# Neutron-proton multiplets in the odd-odd nucleus $^{90}_{37}Rb_{53}$

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Medium-spin excited levels in $^{90}$Rb, populated in the fission of $^{235}$U induced by neutrons, have been observed for the first time. $\gamma$ radiation from fission has been measured by using the EXILL array of Ge detectors at the cold-neutron-beam facility PF1B of the Institut Laue–Langevin, Grenoble. Low-energy levels are interpreted as members of the $\pi p_{3/2}^{-1}\nu(d_{5/2})^3$, $\pi f_{5/2}^{-1}\nu(d_{5/2})^3$, and $\pi g_{9/2}\nu(d_{5/2})^3$ multiplets with the $0^-$ ground state due to the seniority-3 coupling in the $\nu d_{5/2}$ shell. Analogous anomalous coupling within the $\pi g_{9/2}\nu(d_{5/2})^3$ configuration explains the $5^+$, $6^+$, and $7^+$ triplet of states, observed at medium spins, similar to the triplet seen in the $N = 53$ isotone, $^{88}$Br. Shell-model calculations reproduce well the proposed structures in $^{88,90}$Rb and support the seniority-3 coupling in $N = 53$ isotones and its absence in $N = 51$ isotones. The structure of the odd-odd $^{88}$Rb and $^{90}$Rb nuclei provides an argument in favor of the collectivity building up at the neutron number $N = 53$.

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## I. INTRODUCTION

In recent works [1–3] we reported on collectivity building up in the $N = 53$ isotones below $Z = 36$. A characteristic signature of this collectivity in odd-$A$, $N = 53$ isotones is the $j - 1$ anomaly in the $(d_{5/2})^3$ neutron multiplet [4–6], manifested as a doublet of $3/2^+$ and $5/2^+$ levels. Shell-model calculations reproduce well the anomalous, $3/2^+$ ground states and low-lying $5/2^+$ excitations in $^{87}$Se and $^{89}$Kr [1,7], supporting the applicability of recently developed effective interactions [7] for shell-model calculations of neutron-rich nuclei around the $^{78}$Ni core.

The study of odd-odd, $N = 53$ isotones allows us to check whether and how the $j - 1$ anomaly is manifested in the $N = 53$ isotones with an odd proton. For the shell model, the odd-odd nuclei constitute a particular challenge because their structure is sensitive to details of monopole and multipole components of the effective interactions. The data on odd-odd systems also provide a unique benchmark of proton-neutron matrix elements.

Our work on the odd-odd, $N = 53$ isotone $^{88}$Br [3], suggests the $(j,j-1)$ doublet in this nucleus at medium spins and excitations. There, the $(d_{5/2})^3$ neutrons couple to the $g_{9/2}$ proton producing a doublet of $6^+$ and $7^+$ levels. The shell model reproduces well this structure but, in addition, a $5^+$ level is predicted in the multiplet and the experiment provides a possible counterpart. Thus, there could be a $(5^+,6^+,7^+)$ *triplet* of states due to the $\nu d^3_{5/2}$ seniority-3 coupling. Such $(j - 2, j - 1, j)$ triplet is observed in the $N = 85$ isotones, originating from the $\nu f^3_{7/2}$ seniority-3 structure [8]. It is possible that the $(\nu d^3_{5/2})_{j-2}$ coupling at $N = 53$ has not been found in $^{87}$Se due to the low statistics of the data [1].

Nonunique spin and parity assignments in $^{88}$Br [3] prevented the definite confirmation of the discussed triplet in $^{88}$Br. The study of the odd-odd, $N = 53$ isotone $^{90}$Rb may help because the medium-spin, yrast structure in $^{90}$Rb is expected to be similar to the structure observed in $^{88}$Br. The observation of the $\nu(d_{5/2})^3$ anomalous coupling in $^{90}$Rb would also strengthen the evidence for collectivity at $N = 53$. In addition, it is of interest to look for proton-neutron configurations involving the $g_{7/2}$ neutron orbital. So far, the members of the $(\pi g_{9/2},\nu g_{7/2})_j$ multiplet have only been observed in heavier odd-odd Rb isotopes [9–12].

The questions mentioned motivated us to study the $^{90}$Rb nucleus. This work reports on the first observation of medium-spin states in $^{90}$Rb. The experiment, data analysis, and results are presented in Sec. II. In Sec. III the results are discussed and interpreted. The work is concluded in Sec. IV.

## II. EXPERIMENT AND DATA ANALYSIS

We have searched for excited levels in $^{90}$Rb by using the spectrometer EXOGAM at the Institut Laue-Langevin (EXILL) [13,14] at the PF1B cold-neutron beam facility [15] of the ILL in Grenoble to measure $\gamma$ rays following cold-neutron-induced fission of a $^{235}$U target. A detailed description of the experiment can be found in our recent work on $^{88}$Br [3] and in references quoted therein.

 

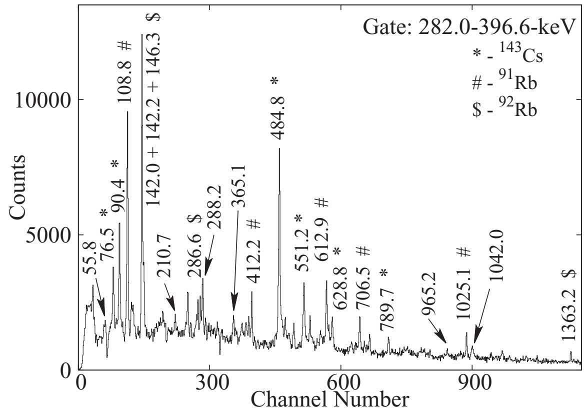


FIG. 1. A $\gamma$-ray spectrum doubly gated on the 282.0 and 396.6 keV $\gamma$ lines of $^{143}$Cs. Energies of $\gamma$ lines are labeled in keV.

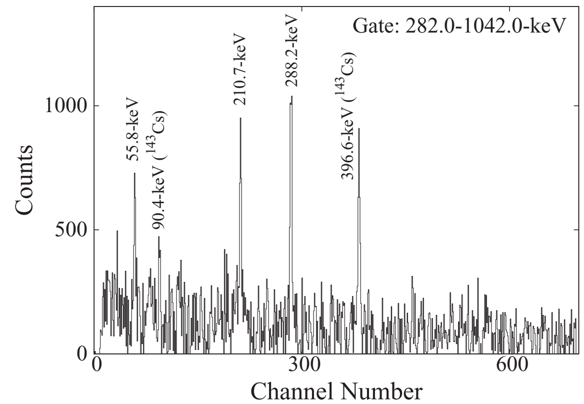


FIG. 2. A $\gamma$-ray spectrum doubly gated on the 282.0 keV line of $^{143}$Cs and the new, 1042.0 keV line.

### A. Excitation scheme of $^{90}$Rb

No medium-spin levels were reported on in the odd-odd $^{90}$Rb nucleus prior to this work. The first extensive study of low-spin levels in $^{90}$Rb, populated in $\beta^-$ decay of the $0^+$ ground state of $^{90}$Kr, was published by Mason and Johns [16]. The authors assigned spin $1^-$ to the ground state and spin $4^-$ to the 106.9 keV isomer, assuming that these levels belong to the $(\pi p_{3/2}^{-1} \nu d_{5/2}^3)_{1^-,2^-,3^-,4^-}$ multiplet. Later, Ekström *et al.* measured $0^-$ spin and parity of the ground state in $^{90}$Rb [17] and Duke *et al.* [18] assigned spin $3^-$ to the 258 s isomer at 106.9 keV in $^{90}$Rb, based on the $M3$ multipolarity of the 106.9 keV isomeric transition.

In the cold-neutron-induced fission of $^{235}$U, on average 2.4 neutrons and no protons are emitted from a pair of primary fission fragments, leading to a pair of secondary fission fragments, which both deexcite simultaneously by emitting $\gamma$ rays. Thus, $\gamma$ rays from the two complementary fragments are in prompt-time coincidence. In fission of $^{236}$U, the most abundant fragments complementary to $^{90}$Rb are $^{143}$Cs and $^{144}$Cs, accompanied by the emission of three and two neutrons, respectively ($3n$ and $2n$ channels). To find new transitions in $^{90}$Rb, we analyzed spectra doubly gated on strong transitions in $^{143}$Cs or $^{144}$Cs, using histograms of triple-$\gamma$ coincidences sorted within a 200 ns time window (prompt-$\gamma$ coincidences).

Figure 1 shows a $\gamma$ spectrum doubly gated on the 282.0 and 396.6 keV lines of $^{143}$Cs [19]. Apart from known lines of $^{91,92}$Rb and $^{143}$Cs, new lines at 55.8, 210.7, 288.2, 365.1, 965.2, and 1042.0 keV are seen. In the $\gamma$ spectrum doubly gated on the 282.0 keV line of $^{143}$Cs and the new 1042.0 keV line, shown in Fig. 2, the 55.8, 210.7, and 288.2 keV lines are seen, but there is no line at 365.1 keV, present in Fig. 1. Figure 3 shows three $\gamma$ spectra obtained by double gating on the new lines. Figure 3(a) shows a spectrum gated on the 55.6 and 1042.0 keV lines. It is dominated by the 210.7 and 288.2 keV lines and there is a weak line at 983.3 keV. In a spectrum, gated on the 55.6 and 965.2 keV lines, shown in Fig. 3(b), a strong 210.7 keV line and a weak 983.3 keV line are seen but, instead of the 288.2 keV line, there is a strong line at 365.1 keV. A $\gamma$ spectrum, gated on the 55.6 and 210.7 keV lines is shown in Fig. 3(c). In the spectrum there are further new lines at 117.2, 714.6, and 880.3 keV. Further gating confirmed that the 55.8, 117.2, 210.7, 288.2, 365.1, 714.6, 880.3, 965.2, 983.3, and 1042.0 keV transitions belong to a new excitation scheme of a Rb isotope.

To assign the new scheme to a particular Rb isotope we used the mass correlation technique as proposed in Ref. [20]. Figure 4 shows, on a logarithmic scale, the ratios of $\gamma$ intensity of the 396.6 keV transition in $^{143}$Cs to $\gamma$ intensity

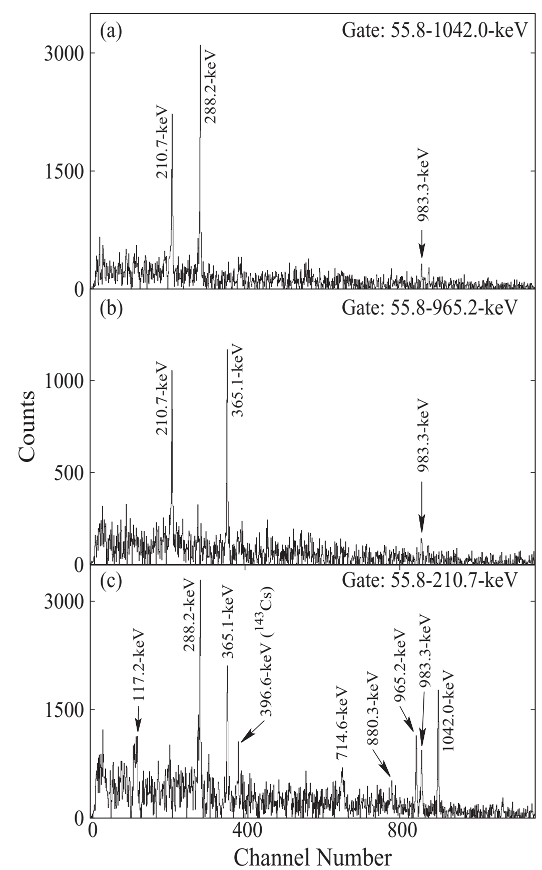


FIG. 3. Coincidence spectra gated on the 55.6 keV line and one of the new, 210.7, 965.2, or 1042.0 keV lines.

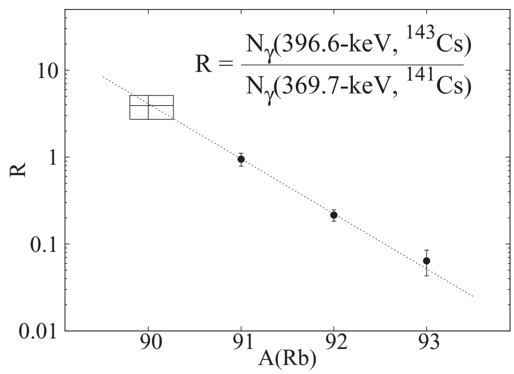


FIG. 4. Mass correlation for Rb isotopes as obtained in this work. See text for further explanation.

of the 369.7 keV transition in $^{141}$Cs [19], as observed in spectra doubly gated on known lines in $^{91}$Rb, $^{92}$Rb, and $^{93}$Rb isotopes [12,21] (solid circles in the figure). Such a ratio varies smoothly with the mass of the gated isotope [20,22], allowing a meaningful extrapolation, represented by the dashed line in Fig. 4. The ratio $R = 3.92(8)$, obtained from spectra doubly gated on lines belonging to the new level scheme, is represented in Fig. 4 by a rectangle (the vertical side of the rectangle represents the error in $R$). The intersection of this data with the dashed line determines the mass, $A = 90.0(2)$ of the Rb isotope, to which this new level scheme belongs. This value indicates uniquely that the excited level structure in question belongs to the $^{90}$Rb nucleus.

TABLE I. Properties of $\gamma$ transitions in $^{90}$Rb, as observed in the neutron-induced fission of $^{235}$U in the present work. Relative $I_\gamma$ values are in arbitrary units.

| $E_\gamma$ (keV) | $I_\gamma$ (rel.) | $E_\gamma$ (keV) | $I_\gamma$ (rel.) | $E_\gamma$ (keV) | $I_\gamma$ (rel.) |
|---|---|---|---|---|---|
| 55.8(1) | 90(9) | 365.1(1) | 39(9) | 983.3(1) | 15(3) |
| 117.2(2) | 7(2) | 714.6(2) | 7(2) | 1007.1(5) | 10(3) |
| 186.5(3) | 5(2) | 830.7(3) | 4(2) | 1042.0(1) | 100(4) |
| 210.7(1) | 44(8) | 880.3(1) | 4(2) | 1133.4(4) | 8(3) |
| 288.2(1) | 58(9) | 965.2(1) | 44(8) | | |

The level scheme of $^{90}$Rb as obtained in this work is shown in Fig. 5. Apart from the 106.9 keV isomer decay reported before [18,23], all other excited levels and transitions are new. Energies and relative $\gamma$ intensities of transitions in $^{90}$Rb, as observed in this work, are presented in Table I, while spin and parity assignments to levels are discussed in Sec. II C. The 880.3 keV transition listed in Table I is not placed in the scheme due to insufficient evidence. It populates either the 2686.9 or the 3517.4 keV level.

Because $\gamma$ intensities of the 365.1 and 965.2 keV lines are equal (within uncertainties), we checked if the order of the two transitions in the cascade could be reversed. In Fig. 6 we show a spectrum, doubly gated on the 210.7 and 288.2 keV lines. In case the order of the 365.1 and 965.2 keV transitions is reversed, there should be a level at 528 keV. In this case one would expect to see a 677 keV branching from the 1204.7 keV level to this 528 keV level, because the spin of this hypothetical level should be in a range $4 < I < 6$. The arrow in Fig. 6 shows the position of the expected 677 keV line, indicating that there is no gamma line of such energy. This result supports the proposed 1127.9 keV level.

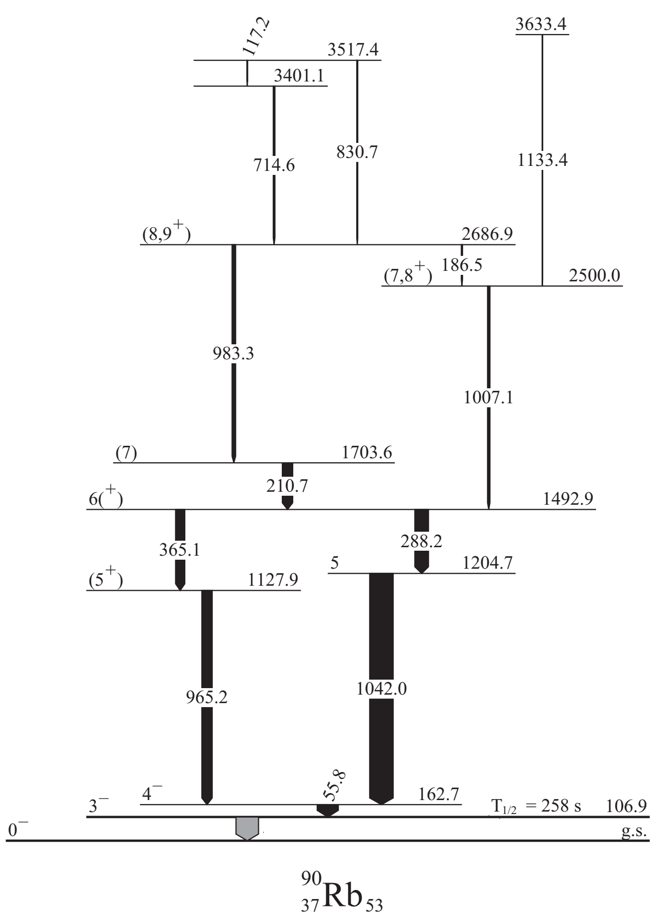


FIG. 5. Level scheme of $^{90}$Rb, as obtained in this work. The half-life of the 106.9 keV isomer is taken from Ref. [23].

## B. Half-life measurements

Half-lives of excited levels provide useful information on multipolarities of their decays, assisting spin and parity

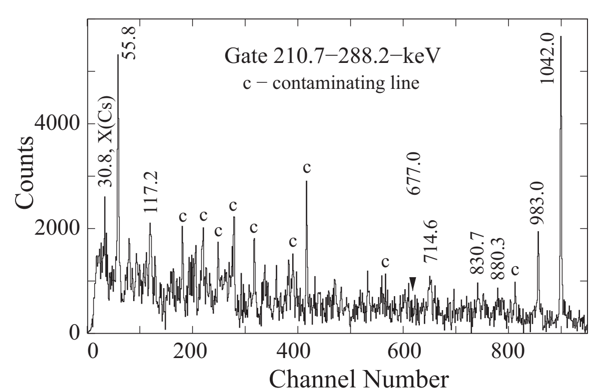


FIG. 6. Coincidence spectrum gated on the 210.7 and 288.2 keV lines of $^{90}$Rb.

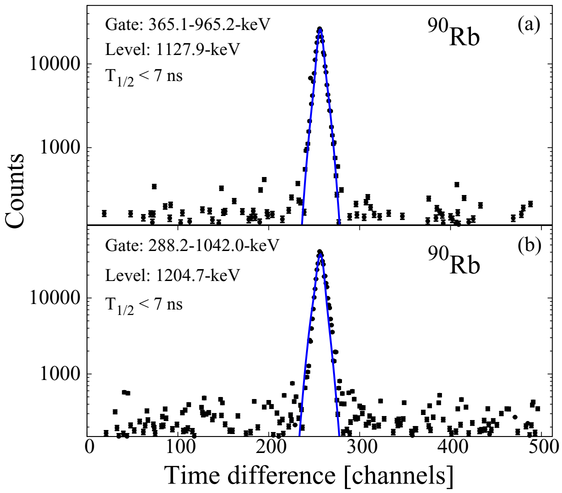


FIG. 7. Time spectra (a) for the 1127.9 keV level and (b) for the 1204.7 keV level in $^{90}$Rb as obtained in this work. The time calibration is 10 ns per channel with time-difference "zero" at channel 256.

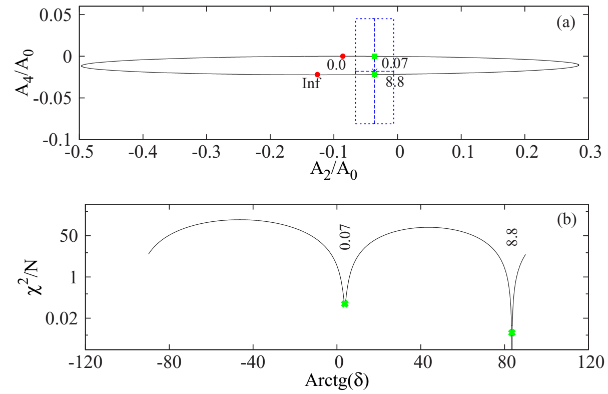


FIG. 8. Angular correlation analysis for the 210.7-365.1 keV cascade in $^{90}$Rb.

assignments. The present experiment, where $\gamma$ signals were accompanied by time stamps from a 100 MHz clock [14], allows us to measure half-lives of levels in the nano- to microsecond range. To determine half-lives of excited levels in $^{90}$Rb we have applied a technique described in detail in our previous work [3], where the accuracy of the method and its lower limit of of 7 ns are illustrated.

The analysis of the time spectra for the 365.1-965.2 and 288.2-1042.0 keV cascades, shown in Fig. 7, indicates half-lives shorter than the limit of 7 ns for the 1127.9 and 1204.7 keV levels, respectively. A similar limit was determined for the 162.7, 1492.9, and 1703.2 keV levels.

### C. Spin and parity assignments to levels in $^{90}$Rb

In the present work we measured angular correlations for $\gamma\gamma$ cascades in $^{90}$Rb by using the eight EXOGAM Clover detectors [24] mounted in the EXILL spectrometer in one plane in an octagonal geometry. This configuration provides three different angles between detectors: 0°, 45° and 90°. More details on the technique are reported in Refs. [3,25].

The experimental angular correlations were analyzed by using programs developed in Ref. [25], based on the formalism of Krane, Steffen, and Wheeler [26]. The theoretical formula for the angular correlation function between two consecutive $\gamma$ transitions in a cascade from a nonoriented state is expressed as a series of Legendre polynomials $P_k$:

$$W(\theta) = \sum_k A_k P_k(\cos\theta), \quad (1)$$

where $\theta$ is the angle between the directions of the $\gamma_1$ and $\gamma_2$ transitions in the cascade.

Theoretical values of $A_k$ coefficients, which depend on level spins and transition multipolarities and their mixing coefficients $\delta$ were calculated for various hypotheses of spins and multipolarities in the cascade studied by using the formalism of Ref. [26] and were compared to experimental $A_k$ coefficients to find solutions.

In Fig. 8 we present an example of such angular-correlation analysis for the 210.7-365.1 keV cascade in $^{90}$Rb, where for the 1703.2, 1492.9, and 127.9 keV levels we have assumed spins 7, 6, and 6, respectively. The "ellipse" in the upper part of Fig. 8 represents theoretical values of $A_2/A_0$ and $A_4/A_0$ coefficients for the assumed spin hypotheses as a function of the mixing coefficients $\delta$, which vary from 0 to $\pm\infty$ (red dots) along the two branches of the "ellipse." The experimental values of $A_2/A_0$ and $A_4/A_0$ with their error bars are represented by the rectangle (blue). The lower part of Fig. 8 shows a plot of the $\chi^2$ function per degree of freedom, calculated from the difference between experimental $A_k/A_0$ and calculated $A_k(\delta)/A_0$ values. There are two solutions: with the mixing coefficient of the 365.1 keV transition $\delta = 0.06(0.42)$ or $\delta = 8.8(-2.4, +4.8)$ (green dots).

Results of the angular correlation analysis for $\gamma\gamma$ cascades in $^{90}$Rb are presented in Table II. Below we discuss spin and parity assignments to levels in $^{90}$Rb. In the discussion we used, in addition, the well-documented observation of the predominant population of yrast levels in the fission process [27] as well as arguments derived from the observed decay branchings and the intensity balance.

#### *1. The 162.7 keV level*

The total conversion coefficient of the 55.8 keV transition, deduced from the total-intensity balance in the 55.8-1042.0-288.2-210.7 and 55.8-965.2-365.1-210.7 keV cascades, performed in spectra gated on two lines of each cascade yields $\alpha_{tot} = 1.35(10)$. This large value indicates a mixed $M1 + E2$ multipolarity for the 55.8 keV transition, considering values for unmixed transitions of $\alpha_{tot}(E1) = 0.53$, $\alpha_{tot}(M1) = 0.74$, $\alpha_{tot}(E2) = 8.04$, and $\alpha_{tot}(M2) = 13.3$ [28]. An $E1 + M2$ multipolarity is unlikely, considering the prompt character of the transition. From the obtained $\alpha_{tot}$ value and using formulas from Ref. [28] we calculated a mixing ratio of $\delta = 0.302(15)$ for the 55.8 keV transition.

The $M1 + E2$ multipolarity of the 55.8 keV transition indicates negative parity for the 162.7 keV level. Due to the yrast character of levels populated in fission, spins of the

TABLE II. Normalized experimental angular correlation coefficients and the corresponding mixing coefficients $\delta$ for $\gamma$ transitions in $^{90}$Rb, as obtained in this work.

| Cascade | $A_2/A_0$ | $A_4/A_0$ | Spin hypothesis | $\delta(\gamma)$[a] |
|---|---|---|---|---|
| 965.2$^a$-55.8 | 0.044(89) | 0.11(21) | $5 \to 4 \to 3$ | $0.24(^{+0.21}_{-0.28})$ |
| | | | $5 \to 4 \to 3$ | $3.0(^{+16.0}_{-3.0})$ |
| | | | $6 \to 4 \to 3$ | 0 |
| 1042.0$^a$-55.8 | −0.046(86) | 0.067(179) | $5 \to 4 \to 3$ | $-0.08(^{+0.26}_{-0.29})$ |
| 288.2$^a$-1042.0 | 0.038(26) | 0.007(56) | $5 \to 5 \to 4$ | $0.76(^{+0.13}_{-0.11})$ |
| | | | $5 \to 5 \to 4$ | $-3.53(^{+0.77}_{-1.4})$ |
| | | | $6 \to 5 \to 4$ | 0.05(0.04) |
| | | | $6 \to 5 \to 4$ | $8.5(^{+4.8}_{-2.2})$ |
| 365.1$^a$-965.2 | −0.059(48) | 0.01(10) | $6 \to 5 \to 4$ | $0.47(^{+0.42}_{-0.31})$ |
| | | | $6 \to 5 \to 4$ | $1.8(^{+2.6}_{-1.7})$ |
| | | | $6 \to 6 \to 4$ | $0.45(^{+0.18}_{-0.16})$ |
| | | | $6 \to 6 \to 4$ | $-1.46(^{+0.56}_{-0.39})$ |
| 210.7$^a$-288.2 | 0.029(31) | 0.064(68) | $6 \to 6 \to 5$ | $1.01(^{+1.1}_{-0.37})$ |
| | | | $6 \to 6 \to 5$ | $-4.4(^{+2.3}_{-Inf})$ |
| | | | $7 \to 6 \to 5$ | $0.01(^{+0.12}_{-0.11})$ |
| | | | $7 \to 6 \to 5$ | $16(^{+Inf}_{-11})$ |
| 210.7$^a$-365.1 | −0.036(30) | −0.018(64) | $6 \to 6 \to 5$ | $0.81(^{+0.15}_{-0.12})$ |
| | | | $6 \to 6 \to 5$ | $-2.92(^{+0.61}_{-1.1})$ |
| | | | $7 \to 6 \to 5$ | 0.07(0.05) |
| | | | $7 \to 6 \to 5$ | $8.8(^{+5.4}_{-2.5})$ |
| | | | $7 \to 6 \to 6$ | 0.06(0.42) |
| | | | $7 \to 6 \to 6$ | $8.8(^{+4.8}_{-2.4})$ |

[a]Indicates a mixed $\gamma$ transition.

1127.9 and 1204.2 keV levels are expected to be higher than the spin of the $3^-$, 106.9 keV isomer. Furthermore, the 1127.9 and 1204.2 keV levels decay to the 162.7 keV level but not to the 106.9 keV level. From this we conclude that the spin of the 162.7 keV level is higher than the spin of the 106.9 keV level and yields $I = 4^-$.

#### *2. The 1127.9 keV level*

For the 55.8-965.2 keV cascade, the angular correlations are consistent with spin 5 or 6 for the 1127.9 keV state when taking the $\delta = 0.302$ for the 55.8 keV transition. Assuming spin 5 for the 1127.9 keV level we obtain a mixed dipole-quadrupole multipolarity of the 965.2 keV transition with $\delta = 0.24(-0.21, +0.28)$ or $\delta = 3.0(-3.0, +16)$. For the $I = 6$ hypothesis a pure $E2$ multipolarity of the 965.2 keV transition is derived, considering its prompt character. Summarizing, spin 5 or $6^{(-)}$ is proposed for the 1127.9 keV level.

#### *3. The 1204.7 keV level*

With $\delta = 0.302$ of the 55.8 keV transition, angular correlations for the 55.8-1042.0 keV cascade are not consistent with spin 4 or 6 for the 1204.7 keV level. Assuming spin 5 we find $\delta = -0.08(-0.29, +0.26)$ for the 1042.0 keV transition, which can have, therefore, either $M1 + E2$ or $E1 + M2$ multipolarity.

#### *4. The 1492.9 keV level*

Angular correlations for the 365.1-965.2 keV cascade are consistent with the $6 \to 5 \to 4$ or $6 \to 6 \to 4$ spin hypotheses for the 1429.9, 1127.9, and 162.7 keV levels. For the 365.1 keV transition a mixed dipole-quadrupole character with large mixing ratio is obtained in both cases, indicating an $M1 + E2$ multipolarity for the 365.1 keV transition and, consequently, the same parity of the 1127.9 and 1492.9 keV levels.

Angular correlations for the 288.2-1042.0 keV cascade are consistent with two spin hypotheses, $5 \to 5 \to 4$ or $6 \to 5 \to 4$, when taking $\delta = -0.08$ for the 1042.0 keV transition. As already shown, for the 1204.7 keV level spin 5 is the only solution. Considering also the result for the 365.1-965.2 keV cascade we propose spin 6 for the 1492.9 keV level. As shown in Table II in this case the respective mixing ratios for the 288.2 keV transition are $\delta = 0.05(4)$ and $\delta = 8.5(^{+4.8}_{-2.2})$. Therefore, this transition may have either $E1$ or $M1 + E2$ multipolarity.

#### *5. The 1703.6 keV level*

For the 210.7-288.2 and 210.7-365.1 keV cascades, angular correlations are consistent with spin 6 or 7 for the 1703.6 keV state. The respective $\delta$ values are shown in Table II and Fig. 8.

#### *6. Other remarks*

The lack of any 1330 keV decay from the 1492.9 keV to the 162.7 keV level is consistent with the spin 6 assignment and positive parity of the 1492.9 keV level. In case of negative parity an $E2$, 1330 keV decay should rather be observed. Consequently, spin and parity of the 1127.9 keV level is $5^+$, considering the $M1 + E2$ multipolarity of the 365.1 keV transition.

Spin 6 for the 1703.2 keV level is less likely than spin 7 because no decay is observed from this level to the 1127.9 and 1204.7 keV levels.

The observed decay branches of the 2500.0 and 2686.9 keV levels favor spins and parities as tentatively proposed in Fig. 5. We note that in the case of spin 7, the 2500.0 keV level would be very nonyrast. Thus, spin $8^+$ is a more likely solution for this level.

## III. DISCUSSION

### A. Expected yrast excitations in $^{90}$Rb

In $^{90}$Rb one expects near the Fermi level the $p_{3/2}$ and $f_{5/2}$ proton holes and the $d_{5/2}$ neutron particle forming two multiplets, $(\pi p_{3/2}^{-1}, \nu d_{5/2})_j$ and $(\pi f_{5/2}^{-1}, \nu d_{5/2})_j$, with spins in a range $1^- \geqslant j^\pi \geqslant 4^-$ and $1^- \geqslant j^\pi \geqslant 5^-$, respectively. When the odd proton is promoted to the $g_{9/2}$ orbital it will form the $(\pi g_{9/2}, \nu d_{5/2})_j$, particle-particle multiplet with spin $2^+ \geqslant j^\pi \geqslant 7^+$ The $7^+$ level is expected to be yrast, as observed in the neighboring $^{86}$Br, $^{88}$Br, and $^{88}$Rb odd-odd nuclei [3,11]. When, in addition, a neutron is promoted to the $g_{7/2}$ orbital, the $(\pi g_{9/2}, \nu g_{7/2})_j$ multiplet should appear, with spin $8^+$ expected low in the multiplet, as seen in $^{92,94}$Rb [10,12].

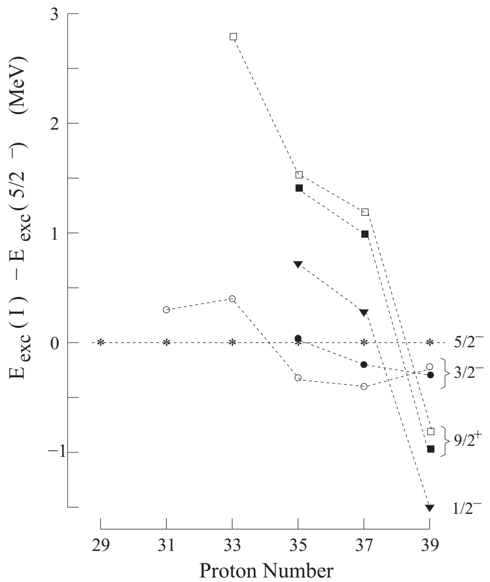


FIG. 9. Excitations in $N = 50$ (empty symbols) and $N = 52$ (solid symbols), odd-$Z$ isotones, shown relative to the $5/2^-$ excitation in these nuclei. Dashed lines are drawn to guide the eye. The data are taken from Refs. [29–39].

#### 1. The ground state of $^{90}$Rb

The $0^-$ spin and parity of the ground state deviates from this simple picture. In Ref. [18] the $(\pi f^{-1}_{5/2},\nu d_{5/2})_{0^-}$ solution was proposed, although the authors were not satisfied with it. Indeed, the $(\pi f^{-1}_{5/2},\nu d_{5/2})_j$ multiplet is expected above the $(\pi p^{-1}_{3/2},\nu d_{5/2})_j$ multiplet, because in odd-$Z$, $^{87}$Br, and $^{89}$Rb nuclei the $\pi f^{-1}_{5/2}$ hole is farther away from the Fermi level than the $\pi p^{-1}_{3/2}$ hole [29,30], as seen in Fig. 9. Second, the $0^-$ member of the $(\pi f^{-1}_{5/2},\nu d_{5/2})_j$, hole-particle multiplet is expected at the high-energy end of the multiplet. Furthermore, the ground state of $^{88}$Rb has spin and parity $2^-$ and the mechanism proposed in Ref. [18] fails there.

We propose that the $0^-$ ground state in $^{90}$Rb results from coupling of the $\pi p^{-1}_{3/2}$ hole to the seniority-3 $(d^3_{5/2})_{j=3/2}$ configuration, where the $j = 3/2$ level is lowered due to the anomalous $j - 1$ coupling. This mechanism is not applicable in $^{88}$Rb, which has only one valence neutron.

#### 2. The $3^-$ isomer in $^{90}$Rb

The $3^-$ isomer in $^{90}$Rb is a likely member of the $(\pi p^{-1}_{3/2},\nu d^3_{5/2})$ or $(\pi f^{-1}_{5/2},\nu d^3_{5/2})$, hole-particle multiplet. A similar $3^-$ isomer in $^{92}$Rb was explained in this way [12], although low-energy, $3^-$ levels in odd-odd Rb isotopes may also have another origin. In Fig. 9 the $1/2^-$ level follows the $9/2^+$ level, corresponding to the $1g_{9/2}$ proton excitation. The $1/2^-$ level, located about 1 MeV below the $9/2^+$ level in $^{93}$Rb and $^{95}$Y [21,40] is most likely due to the $2p_{1/2}$ proton excitation. At N < 57 and $Z > 36$ this proton may produce a low-lying, $(\pi p_{1/2},\nu d_{5/2})_{3^-}$ configuration, which will contribute to the wave function of the $3^-$ level, lowering its energy.

#### 3. $4^-$ and $5^-$ levels in $^{90}$Rb

The $4^-$ level at 162.7 keV could be a member of the $(\pi p^{-1}_{3/2},\nu d^3_{5/2})$ or $(\pi f^{-1}_{5/2},\nu d^3_{5/2})$ multiplet. The latter option is less likely because at $Z = 37$ the $\pi f^{-1}_{5/2}$ hole is expected higher in energy than the $\pi p^{-1}_{3/2}$ one. Probably for this reason the $(\pi f^{-1}_{5/2},\nu d^3_{5/2})_{5^-}$ level, observed only 300 keV above the $4^-_1$ level in $^{86}$Br and $^{88}$Br, is not seen in $^{90}$Rb. A possible candidate for the $(\pi f^{-1}_{5/2},\nu d^3_{5/2})_{5^-}$ configuration is the 1204.7 keV experimental level, over 1 MeV above the $4^-$, 162.7 keV level. We note that the truth may be more complex because in $^{88}$Rb the $5^-_1$ level is reported about 400 keV above the $4^-$ level.

#### 4. The $(\pi g_{9/2},\nu d^3_{5/2})_{5^+,6^+,7^+}$ triplet in $^{90}$Rb

Candidates for the $6^+$ and $7^+$ doublet are seen at 1492.9 and 1703.6 keV, respectively. A similar doublet in $^{88}$Br [3] was explained as coupling of the $(\nu d^3_{5/2})_{3/2,5/2}$ doublet to the $g_{9/2}$ proton. The 1492.9 and 1703.6 keV level support the anomalous coupling and the underlying collectivity in $^{90}$Rb, in addition to the similar effect proposed at the ground state of $^{90}$Rb. We note that no $6^+$ excitation is seen near the $7^+$ level in $^{88}$Rb [11], which has only one $\nu d_{5/2}$ valence neutron (a similar difference is observed between the $^{86}$Br and $^{88}$Br nuclei [3]).

In the introduction we propose that these levels may belong to the $(\pi g_{9/2},\nu d^3_{5/2})_{j-2,j-1,j}$ *triplet*. In $^{88}$Br, the experimental evidence was not conclusive but, in $^{90}$Rb, we see now a candidate for the $5^+$ excitation, which supports the triplet scenario at $N = 53$. We note that neither the $6^+$ nor the $5^+$ level are seen in $N = 51$ $^{88}$Rb or $^{86}$Br isotones, which have only one valence neutron.

The $5^+$, $6^+$, and $7^+$ levels in $^{90}$Rb and the $7^+$ level in $^{88}$Rb, with the proposed $(\pi g_{9/2},\nu d^3_{5/2})_{5^+,6^+,7^+}$ configuration, are, on average, about 1.4 MeV above the $3^-$ level. This energy difference is 0.4 MeV lower than the analogous difference observed in $^{86,88}$Br, reflecting the fact that the $g_{9/2}$ orbital is about 0.4 MeV closer to the Fermi level in Rb isotopes, as illustrated in Fig. 9.

### B. Shell-model calculations of yrast levels in $^{90}$Rb

To verify the proposed interpretations we calculated excitations in $^{90}$Rb by using the shell model, taking the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$ orbitals for protons and the $2d_{5/2}$, $3s_{1/2}$, $1g_{7/2}$, $2d_{3/2}$, $1h_{11/2}$ orbitals for neutrons, outside the $^{78}$Ni core. Similar calculations were performed for the odd-$A$, $N = 52$ and $N = 53$ isotones [1,2] and $^{86,88}$Br isotopes [3]. The effective interaction is described in Refs. [7,41], with the proton-proton part of the interaction updated to reproduce new data in $N = 50$ isotones [33]. The calculations were done by using the $m$-scheme shell-model code ANTOINE [42] and the coupled-scheme code NATHAN [43]. Full diagonalizations in the model space have been achieved.

In Fig. 10 the results of the calculation for $^{90}$Rb are compared to experimental levels, normalized at the $3^-_1$ level,

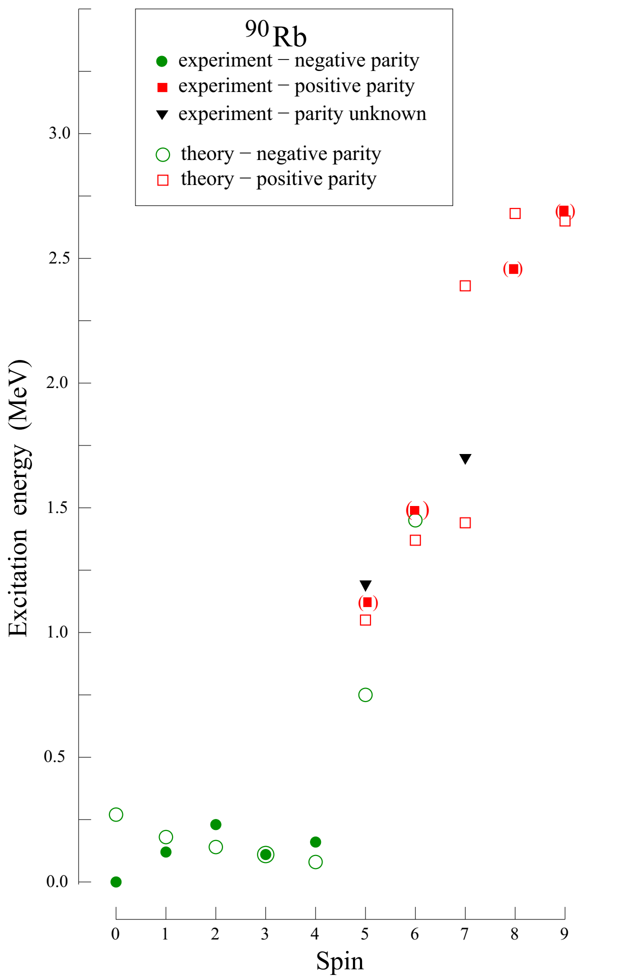


FIG. 10. Comparison of excited levels in $^{90}$Rb, observed in this work, to the present shell-model calculations. The experimental $1^-$ and $2^-$ levels are drawn after Ref. [18].

which is a pronounced feature of odd-odd Rb isotopes. Brackets denote tentative spin and/or parity assignments.

The shell model reproduces well the overall scale of excitations in $^{90}$Rb. The individual levels are reproduced within less than 200 keV, on average, which is a satisfactory precision in shell-model calculations in the region.

The $1^-$ to $4^-$ levels are calculated close to their experimental counterparts, although the $0^-$ level is not calculated as the ground state. This may require some readjustment of the pairing matrix elements. About 46% of the $0^-$ wave function comes from the configuration, in which the neutron $d_{5/2}^2$ pair is broken. Such a component is considerable also in the $3^-$ and $4^-$ states (45% and 40%, respectively).

The $5^+$, $6^+$, and $7^+$ levels are calculated close to the proposed experimental counterparts. The calculated levels have in their wave function one proton in the $g_{9/2}$ orbital. While the $7^+$ wave function is dominated by seniority-1 configuration, with 65% of $(\pi g_{9/2}, \nu d_{5/2})$, the wave functions of the $5_1^+$ and $6_1^+$ states contain about 60% of higher-seniority components with a large fraction of the seniority-3 $(\nu d_{5/2})^3$ configuration. Thus the shell model supports the presence of

TABLE III. Occupation of neutron and proton orbitals, calculated in this work for the $5_1^-$ and $6_1^-$ levels in $^{90}$Rb by using the shell model.

| Levels | Neutrons $d_{5/2}$ | $s_{1/2}$ | $g_{7/2}$ | $d_{3/2}$ | $h_{11/2}$ | Protons $f_{5/2}$ | $p_{3/2}$ | $p_{1/2}$ | $g_{9/2}$ |
|---|---|---|---|---|---|---|---|---|---|
| $5_1^-$ | 2.66 | 0.10 | 0.06 | 0.09 | 0.09 | 4.77 | 3.19 | 0.66 | 0.38 |
| $6_1^-$ | 2.79 | 0.04 | 0.03 | 0.08 | 0.06 | 5.45 | 2.71 | 0.40 | 0.44 |

a multiplet of states connected with the seniority-3 neutron coupling.

At about 2.6 MeV, three close-lying, $7_2^+$, $8_1^+$, and $9_1^+$ levels are calculated, for which possible counterparts are seen in experiment at 2500.0 and 2686.9 keV. Unlike in $^{86}$Br and $^{88}$Br, where the $8_1^+$ level is calculated too high in energy, in $^{90}$Rb it is close to experiment. The lower energy of the $8^+$ state in Rb may be due to a lower excitation energy of the $g_{9/2}$ proton in Rb, as compared to Br isotopes.

Shell-model calculations for $^{92}$Rb, where the $8^+$ state has been reproduced well, predict one $g_{7/2}$ neutron in the wave function of this level (see Table II in Ref. [12]). In contrast in $^{88,90}$Rb and in $^{86,88}$Br [3], the calculated $8_1^+$ level contains very little of the $g_{7/2}$ neutron in its wave function. In $^{90}$Rb, the wave function of the $8_1^+$ level is based on the $\pi g_{9/2}^1 \nu d_{5/2}^3$ configuration. It remains to be determined where exactly the $g_{7/2}$ neutron orbital is located in the $^{78}$Ni potential, how it evolves with proton number, and what its role is in the positive-parity states of the discussed nuclei.

Finally, in Table III we show the occupation of neutron and proton orbitals, calculated in this work for the $5_1^-$ and $6_1^-$ levels in $^{90}$Rb. As mentioned above, the structure of the $5_1^-$ level is more complex than just a $\pi f_{5/2}^{-1} \nu d_{5/2}$ configuration. The shell model supports the $\pi f_{5/2}^{-1}$ hole contribution to the wave function of the $5_1^-$ level, however increased, as compared to $^{88}$Br [3], $\pi g_{9/2}$ particle contribution is seen in $^{90}$Rb. The same holds for the $6_1^-$ level. The increased $\pi g_{9/2}$ occupation may push the two levels up in energy.

### C. Shell-model calculations of yrast levels in $^{88}$Rb

To get further insight into the role of the $\nu d_{5/2}^3$ anomalous coupling at $N = 53$, we performed shell-model calculations for $^{88}$Rb, which has only one valence neutron, by using the same effective interaction as in $^{90}$Rb. Figure 11 compares calculated levels to experimental levels in $^{88}$Rb, as reported in Ref. [11].

The calculations reproduce well the overall scale of excitations in $^{88}$Rb as well as the individual excitations, except the $1^-$ level, calculated about 400 keV above the experiment. The most pronounced and important difference, relative to $^{90}$Rb, is observed for the $0^-$, $5^+$, and $6^+$ levels, which in $^{88}$Rb is calculated much higher in energy. Furthermore, in $^{88}$Rb the $5^+$ and $6^+$ levels do not have experimental counterparts. In this way the shell model supports the presence of the $d_{5/2}^3$ seniority-3 multiplet at $N = 53$, which, coupled to $p_{3/2}$ and $g_{9/2}$ protons, produces low-lying $0^-$, $5^+$, and $6^+$ levels in $^{90}$Rb.

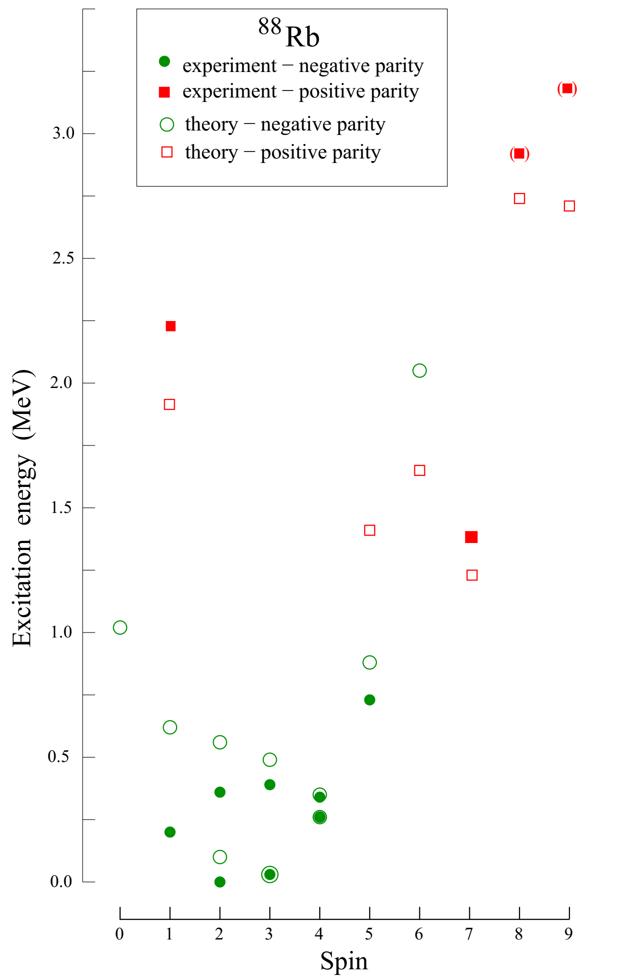


FIG. 11. Comparison of experimental excited levels in $^{88}$Rb [11] with the present shell-model calculations.

The $8_1^+$ level in $^{88}$Rb is reproduced well by the shell model. Its calculated energy is the same as in $^{90}$Rb, although the proposed experimental $8_1^+$ excitation energies differ by 0.5 MeV. This and the discrepancies between calculated and measured $1^-$ level in $^{88}$Rb $5^-$ level in $^{90}$Rb and the $8^+$ level in $^{86,88}$Br [3] suggest shell-evolution effects not yet included in our shell-model effective interaction. On the other hand, the energy split within the low-energy multiplets (spins $1^-$ to $4^-$), which are higher in $^{88}$Rb than in $^{90}$Rb, is reproduced well, indicating that our $\pi\nu$ interactions are rather correct.

### D. Shell-model calculations of low-spin levels in $^{90}$Rb

The $\nu d_{5/2}^3$, seniority-3 multiplet at $N = 53$, coupled to valence protons is expected to produce more low-spin levels in $^{90}$Rb than observed in $^{88}$Rb. The simple picture of $^{88}$Rb, which has only one $d_{5/2}$ neutron has been studied and explained in Refs. [11,44]. In the present work we have not observed nonyrast levels in $^{90}$Rb, but they are available in the literature [18]. In experiment, below 2.5 MeV of excitation energy there are indeed more low-spin levels in $^{90}$Rb than in $^{88}$Rb. It is, therefore, of interest to check, whether the shell model can reproduce this effect.

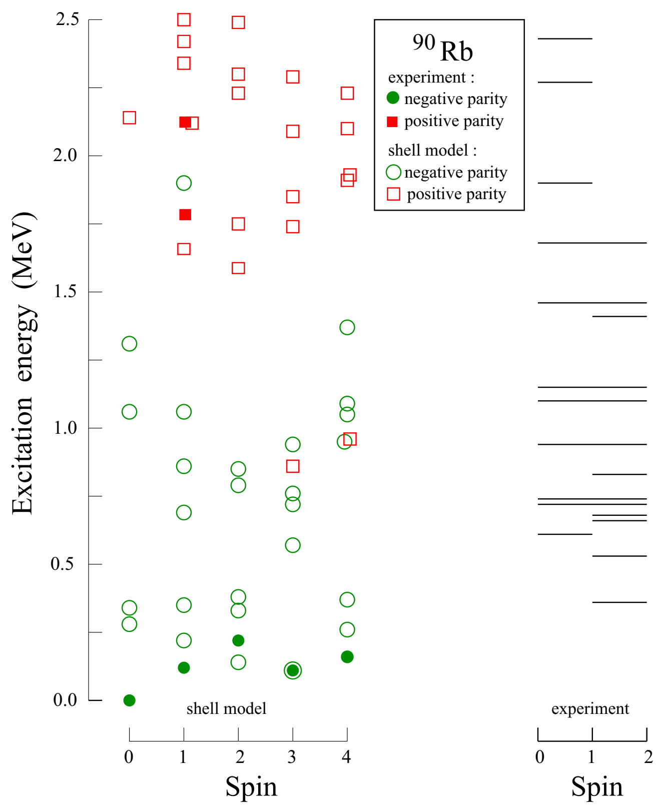


FIG. 12. Comparison of low-spin, excited levels in $^{90}$Rb [18] with the present shell-model calculations. See text for more explanations.

In Fig. 12 we show all low-spin levels up to 2.5 MeV of excitations calculated (open symbols) in this work for $^{90}$Rb using the shell model. Filled symbols and lines represent experimental levels taken from Ref. [18], except the $4^-$ level identified in this work. The line extending from spin 0 to spin 2 represents the experimental level, which has been tentatively assigned spin 0, 1, or 2 (analogously for the other lines). The experimental levels with known spin and parity are drawn in the left-hand part of the figure. The calculations are normalized to the experimental data at the $3_1^-$ level.

While the lack of unique spin and parity assignments to the majority of levels reported in Ref. [18] prevents any detailed comparison between experimental and calculated levels, one still can note some interesting gross features in the calculated scheme:

(i) Most of the levels calculated below 1.5 MeV of excitation have negative parity, while most of those calculated between 1.5 MeV and 2.5 MeV have positive parity. This is connected with the promotion of the odd proton to the $\pi g_{9/2}$ orbital.

(ii) Both groups contain significantly more levels than the number of levels corresponding to coupling of a single valence neutron to the available valence protons. This supports the active role of the $\nu d_{5/2}^3$ seniority-3 multiplet in forming the multitude of the negative- and positive-parity low-spin levels at $N = 53$.

(iii) The number of negative-parity, experimental levels below 1.5 MeV with spins 0, 1, and 2 proposed in

Ref. [18] is comparable to the number of $0^-$, $1^-$, and $2^-$ levels calculated in this energy range, again supporting the the presence of the $d^3_{5/2}$ seniority-3 multiplet.

We also note the $3^+$ and $4^+$ levels calculated at rather low energies, for which experimental counterparts are not known. This specific prediction calls for further experimental studies to look for such levels as well as to provide more information on spins and parities of levels reported in Ref. [18]. Such new data might also tell if there are any experimental counterparts for the numerous positive-parity, low-spin levels predicted in the 1.5–2.5 MeV excitation range.

## IV. SUMMARY

We observed for the first time medium-spin yrast excitations in the odd-odd, $^{90}$Rb nucleus. Low-energy levels are interpreted as members of the $(\pi p^{-1}_{3/2},\nu d^3_{5/2})_j$ and $(\pi f^{-1}_{5/2},\nu d^3_{5/2})_j$ multiplets. It is proposed that the $0^-$ ground state is due to seniority-3 $[\pi p_{3/2},(\nu d^3_{5/2})_{3/2}]_{0^-}$ coupling. At medium energy a similar anomalous coupling is proposed within the $(\pi g_{9/2},\nu d^3_{5/2})_j$ multiplet, explaining the $5^+$, $6^+$, and $7^+$ triplet of states. Our calculations confirm the absence in $^{88}$Rb of levels analogous to the seniority-3 coupling. The results obtained in this work for $^{90}$Rb and $^{88}$Rb are in full analogy to our recent study of their isotones $^{88}$Br and $^{86}$Br [3]. The structure of these four odd-odd nuclei provides arguments in favor of collectivity building up at $N = 53$.

Further studies are needed to explain some discrepancies between the experiment and the shell-model results. In particular, one should explain the role of the $g_{7/2}$ neutron orbital in the region, which is expected to form the $(\pi g_{9/2},\nu g_{7/2})_{8^+}$ configuration. More detailed studies of low-energy, low-spin excitations in the four mentioned odd-odd nuclei may also help improving the proton-neutron effective interactions used.

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