Structure of the proton drip line nucleus $^{17}\text{F}$

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Abstract

The odd $A$ proton drip line nucleus $^{17}\text{F}$ has been studied in a semi-microscopic model which couples proton quasiparticle motion to the vibrational motion of the neighbouring even-even $^{18}\text{Ne}$ core. The experimentally observed low lying excitation spectrum, electric quadrupole moment, magnetic dipole moment, $B(E1)$ and $B(E2)$ values have been fairly well reproduced. The calculated rms radius of the first excited state is well reproduced and is found to be larger than that of the ground state which agrees with the experimental observation.

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I. INTRODUCTION

With the advent of radioactive ion beam facilities, new experimental data concerning exotic nuclei are becoming available. Some of the exotic nuclei show halo structures which has generated a lot of interest, in recent times, among various theoretical and experimental groups. Experimental investigations have shown the enhancement of sub-barrier fusion cross-section in reactions involving exotic nuclei [1,2], which is thought to be related to the sizes and structure of such nuclei. Thus the understanding of the structure of such nuclei is of utmost importance to the study of various phenomena involving these nuclei.

It is well known that the very low binding energy of the last unpaired nucleon is responsible for the large matter radii of one-nucleon halo nuclei. A number of one-neutron halo nuclei have been identified and studied in recent times. In a similar way, one-proton halo nuclei ought to exist except for the fact that the proton wave function, unlike the neutron wave function, is squeezed due to the Coulomb barrier. The nucleus $^{17}$F may be a good candidate for a proton halo nucleus since the binding energy of the last proton is only 0.60 MeV. Experimental studies [3–5] have revealed that the spin-parity of the ground state of $^{17}$F is $\frac{5}{2}^+$ and has spectroscopic strength equal to 0.93. The first excited state is known to be $\frac{1}{2}^+$, with a dominant $2s_{1/2}$ single particle (s.p.) configuration having binding energy equal to 0.1 MeV. However, the root mean square (rms) radius of the ground state is 3.78 fm whereas that of the first excited state, at 500 keV excitation, is observed to be 5.33 fm [6]. Considering the ground state and the first excited state to be pure single particle configurations of $1d_{5/2}$ and $2s_{1/2}$, respectively, the rms radii of the last proton, using Harmonic oscillator wave functions, turn out to be the same, which is contrary to the experimental findings. This indicates that coupling of the odd proton motion and that of the core may modify the wave function of $^{17}$F sufficiently to affect the rms radius of the ground state and that of the first excited state. The neighbouring even-even cores for this nucleus are $^{16}$O and $^{18}$Ne. The first, $^{16}$O, is a doubly closed shell nucleus without any vibrational structure, whereas the second, $^{18}$Ne, shows a well developed vibrational structure with the first $2^+$ state at 1.88 MeV [7]. As such, the behaviour of the core changes abruptly if one goes from O to Ne. Therefore, the nature of the $^{17}$F nucleus is in between the two extremes and the structure of this nucleus needs to be explored. Furnstahl and Price [8], through a relativistic Hartree calculation, found the rms charge radius to be 2.76 fm and the magnetic dipole moment to be 4.87 $\mu_N$. On the other hand, the density functional method of Lombard [9] provided the total binding energy (B.E. = 126.6 MeV). However, the detailed structure information regarding the excitation mechanism is lacking at present.

We have shown earlier [10] that the structures of the one-neutron halo nuclei $^{11}$Be and $^{19}$O could be explained satisfactorily through the coupling of collective vibrations of the respective even-even cores with the motion of the odd valence neutron. In the present work, we have shown that similar idea can be applied in explaining the important features of the excitation spectrum of the proton rich exotic nucleus $^{17}$F by coupling single proton quasiparticle motion to the collective vibrational motion of the even-even $^{18}$Ne core. In this paper, we present the results of our calculations for the studies of the low lying excitation spectrum and the electromagnetic (EM) properties of the $^{17}$F nucleus. The model used in the present calculations is discussed briefly in section II. The method of calculation is given in section III. Section IV contains the results and discussion and finally the conclusions are
given in section V.

II. MODEL

The model used in the present calculations is given in our earlier work \cite{17,18} and here we are giving it just for the sake of completeness. The total Hamiltonian for a coupled system of a quasiparticle and collective excitation of the core may be written as

\[ H = H_{\text{core}} + H_{s.p.} + H_{\text{int}} \]  

where \( H_{\text{core}} \) describes the harmonic collective vibrations of the even-even core. \( H_{s.p.} \) describes the motion of the valence nucleon (-hole) in an effective potential. The basis states, which are eigen functions of \( H_{\theta} = H_{\text{core}} + H_{s.p.} \), can be written as \([\{N_2 V_2 L_2, N_3 V_3 L_3\}L (n l 1/2)^i\}^{J,M}\), where \((N_\lambda V_\lambda L_\lambda)\) is the totally symmetric state of \(N_\lambda\) phonons of multipolarity \(\lambda\) coupled to angular momentum \(L_\lambda\) and \(V_\lambda\) represents all the additional quantum numbers necessary for complete specification of the state; \(L_2\) and \(L_3\) are coupled to the angular momentum \(L\) of the core which is then coupled to \(j\) of the quasiparticle to form the resultant \(J\). \((n l 1/2)\) represents a quasiparticle state having radial quantum number \(n\), orbital quantum number \(l\) and spin \(1/2\). The eigen values of \(H_{\theta}\) are the sum of the single particle energies \(\epsilon_p\) and the core energies. The core particle interaction is given by

\[ H_{\text{int}} = \sum_{\lambda}^{2,3} K_\lambda(r) \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda \mu}^* Y_{\lambda \mu}(\theta_p, \phi_p), \]  

(2)

\(Y_{\lambda \mu}\) are the spherical harmonics corresponding to the particle coordinates. The collective coordinates \(\alpha_{\lambda \mu}\) can be expressed as a linear combination of the phonon creation and destruction operators \(b^+, b\) respectively, for the core. The matrix elements of the interaction Hamiltonian, after taking care of the pairing effects, are given by

\[ \langle \{[N_2 V_2 L_2, N_3 V_3 L_3]L (n l 1/2)^i\}^{J,M}|H_{\text{int}}|\{[N_2 V_2 L_2', N_3 V_3 L_3']L' (n' l' 1/2)^{i'}\}^{J,M}\rangle \]

\[ = \sum_{\lambda}^{2,3} X_{\lambda} < n l |[(m \omega_0 / \hbar)^{1/2} r_p]|^\lambda |n' l' > (-1)^{J-1/2+\lambda} \times \frac{1}{2} \times \{[L][L'][j][j']\}^{1/2} \times \left( \frac{1 + (-1)^{l+l'+\lambda}}{2} \right) \times \delta_{\lambda,2} + \delta_{\lambda,3} (-1)^{L+L'+L_3+L_\lambda} \left( \begin{array}{ccc} j' & \lambda & j \\ 1/2 & 0 & -1/2 \end{array} \right) \times \left( \begin{array}{ccc} L & L' & \lambda \\ L_\lambda & L_\lambda & \lambda \eta \end{array} \right) \times (U' j U_j - V_j V_j) \delta_{N_\eta N_\eta'} \delta_{L_\eta L_\eta'} \delta_{V_\eta V_\eta'} \times \left[ \delta_{N_\lambda N_\lambda-1} \times (-1)^{L_2+L_3} \times <N_\lambda L_\lambda ||b_\lambda^\dagger||N_\lambda' L_\lambda' > + \delta_{N_\lambda N_\lambda+1} \times (-1)^{L_2+L_\lambda} <N_\lambda' L_\lambda ||b_\lambda^\dagger||N_\lambda L_\lambda > \right]. \]

In the above, \(X_2\) and \(X_3\) are the quadrupole and octupole interaction strengths respectively, and \(\eta = 2\) when \(\lambda = 3\) and vice versa. \(X_\lambda\)'s are given by

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\[ X_\lambda = K_\lambda \sqrt{2(\lambda + 1)} \sqrt{\frac{\hbar \omega_\lambda}{2\pi C_\lambda}} , \]  

where \( K_\lambda \) are the average values of the radial integrals. The quantities \( V_j \)'s and \( U_j \)'s are the occupation and non-occupation probabilities of the respective single particle states. Diagonalising the Hamiltonian of the coupled system in the basis space of \( \hat{H}_\theta \), one obtains the eigenvalues and the eigen vectors. The eigen vectors, thus obtained, are used to calculate the static electric quadrupole and magnetic dipole moments, the electric and the magnetic multipole transitions. The expressions for the static magnetic dipole and the electric multipole operators for the coupled system are \[ O(M1, \mu) = \left( \frac{3}{4\pi} \right)^{1/2} (g_\mu l_\mu + g_s s_\mu + g_R R) , \]  

\[ O(E\lambda, \mu) = \frac{3}{4\pi} ZeR_0^{1/2} \left( \frac{\hbar \omega_\lambda}{2C_\lambda} \right)^{1/2} (b_\lambda^+_{\mu} + (-)^\mu b_{\lambda,-\mu}) + \left( e_p + \frac{Ze}{A^2} \right) r_p^{1/2} Y_{\lambda,\mu}(\theta, \phi) \]  

where \( Z, A \) and \( R_0 \) are the charge, mass and the radius of the core, respectively. The quantity \( C_\lambda \) refers to the stiffness constant of the vibrating core. The magnetic dipole moment \( \mu \) and the electric quadrupole moment (QM) \( Q \) of a state \(| J, M, \alpha > \) are defined as \[ \mu = \langle J, M = J, \alpha | \left( \frac{4\pi}{3} \right)^{1/2} O(M1, 0) | J, M = J, \alpha > \]  

and \[ Q = \langle J, M = J, \alpha | \left( \frac{16\pi}{5} \right)^{1/2} O(E2, 0) | J, M = J, \alpha > . \]  

The reduced electromagnetic transitions are given as \[ B(E\lambda : J_i \rightarrow J_f) = \langle J_f || O(E\lambda) || J_i >^2 (2J_i + 1)^{-1} \]  

The detailed expressions, after carrying out angular momentum algebra, are given in Heyde and Brussaard \[ ] except for a multiplicative factor in the particle part involving \( V_j \)'s and \( U_j \)'s. The rms radius of a state is obtained by taking the expectation value of the operator \( r_p^{2} \), in the respective state. The core contribution to the rms radius is either taken from the experiment, if available. Otherwise, it is taken as \( R_0^2 = (1.2A^{1/3})^2 \).  

### III. METHOD OF CALCULATION

There are several parameters in this calculation viz. (i) the quasiparticle energies \( \epsilon_j \), (ii) the \( U_j \)'s and \( V_j \)'s factors and (iii) the interaction coupling strengths \( X_2 \) and \( X_3 \). The vibrational energies for the \(^{18}\text{Ne} \) core are taken from the experimental data \[ ] . The experimental excitation spectrum of \(^{18}\text{Ne} \) shows the behavior of a vibrator. The first \( 2^+ \) excited state occurring at 1.887 MeV can be identified as one quadrupole phonon excited state. The second \( 0^+, 2^+ \) states and the first \( 4^+ \) state occurring at 3.576 MeV, 3.616 MeV and 3.376 MeV.
MeV, respectively, can be taken as the members of the multiplet of two quadrupole phonon excitations. The calculations have been restricted to only two quadrupole phonon space as the calculated spectra have been found to be insensitive to the inclusion of octupole phonons. Therefore, $X_3$ is kept equal to zero. The single particle space, in the present calculations, is confined to $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbitals for the positive parity states and $1p_{3/2}$, $1p_{1/2}$ orbitals for the negative parity states. The $U_j(V_j)$ factors for the $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ single particle states are available from the $(\alpha, t)$ and $(^3He, d)$ reaction studies [14,4]. However, the experimental spectroscopic information for the $1p_{3/2}$ and $1p_{1/2}$ single particle states is not very clear. From the $(d, ^3He)$ reaction, Firestone et al. [15] overestimated the strengths for the $1p_{3/2}$ and $1p_{1/2}$ single particle states by 30–40% and, to the best of our knowledge, no other data are available. Therefore, we have taken them as free parameters. The $U_j(V_j)$ factors used in the present calculation to reproduce the experimental data are given in Table I. The relative quasiparticle energies, $\epsilon_j$, with respect to the lowest single particle state in the conventional shell model basis and the interaction coupling strength $X_2$ are treated as free parameters. These are varied to fit the experimental level scheme and the spectroscopic factors. The set of best fit parameters used in the present calculations are given in Table II.

The wave function of a state with angular momentum $J$ with $z$-component $M$ and energy $E^\alpha$ ($\alpha$ distinguishes between states of same spin and parity) is given by

$$|E^\alpha, JM > = \sum_{N_2,L_2,j} C_\alpha(N_2L_2, j, J)|N_2L_2, j; JM >, (9)$$

and the spectroscopic factor is defined as

$$S^\alpha(l, j = J) = U_j^2|C_\alpha(00, j, J)|^2. \quad (10)$$

IV. RESULTS AND DISCUSSION

A. Even parity states

For the even parity states, the odd quasiparticle motion was restricted to be in the $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbitals. The collective states of $^{18}$Ne, used in the present calculation, to which the quasiparticle couples, were taken from the experimental data [7]. The calculated low lying levels and the spectroscopic factors are shown in Fig.1, along with the experimental data, [16], for the sake of comparison. It is seen from this figure that the present calculation is able to reproduce the positive parity level spectrum quite well. The present calculation predicts two weak $\frac{5}{2}^+$ and $\frac{1}{2}^+$ states, not observed experimentally, at $\sim$2 MeV excitation with the spectroscopic strengths 0.05 and 0.06, respectively (not shown in Fig. 1). The calculated spectrum is found to have three $\frac{3}{2}^+$ states lying between 4.50 and 4.75 MeV excitation with single particle strengths equal to 0.05, 0.51 and 0.07, respectively. The state at 4.63 MeV with a spectroscopic strength of 0.51 may correspond to the experimentally observed $\frac{3}{2}^+$ state at 5 MeV excitation with spectroscopic strength 0.54. Whereas, the calculated state at 4.75 MeV may correspond to the observed state at 5.82 MeV. The calculated $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states at 6.83 MeV and 6.84 MeV may correspond to the observed
levels at 6.56 MeV and 7.36 MeV, respectively. It is conjectured that the experimentally observed $\frac{5}{2}^+$ state at 8.07 MeV may be associated with the calculated state at 8.20 MeV.

There is an overall good agreement between the calculated and the experimental level energies and the spectroscopic factors. However, almost all the calculated $\frac{3}{2}^+$ states are depressed in energy by 500 keV as compared to the corresponding experimentally observed states. The observed $1d_{\frac{5}{2}}$ single particle strength is found to be almost totally concentrated on the $\frac{5}{2}^+$ state though the present calculation predicts a $\frac{5}{2}^+$ state at 2 MeV with a very small spectroscopic strength. A similar situation is observed with the $1d_{\frac{3}{2}}$ single particle strength distributions. The available $1d_{\frac{3}{2}}$ single particle strength is found to be fragmented amongst three states lying between 4.50 MeV and 4.75 MeV, the major part of strength being concentrated on the state at 4.63 MeV excitation.

### B. Odd parity states

For generation of the odd parity states, the single particle space considered in the present calculation is spanned by $1p_{\frac{1}{2}}$ and $1p_{\frac{3}{2}}$ states. The quadrupole interaction coupling strength $X_2$ was kept identical to that used in the case of the even parity states and the single particle energies $\epsilon_{1p_{\frac{1}{2}}}$ and $\epsilon_{1p_{\frac{3}{2}}}$ were treated as free parameters. The calculated level spectrum of the low lying odd parity states is shown in Fig. 2 alongwith the experimental one [16]. It is seen from this figure that there is an overall good agreement between the calculated and the experimental spectra except for the $\frac{3}{2}^-$ states which are overpredicted by $\sim 1$ MeV. The calculation predicts that almost the total available $1p_{\frac{3}{2}}$ single particle strength is concentrated on the $\frac{1}{2}^-$ state at 3.186 MeV. The $1p_{\frac{3}{2}}$ single particle strength is predicted to be fragmented into three $\frac{3}{2}^-$ states lying at 4.74 MeV, 5.20 MeV and 7.33 MeV with major part of the strength going to the state at 4.74 MeV. The structure of the calculated $\frac{5}{2}^-$ state at 4.86 MeV is found to be mainly consisting of a $2^+$ collective state coupled to the $1p_{\frac{1}{2}}$ single particle orbital. Similar are the structures of the $\frac{7}{2}^-$ and $\frac{9}{2}^-$ states. However, no experimental data are available for the spectroscopic strengths for the odd parity states of $^{17}$F to compare with.

### C. RMS radii, EM moments and Transition probabilities

The stringent test of the wave functions obtained by diagonalising the Hamiltonian is to see whether they are able to reproduce the electromagnetic moments and the multipole electromagnetic transition probabilities. However, in the case of the exotic nuclei an important aspect of structure study is the reproduction of the experimentally observed rms radius of proton or neutron distribution which provides a measure of the proton or neutron halo. The rms radii of the ground state and the excited states of $^{17}$F contains two parts - (i) from the core and (ii) from the extra quasiparticle. In order to evaluate the proton rms radii of these two states, initially, we performed our calculation with the Harmonic Oscillator (H.O.) wave functions to extract the contribution from the quasiparticle part. The calculated values of the proton rms radius for the $\frac{5}{2}^+$ ground state and the $\frac{1}{2}^+$ first excited state were found to be
4.01 fm and 4.15 fm, respectively. Though the experimental trend for the rms radii for these two states is reproduced, the calculated values are not in agreement with the experimentally observed values of 3.78 fm and 5.33 fm, respectively. This discrepancy may be attributed to the fact that the H.O. wave functions do not carry any effect of the low binding energy of the last valence nucleon. This behaviour of the H.O. wave functions, through the radial integrals, consequently affects the calculated values of the electric quadrupole moment and the electromagnetic transition rates (Eq. 5).

To overcome this difficulty, we have used a generalised average one-body potential of Woods-Saxon type to generate the s.p. wave functions. Keeping all the parameters fixed, the depth $V_0$ and the radius parameter $r_0$ were varied to reproduce the experimentally observed binding energies, 0.600 MeV and 0.105 MeV of the $1d_{5/2}$ and $2s_{1/2}$ s.p. states, respectively. The parameters of the single particle potential are given in Table II. These W-S wave functions could be used for calculating the rms radius and the electromagnetic properties of the states of $^{17}$F but for the wave function of the $1d_{3/2}$ state, which is unbound.

In order to circumvent this problem to get the wave function of the unbound $1d_{3/2}$ s.p. state, we developed the W-S wave function in the H.O. basis (WSHO). This was done by diagonalising the W-S potential (Table II) for each $(l, j)$ state in H.O. basis states $(n, l, j)$ with nodal quantum number $n=10$ and properly picking up the $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$, $1p_{3/2}$ and $1p_{1/2}$ states. The $<r^2>$ values for the even parity s.p. states, thus developed, are given in Table III. From the table it is observed that $<r^2>$ values calculated with the W-S wave function in the H.O. basis are smaller than those calculated with the W-S wave functions and quite larger than those calculated with the H.O. wave functions. The calculated values of the rms radii of $^{17}$F using the quasiparticle wave functions WSHO are given in Table IV. For the first excited state, the calculated value of the rms radius agrees quite well with the experimental one. However, for the ground state the calculated value of the rms radius overestimates the corresponding experimental value.

The same quasiparticle wave functions, as used in the calculation of the rms radii, have been used to calculate the electric quadrupole moment of the ground state and the EM transition probabilities among the various states of $^{17}$F obtained earlier. Effective proton charge, $(e_p)_{eff} = 1.5 \ e$ and effective charge of the core, $Z_{eff} = 0.2 \ e$ have been used in the present calculation ($e$ being the charge of proton). However, we made a rough estimate of the value of $Z_{eff}$ (defined as $Z(\hbar\omega^2/2C^2)^{1/2}$) from the value of the quadrupole interaction strength parameter $X_2$ (see Eq. 3) used earlier. Taking value of $\hbar\omega_2$, the quadrupole phonon energy $\approx 2$ MeV, and of $<K>$, the average radial integral $\approx 40$ MeV, the calculated value of $Z_{eff}$ is found to be equal to 0.20 $e$, almost same as the one used in the calculations of the QM and the EM transition probabilities. The calculated values of the QM and the reduced transition probabilities $B(E2)$ and $B(E1)$ are given in Tables IV and V along with their corresponding experimentally measured values. For evaluation of the magnetic dipole moment, the values of $g_s$, $g_l$ and $g_R$ were 5.585, 1.0 and 1.0, respectively. The calculated values of the electric quadrupole moment and the magnetic dipole moment are 0.108 eb and 4.708 $\mu_N$, respectively and they compare very well with the experimental values of 0.10 ±0.02 eb and 4.72130 ± 0.00025 $\mu_N$, respectively (see Table IV). The calculation is able to reproduce well the observed reduced transition probabilities, $B(E2)$ and $B(E1)$ (Table V). However, the calculated $B(E1)$ value between the $1^-_{21}$ and $1^+_{21}$
states underestimate the experimental value by an order of magnitude.

V. SUMMARY AND CONCLUSION

The low lying excitation spectrum of the proton drip line nucleus $^{17}$F has been studied in the quasiparticle-core coupling model in which the motion of the odd quasiparticle is coupled with the neighbouring even-even vibrating core. The core excitation energies, which take into account all the correlations arising out of the many particle core system, were taken from the experiment. The relative single particle energies and the quadrupole interaction strength were treated as parameters. The calculated energies and the spectroscopic factors for both the even and the odd parity states agree quite well with the corresponding experimental results. The calculated values of the rms radii of the ground state and the first excited state using single particle H.O. wave functions follow the experimental trend but are grossly underestimated (particularly the rms radius of the first excited state). However, the value of the rms radius of the first excited state is well reproduced by using the WSHO single particle wave functions. The calculated values of the electric quadrupole moment of the ground state and the reduced transition probabilities using the WSHO wave functions compare quite well with the corresponding experimental values. The calculated value of the ground state magnetic dipole moment agrees very well with that of the experimental one.

In conclusion, it may be inferred that within a simple quasiparticle-vibration coupling model, one can very well reproduce the experimental observables associated with the structure of the light proton drip line nucleus $^{17}$F without going into sophisticated calculations.

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FIG. 1. Calculated and experimental even parity levels of $^{17}\text{F}$. The excitation energies, spin-parities and spectroscopic factors of the levels are shown.
FIG. 2. Same as in fig. 1 for odd parity levels of $^{17}$F.
TABLES

TABLE I. Parameters of the Calculation

| \(1d_{\frac{5}{2}}\) | \(2s_{\frac{1}{2}}\) | \(1d_{\frac{3}{2}}\) | \(1p_{\frac{1}{2}}\) | \(1p_{\frac{3}{2}}\) | \(2s_{\frac{1}{2}}\) | \(1d_{\frac{3}{2}}\) | \(1p_{\frac{1}{2}}\) | \(1p_{\frac{3}{2}}\) | \(\epsilon_j\) (MeV) | \(X_2\) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.985 | 0.866 | 0.800 | 0.142 | 0.313 | 0.0 | 0.550 | 4.500 | 4.800 | 3.00 | 0.5 |

TABLE II. Parameters of Woods-Saxon s.p. potential

| \(V_0\) | \(r_0\) | \(a_0\) | \(V_s\) | \(r_s\) | \(a_s\) |
|---|---|---|---|---|---|
| 49.091 | 1.404 | 0.685 | 23.937 | 0.819 | 1.060 |

TABLE III. Mean square radius for single particle orbitals

| \(< r^2 >\) | W-S wave function in H.O.Basis | W.S wave function\(^a\) | H.O. wave function |
|---|---|---|---|
| \(1d_{\frac{5}{2}}\) | 14.154 | 16.012 | 8.819 |
| \(2s_{\frac{1}{2}}\) | 19.342 | 29.925 | 8.819 |
| \(1d_{\frac{3}{2}}\) | 17.690 | 8.819 | 8.819 |

\(^a\)Parameters of Table 1

TABLE IV. Electromagnetic moments and rms radius

| \(J^\pi\) | Quadrupole Moment (eb) | Magnetic Moment(\(\mu_N\)) | rms radius (fm) |
|---|---|---|---|
| \(\frac{1}{2}^+\) | 0.108 | 4.7080 | 4.83 |
| \(\frac{1}{2}^+\) | 0.10±0.02 | 4.72130±0.00025 | 3.78 |
| \(\frac{3}{2}^+\) | 2.7706 | 5.34 | 5.33 |

TABLE V. Reduced Electric transitions probabilities \(B(E2)\) and \(B(E1)\)

| \(J_i^\pi\) | \(J_f^\pi\) | \(E_i\) (MeV) | \(E_f\) (MeV) | Mult. | Calc. (W.u.) | Expt. (W.u.) |
|---|---|---|---|---|---|---|
| \(\frac{1}{2}^+\) | \(\frac{3}{2}^+\) | 0.517 | 0.0 | E2 | 21.9 | 25.0±0.5 |
| \(\frac{1}{2}^-\) | \(\frac{1}{2}^+\) | 3.087 | 0.517 | E1 | 0.2×10\(^{-3}\) | (1.5±0.3)×10\(^{-3}\) |
| \(\frac{5}{2}^-\) | \(\frac{5}{2}^+\) | 4.848 | 0.0 | E1 | 6.1×10\(^{-3}\) | (4.3±0.8)×10\(^{-3}\) |