformation and the intrinsic $Q_0$ moments are tabulated in Table IV for $^{17}$C, and $^{21}$Ne. The ground states are predicted to be $K^\pi=3/2^+$ state in both nuclei having large prolate deformations $\beta_2=0.266$ for $^{17}$C and 0.391 for $^{21}$Ne, respectively. The spin-parity of calculated results can be compared with the observed ones $I^\pi=3/2^+$ in both nuclei. In $^{17}$C, the first excited state is predicted to be $K^\pi=1/2^+$ state with a large oblate deformation $\beta_2=-0.270$. The energy difference from the ground state is rather small with $E_X=0.56$MeV. On the other hand, the first excited $K^\pi=1/2^+$ in $^{21}$Ne is predicted to have a large prolate deformation $\beta_2=0.287$ with a large excitation energy $E_X=2.33$MeV. This difference in $K^\pi=1/2^+$ state can be understood as a manifestation of the nuclear Jahn-Teller effect due to the proton configuration $2^+$ in both nuclei. In general, a few particles top of the closed shell drives prolate deformation, while a few holes prefer oblate deformation. There is a strong competition between prolate driving N=11 neutrons and oblate driving Z=6 protons in $^{17}$C. Namely, the Z=6 proton configuration, two proton holes in the Z=8 closed shell, prefers the oblate deformation as is the case of the ground state of $^{12}$C, while the N=11 neutrons tends to drive prolate deformation. Consequently, in $^{17}$C, the ground state is prolate deformed due to the effect of neutron configuration. However, the first excited $K^\pi=1/2^+$ state becomes oblate under the influence of the deformation driving force of protons. In $^{21}$Ne, both the proton and neutron configurations drive prolate deformation so that there is no sign of the shape coexistence. The observed excitation energy of the first $I^\pi=1/2^+$ state is very low in $^{17}$C as $E_X=0.212$MeV, while that of $^{21}$Ne is higher as $E_X=2.79$MeV. These experimental observations are consistent with the calculated results in Table IV as far as the excitation energies are concerned. Thus we identify the first excited $I^\pi=1/2^+$ state as $K^\pi=1/2^+$ in both $^{17}$C and $^{21}$Ne with different large deformations $\beta_2=-0.270$ and 0.287, respectively. The $I=1/2^+$ in $^{21}$Ne was interpreted in [11] as the head of rotational band with a large prolate deformation $1/2^+$. The $I^\pi=5/2^+$ state is observed at very low excitation energy around $E_X=0.3$MeV in both nuclei. In the HF calculations, no $K^\pi=5/2^+$ state appears at the energy below $E_X \sim 1$MeV. Thus, we interpret that the observed first excited $I^\pi=5/2^+$ state in both nuclei is a member of the rotational band with $K^\pi=3/2^+$. In the case of $^{21}$Ne, the ground state and the first excited state were identified as members of the same rotational band giving consistent predictions of associated observed properties [12]. This interpretation is also supported by the large deformation length observed in the excitation to $I^\pi=5/2^+$ state in the proton inelastic scattering on $^{17}$C [13].

![Energy surfaces as a function of deformation parameter $\beta_2$ in $^{17}$C and $^{21}$Ne. Deformed HF+blocked BCS calculations are performed with a Skyrme interaction SkO'.](image)

FIG. 1: Energy surfaces as a function of deformation parameter $\beta_2$ in $^{17}$C and $^{21}$Ne. Deformed HF+blocked BCS calculations are performed with a Skyrme interaction SkO'.

We study the magnetic dipole transitions between the excited and ground states in $^{17}$C and $^{21}$Ne using the deformed HF wave functions. For axially symmetric deformation, the deformed many-particle initial and final states are expressed as a direct product of neutron and proton single-particle states:

$$|K\rangle = |\nu\rangle |\pi\rangle,$$

(2)
TABLE IV: Energies, deformations, Q moments and magnetic moments in \(^{17}\text{C}\) and \(^{21}\text{Ne}\) with a Skyrme interaction SkO'. The magnetic moment \(\mu\) is calculated for \(I = K\) state with the bare neutron g-factor. Experimental data are the same as for Table III (experimental uncertainties are omitted).

| \(K^+\) | \(E_x\) | \(\beta_2\) | \(Q_{yy}\) \((\text{fm}^2)\) | \(Q_{os}\) \((\text{fm}^2)\) | \(g_K\) \((\mu_N)\) | \(\mu(\text{exp})\) \((\mu_N)\) |
|-----|-----|-----|-----|-----|-----|-----|
| \(^{17}\text{C}\) | \(\frac{1}{2}^+\) | 0.0 | 0.366 | 16.24 | 53.05 | -1.197 | -0.877 | 0.758 |
| | \(\frac{3}{2}^+\) | 0.56 | -0.270 | -15.27 | -35.94 | -3.420 | -1.767 |
| | \(\frac{5}{2}^+\) | 0.99 | -0.247 | -13.40 | -34.43 | -0.764 | -1.126 |
| | \(\frac{7}{2}^+\) | 1.21 | 0.272 | 13.59 | 40.75 | -1.101 | -0.947 |
| \(^{21}\text{Ne}\) | \(\frac{1}{2}^+\) | 0.0 | 0.391 | 42.15 | 46.98 | -1.112 | -0.728 | -0.661797 |
| | \(\frac{3}{2}^+\) | 2.33 | 0.287 | 31.67 | 32.05 | -2.557 | -1.523 |
| | \(\frac{5}{2}^+\) | 2.92 | 0.226 | 25.85 | 23.83 | -0.764 | -1.040 | 0.49 | 0.88 |
| | \(\frac{7}{2}^+\) | 4.91 | 0.357 | 39.517 | 43.547 | -0.231 | -0.594 |

where the component of the total angular momentum along the symmetry axis is denoted by \(K\) [14, 15] and \(|\nu(\pi)\rangle = a_{\lambda 1}^I a_{\lambda 2}^I \cdots |f(\beta_2)\rangle\) denotes the multi-quasiparticle neutron (proton) state. The state \(|f(\beta_2)\rangle\) is the quasiparticle vacuum with deformation \(\beta_2\). The quasiparticle operator \(a^\dagger_\lambda(\beta_2)\) is connected to the real particle operators \(c^\dagger(\beta_2)\) and \(c(\beta_2)\) in the deformed basis by

\[
a_{\lambda\mu}(\beta_2) = u_{\lambda\mu}(\beta_2)c_{\lambda\mu}^\dagger(\beta_2) - v_{\lambda\mu}(\beta_2)c_{\lambda\mu}(\beta_2),
\]

where \(\lambda\) specifies the quantum numbers of Nilsson orbit, \(v_{\lambda\mu}(\beta_2)\) is the BCS occupation amplitude and \(u_{\lambda\mu}(\beta_2) = \sqrt{1 - v_{\lambda\mu}(\beta_2)^2}\). The operators \(c_{\lambda\mu}^\dagger(\beta_2)\) and \(c_{\lambda\mu}(\beta_2)\) are further expanded by the spherical bases as \(c_{\lambda\mu}^\dagger(\beta_2) = \sum_a d_{\lambda\mu}^a(\beta_2)c_{\lambda\mu}^a\) where the amplitude \(d_{\lambda\mu}^a(\beta_2)\) is denoted by the quantum numbers \(a = (n, l, j)\).

The intrinsic 

\[
\mathcal{M}(M) = \sqrt{\frac{4\pi}{\mu_N}} \times \sum_i \left( -g_i(i)\, g_s(i) + g_R \right) l + \left( g_s(i) - g_R \right) s_i + g_R I \right)
\]

where \(g_i(i), g_s(i)\) and \(g_R\) are the orbital, spin g factors and the gyromagnetic ratio of the rotor respectively, in unit of the nuclear magneton \(\mu_N = e\hbar/2m_e c\).

The transition matrix element can be written for one neutron quasiparticle states as

\[
\langle \nu'\pi'K'|\mathcal{M}(M)\rangle\langle \nu\pi K \rangle = \langle \nu|a_{\lambda\mu}(\beta_2)\mathcal{M}(M)\rangle c_{\lambda\mu}^\dagger(\beta_2)|\nu'\rangle|\pi'\rangle \]

where \(|\pi'\rangle\) and \(|\nu'\rangle\) are quasi-particle vacuum overlaps of neutrons and protons, respectively.

The in-band M1 transition probability can be written, for a band with \(K > \frac{1}{2}\), as

\[
B(M1; KI_1 \to KI_2) = \frac{\langle \pi'|\pi\rangle}{K^2} \sum_{\nu}(g_K - g_R)^2K^2 < I_1K10|I_2K^2 >
\]

where \(g_R = \frac{2\pi}{\nu}\) and \(g_K\) is the intrinsic g factor. \(kg_K = \langle K|g_I3 + g_s33|K\rangle\). The magnetic moment is expressed as

\[
\mu = gRI + (g_K - g_R)K^2 I + 1
\]

For \(K \neq K'\) case, the M1 transition probability is written to be

\[
B(M1; KI_1 \to K'\nu, I_2) = \frac{2\pi}{\nu}\mu_N^2 \times < K_1K'1 - K|I_2K^2 >^2 G^2 < |\pi'|\pi >^2
\]

where

\[
G = \langle g_s - g_R \rangle \langle \nu|a_{\lambda\mu}(\beta_2)\mathcal{M}(M)\rangle c_{\lambda\mu}(\beta_2)|\nu'\rangle + \langle g_s - g_R \rangle \langle \nu|a_{\lambda\mu}(\beta_2)\mathcal{M}(M)\rangle c_{\lambda\mu}(\beta_2)|\nu\rangle.
\]
the transition to the \( K = 3/2 \) ground state. It is expected that a small mixing of the \([N \hbar n_\pi \Omega] = [2111/2]\) state increases the \( B(M1) \) value between the \((I_1 = K_1 = 1/2^+ \rightarrow I_2 = K_2 = 3/2^+)\). We notice that the optimal quenching spin \( g \) factor of the deformed HF results is slightly smaller than that of the shell model calculations. It is an interesting open question to compare more systematically the transition strength of two models in a quantitative level. It was mentioned in ref. [1] that the halo effect of \( ^{17}\text{C} \) may play a role to decrease \( B(M1) \) value of \((I_1 = 1/2^+ \rightarrow I_2 = 3/2^+)\). However no serious attempt has been made so far to take into account the halo effect on the M1 transitions in \( ^{17}\text{C} \).

The calculated magnetic moments \( \mu \) are shown in Table [V]. The observed magnetic moments show a small quenching effect in comparison with the calculated values for the ground states of \( ^{17}\text{C} \) and \( ^{21}\text{Ne} \). The results of deformed HF calculations provide similar quantitative predictions to those of the shell models as far as the magnetic moments of the ground states are concerned. The observed magnetic moment for the excited \( I^\pi = 5/2^+ \) state in \( ^{21}\text{Ne} \) is still not accurate enough to perform precise comparison with the calculated results.

The second \( K = 1/2^+ \) state is found in Table [V] at rather low energy \( E_x = 1.21\text{MeV} \) by the deformed HF model, while the \( I = 1/2^+ \) state is located at \( E_x \sim 5\text{MeV} \) in the shell model calculations in Table [I]. So far the second \( 1/2^+ \) is not identified experimentally [18]. It is quite interesting to find the \( 1/2^+_2 \) state experimentally to disentangle the applicability of the two models.

IV. SUMMARY

We have studied the magnetic dipole transitions in \( ^{17}\text{C} \) and \( ^{21}\text{Ne} \) using microscopic shell model wave functions and deformed HF wave functions. The energy spectra as well as M1 transition probabilities of \( ^{21}\text{Ne} \) are well reproduced by the shell model calculations, while we need a quenching factor for the spin \( g \) factor to obtain reasonable quantitative agreement. On the other hand, the observed M1 transition probability from the first excited \( 1/2^+ \) to the \( 3/2^+ \) ground state in \( ^{17}\text{C} \) was found to be hindered by one order of magnitude compared with the shell model calculations. The shell model prediction of energy spectra is also poor in \( ^{17}\text{C} \) compared with the experimental data. The deformed HF+blocked BCS calculations are performed with a Skyrme interaction SkO'. The ground states of \( ^{17}\text{C} \) and \( ^{21}\text{Ne} \) are predicted as largely prolate deformed states with \( K^\pi = 3/2^+ \). In \( ^{21}\text{Ne} \), the first \( K^\pi = 1/2^+ \) state appears at the energy \( E_x \sim 2.3\text{MeV} \) with a large prolate deformation. On the other hand, the first \( K^\pi = 1/2^+ \) state in \( ^{17}\text{C} \) has a large oblate deformation with \( E_x \sim 0.5\text{MeV} \) as the result of competition between the deformation driving force of protons and neutrons. The calculated energy difference between \( K^\pi = 3/2^+ \) and \( K^\pi = 1/2^+ \) states is close to the observed energy difference between \( I^\pi = 3/2^+ \) and \( I^\pi = 1/2^+ \) states both in \( ^{21}\text{Ne} \) and \( ^{17}\text{C} \). The strong hindrance of the B(M1) transition between the first excited \( 1/2^+ \) to the ground state \( 3/2^+ \) of \( ^{17}\text{C} \) can be attributed to the shape difference between the lowest \( K^\pi = 1/2^+ \) and the first \( K^\pi = 3/2^+ \) state as is predicted by the deformed HF+blocked BCS calculations.

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