Three-quasiparticle excitations in ^{77}Br

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Excited states in ^{77}Br were investigated via the reactions ^{75}As$(\alpha,2n)^{77}$Br and ^{73,74}Ge(^{7}Li,xn)^{77}Br at beam energies of 27 and 35 MeV, respectively. On the basis of coincidence and angular distribution data of the γ rays the known level sequences of positive and negative parity were extended to tentative spins of $\frac{25}{2}\hbar$, and a new decay sequence beginning at spin and parity of $(\frac{17}{2}^-)$ was found. This new sequence is discussed in terms of the 3-quasiparticle configuration $(\pi g_{9/2}\otimes\nu g_{9/2}\otimes\nu(p_{1/2},p_{3/2},f_{5/2}))$. Moreover, the irregularity found in the moments of inertia at $\hbar\omega\approx 0.4$ MeV for the negative-parity band is attributed to a $g_{9/2}$ quasiproton alignment.

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Nuclei in the neutron deficient part of the $A = 80$ mass region exhibit a large variety of nuclear structure phenomena, such as shape coexistence of prolate, oblate and/or triaxial deformations, quasiparticle (qp) alignments, band crossing, core polarization, and shape driving effects by the unpaired particles occupying the unique-parity $g_{9/2}$ subshells. Some of these phenomena were inferred, e.g., from high-spin studies of the odd-neutron isotopes ^{75,77}Kr [1–5] and odd-proton isotopes ^{73,75}Br [6–8] following their production in nuclear reactions.

In the light odd-proton nucleus ^{75}Br the rotational bands of positive and negative parity were observed up to states of $(\frac{45}{2}^+)$ and $(\frac{49}{2}^-)$, respectively, and quasiparticle alignments of both $g_{9/2}$ protons [7] at $\hbar\omega = 0.38$ MeV and $g_{9/2}$ neutrons [8] at $\hbar\omega = 0.65$ MeV were identified in conjunction with near-prolate shapes with quadrupole deformations of $0.28 \leq \beta_2 \leq 0.35$ [7].

On the other hand, in the heavier odd-proton isotopes ^{79,81}Br [9,10] the bands are known to medium spins only. In particular, the higher-lying members of the rotational-like bands of negative parity are less strongly populated since a large fraction of the feeding intensity flows to 3-qp states found in both nuclei on top of $\frac{13}{2}^-$ states at about 2.4 MeV excitation energy. These 3-qp structures exhibit large $M1$ transition strengths of $B(M1)\approx 0.5$ W.u. Such states have, so far, not been identified in the nucleus ^{77}Br. Therefore, the main goals of this ^{77}Br in-beam study were the search for high-lying 3-qp states of weak collectivity and the investigation of qp alignment as found previously in the adjacent odd-mass Br isotopes.

The information so far available on excited states in ^{77}Br is summarized in a recent compilation [11], e.g., containing data derived from the β decay of ^{77}Kr [12], from the ^{75}As$(\alpha,2n)$ reaction at 28 MeV [13], from the ^{77}Se(p,n) reaction at 2.15–2.85 MeV [14], and from the ^{74}Ge(^{6}Li,3n) reaction at 19–30 MeV [15] where the results of the latter experiment have not yet been published. In addition, some picosecond lifetimes were measured via the ^{64}Ni(^{16}O,$p2n$) reaction at 60 MeV employing the recoil distance Doppler shift method [16]. The deduced $E2$ transition probabilities could be well interpreted using a particle-plus-rotor model with a deformation of 0.30.

In the present study the ^{75}As$(\alpha,2n)$ reaction at 27 MeV beam energy has mainly been employed to investigate high-spin states in ^{77}Br. The α particle beam was provided by the Rossendorf cyclotron. Preliminary results of the new 3-qp structure found have been published elsewhere [17] and our proposal for the configuration of these states has meanwhile been underlined in a theoretical deformed shell-model consideration [18]. Very recently, a new investigation [19] of ^{77}Br has been undertaken via the ^{65}Cu(^{18}O,$\alpha 2n$) reaction at the Florida State University, where the level scheme established in the present study has been confirmed and extended to higher spins.

Measurements of γ-γ coincidences and angular distributions of the γ rays have been performed via the $(\alpha,2n)$ reaction at 27 MeV using Ge(Li) detectors of up to 7% efficiency. In addition, singles γ-ray spectra have also been measured in conjunction with irradiations of ^{73,74}Ge isotopes with 35 MeV ^{7}Li ions where ^{77}Br is formed by the (^{7}Li,3n) and (^{7}Li,4n) reactions, respectively.

In the coincidence experiment a target was used consisting of a 20 mg cm^{-2} thick powder layer of ^{75}As (100% abundance) glued on a Mylar foil. The γ rays were recorded with two Ge(Li) detectors placed at 90° with respect to the beam axis. More than 3×10^8 prompt coincidence events were stored on magnetic tape and sorted off line in a total coincidence array of size 2048 × 2048 channels. The level scheme of ^{77}Br as shown in Fig. 1 was constructed on the basis of coincidence γ-ray spectra obtained by setting gates on the peaks of interest with appropriate background subtraction. In this way the yrast level sequences of positive and negative parity known from a former $(\alpha,2n)$ reaction study [13] up to

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$(\frac{21}{2}^+)$ and $(\frac{17}{2}^-)$, respectively, could be confirmed. In addition, some new level sequences and linking transitions were assigned to ^{77}Br, partly in agreement with the results of the in-beam study [15].

For many transitions angular distribution coefficients were determined from γ-ray spectra measured at angles of 30°, 40°, 90°, 105°, 120°, 130°, 140°, and 150° with respect to the beam axis. The target used was the same as in the coincidence measurement. The γ radiation was recorded with a Ge(Li) detector of about 7% efficiency and a resolution of full width at half maximum (FWHM) = 2.1 keV at 1332 keV. A portion of a spectrum measured at 90° is shown in Fig. 2. The normalization of this measurement was obtained by assuming stretched $E2$ multipolarities for the intense γ rays at 534.2 and 842.1 keV which is in agreement with the angular distribution data given in Ref. [13]. The energies and angular distribution coefficients for some selected transitions assigned to ^{77}Br, e.g., to the new 3-qp structure, are compiled in Table I.

The nuclear spin of the ^{77}Br ground state is known to be $\frac{3}{2}\hbar$ [11] and the measured magnetic moment [20] supports negative parity. A spin of $I = \frac{9}{2}\hbar$ was measured by on-line atomic-beam magnetic resonance techniques [21] for the 4.3 m isomer decaying via an 105.6 keV γ ray, confirming the spin assignment deduced from the β-decay data of ^{77}Kr [11,12]. Our spin and parity assignments are based on these previous data and the measured angular distribution coefficients.

As a striking feature, a new decay sequence of three transitions has been identified starting at a $(\frac{17}{2}^-)$ level at 2931.6 keV. All three γ rays have angular distribution coefficients compatible with a $\Delta I = 1$ multipolarity (see Table I). In our coincidence spectra there is no indication for the presence of $\Delta I = 2$ crossover transitions. A search for the $\frac{15}{2}^-$ and $\frac{13}{2}^-$ members of this sequence as seen in ^{79,81}Br has been made but no levels could be found. Instead, we found that already the $(\frac{17}{2}^-)$ and $(\frac{19}{2}^-)$ states decay to known [13] states of negative or positive parity. Moreover, the negative-parity sequences were extended by a few transitions. In most cases these transitions are in agreement with the data of the in-beam study [15], except for the 850.1 keV γ ray depopulating the $(\frac{23}{2}^-)$ state. Instead, we found this level at an energy of 3729 keV which decays via γ rays at 936 and 1179.5 keV. The 1179.5 keV transition links this level to the positive-parity yrast sequence.

For the known [11,14] level at 417.5 keV spin and parity of $\frac{7}{2}^+$ were assigned on the basis of our angular distribution data for the 311.9 keV γ ray (see Table I) and the feeding pattern of the state. This $\frac{7}{2}^+$ state and the levels at 947.4, 1746.6, and 2647.6 keV are suggested to be members of the unfavored yrast positive-parity sequence. However, there are additional states at 1826.6 and 2926.0 keV with spins of $(\frac{15}{2}^+)$ and $(\frac{19}{2}^+)$, respectively, which decay also to the yrast positive-parity band. They might also be considered as continuation of the unfavored sequence.

Furthermore, new spin assignments of $\frac{9}{2}^+$, $\frac{13}{2}^+$, and

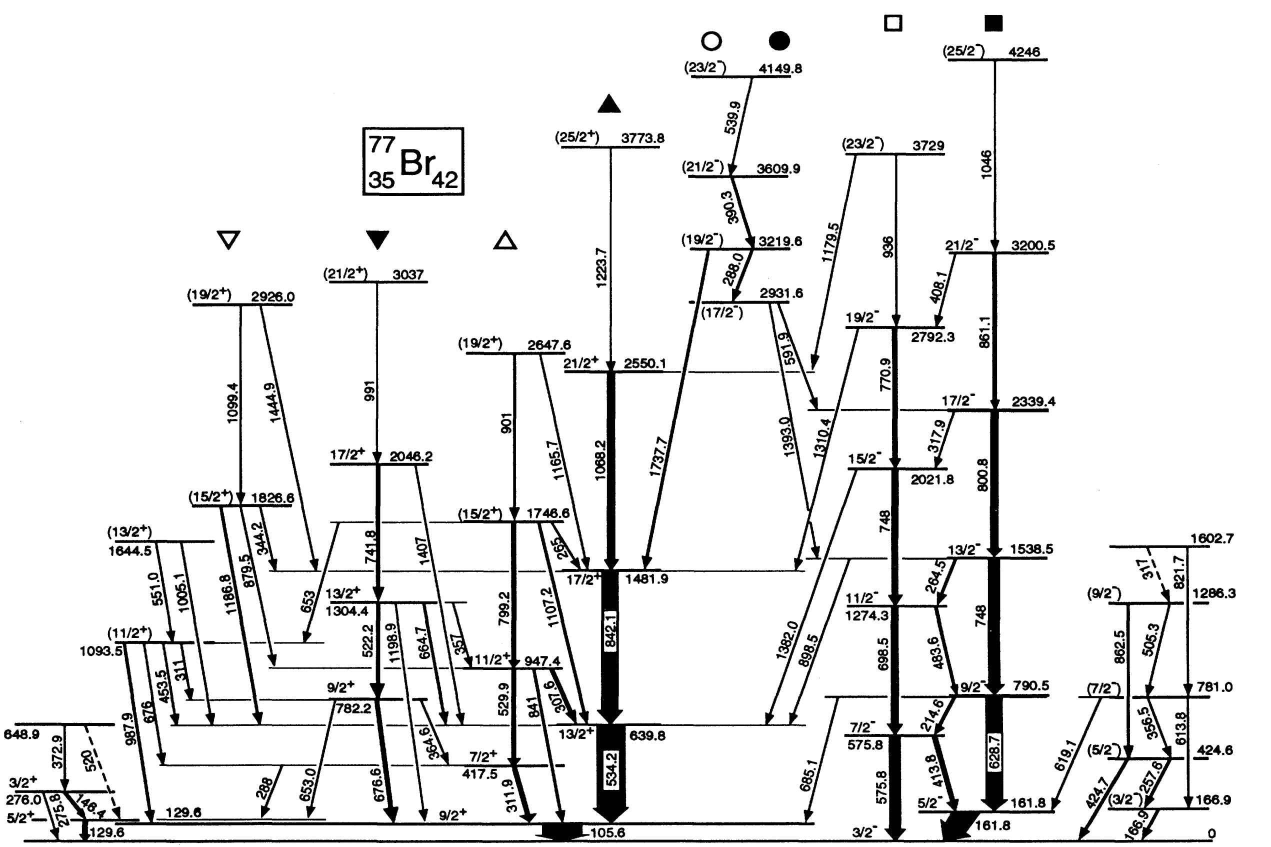

FIG. 1. Level scheme of ^{77}Br as found in the present ^{75}As$(\alpha, 2n)$ reaction study.

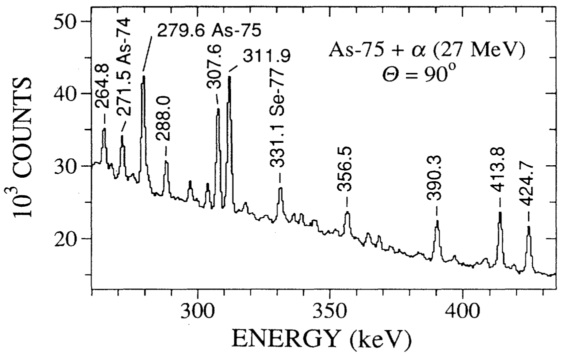

FIG. 2. Portion of a singles γ-ray spectrum measured at 90°. The lines marked with their energy in keV are assigned to ^{77}Br.

$\frac{17}{2}^{+}$ have been made for the known [13] levels at 782.2, 1304.4, and 2046.2 keV, respectively, based on the measured angular distributions of the deexciting γ rays (see Table I). These levels form a second positive-parity band with signature $\alpha = +\frac{1}{2}$ which has not been observed in neighboring odd-A Br nuclei.

Quasiparticle alignments and structural changes due to rotation can be examined by analyzing the experimental data according to the prescription of the cranked shell model [22]. The gain in angular momentum due to quasiparticle alignment can be inferred from the I_x plot given in Fig. 3. The negative-parity sequences show an upbend at $\hbar\omega \approx 0.4$ MeV and a gain in alignment of about $i \approx 3\hbar$–$4\hbar$. This value is comparable with the observed alignments in ^{75}Br [8] and ^{79}Br [9]. The positive-parity bands with $\alpha = +\frac{1}{2}$ show a smooth behavior, but for the unfavored sequence with $\alpha = -\frac{1}{2}$ a slight upbend is indicated.

The kinematic ($J^{(1)} = I_x/\omega$) and the dynamic ($J^{(2)} = dI_x/d\omega$) moments of inertia are shown as a function of rotational frequency in Figs. 4 and 5 for both signatures of the negative-parity band of ^{77}Br in comparison with known data of the corresponding sequences in ^{75}Br. These moments of inertia reveal a striking irregularity for ^{77}Br at $\hbar\omega \approx 0.4$ MeV, very close to the first irregularity found in the negative-parity bands of ^{75}Br but much more pronounced in ^{77}Br than in ^{75}Br. This behavior is being interpreted as caused by the crossing of a pair of aligned $g_{9/2}$ quasiprotons. The second irregularity [8] observed in ^{75}Br at $\hbar\omega = 0.65$ MeV (see Fig. 4) is thought to arise from a $g_{9/2}$ quasineutron crossing and has not been excited in our experiment.

The moments of inertia for the yrast positive-parity band (not shown) exhibit the onset of a band crossing at a rotational frequency of about 0.6 MeV which might be related to a $g_{9/2}$ quasineutron alignment, since the $g_{9/2}$ quasiproton alignment is blocked. But more experi-

TABLE I. Energies and angular distribution coefficients of selected γ rays assigned to ^{77}Br.

E_γ[a] (keV)	A_2[b]	A_4[b]	I^{π}[c]	E_x[d] (keV)
288.0(2)	−0.56(4)	0.01(6)	$(\frac{19}{2}^-)$	3219.6
311.9(2)	−0.25(3)	−0.06(4)	$\frac{7}{2}^+$	417.5
390.3(2)	−0.66(4)	0.01(6)	$(\frac{21}{2}^-)$	3609.9
522.2(3)	0.26(4)	−0.01(5)	$\frac{13}{2}^+$	1304.4
539.9(3)	−0.70(10)	0.19(17)	$(\frac{23}{2}^-)$	4149.8
591.9(3)	0.4(2)	e	$(\frac{17}{2}^-)$	2931.6
676.6(2)	0.15(3)	−0.04(5)	$\frac{9}{2}^+$	782.2
1393.0(3)	0.33(15)	e	$(\frac{17}{2}^-)$	2931.6
1737.7(4)	−0.46(11)	−0.03(18)	$(\frac{19}{2}^-)$	3219.6

[a] Errors in the last digit are shown in parentheses.
[b] Angular distribution coefficients deduced from the ^{75}As(α, $2n$) reaction at 27 MeV.
[c] Spin and parity of the initial state.
[d] Energy of the initial state.
[e] A_4 has not been fitted.

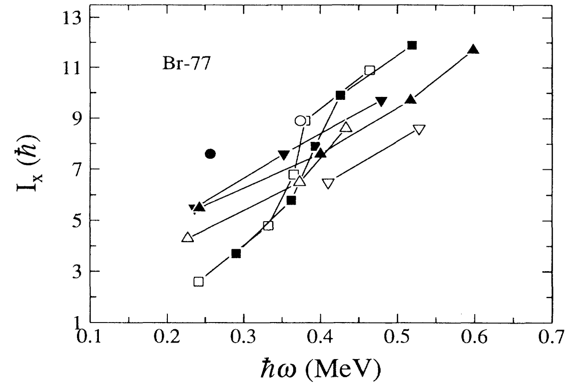

FIG. 3. Aligned angular momentum I_x as a function of rotational frequency. The symbols used for the different bands are defined in Fig. 1. The K values used in the analysis are $\frac{5}{2}$, $\frac{3}{2}$, and $\frac{13}{2}$ for the positive-parity, negative-parity, and 3-qp bands, respectively.

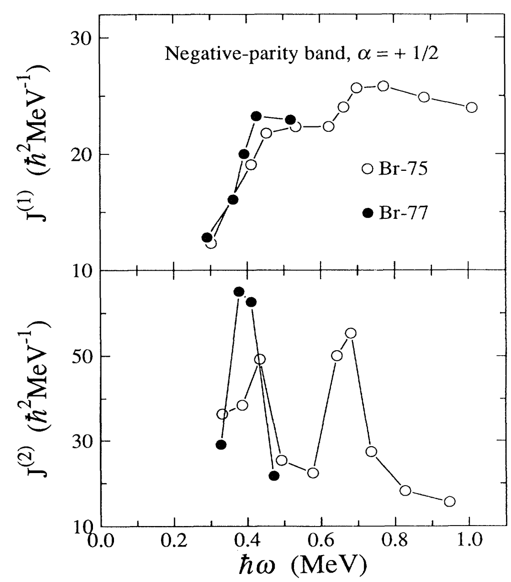

FIG. 4. Kinematic ($J^{(1)}$) and dynamic ($J^{(2)}$) moments of inertia for the negative-parity bands with signature $\alpha = +\frac{1}{2}$ in ^{75,77}Br as a function of rotational frequency. A value of $K = \frac{3}{2}$ has been used. The ^{75}Br data has been taken from Ref. [8].

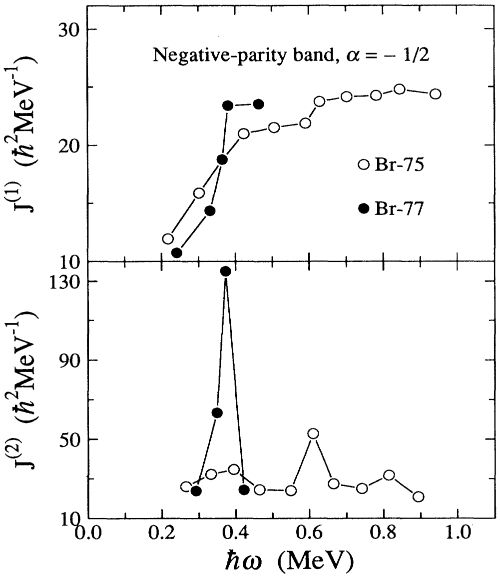

FIG. 5. Kinematic ($J^{(1)}$) and dynamic ($J^{(2)}$) moments of inertia for the negative-parity bands with signature $\alpha = -\frac{1}{2}$ in ^{75,77}Br as a function of rotational frequency. A value of $K = \frac{3}{2}$ has been used.

mental data is needed before any firm conclusions can be made.

For the high-lying structure beginning at spin and parity of $(\frac{17}{2}^-)$ an aligned angular momentum of about $i_{3-qp} \approx 4\hbar$ has been inferred from the two points given in Fig. 3. Thus, we propose the 3-qp configuration $[\pi g_{9/2} \otimes \nu g_{9/2} \otimes \nu(p_{1/2}, p_{3/2}, f_{5/2})]$. This 3-qp configuration has also been suggested from deformed shell-model calculations [18] where the intrinsic state of this configuration was identified lowest in energy for ^{77,79}Br compared to alternative configurations. It was found that the proposed 3-qp states do not mix much with the states of the low-lying negative-parity bands which might explain the observed decay to states of both positive and negative parity.

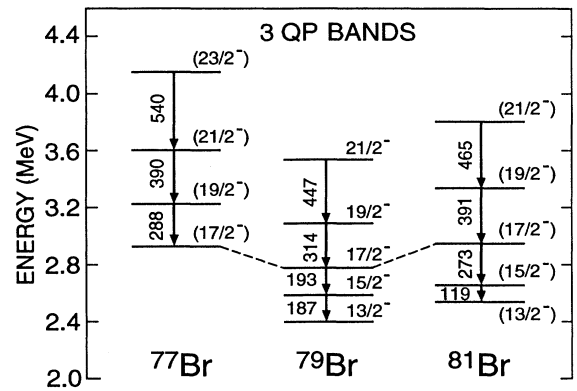

FIG. 6. Excitation energies of negative-parity levels interpreted as 3-qp states in ^{77,79,81}Br. The experimental data has been taken for ^{79}Br from Ref. [9] and for ^{81}Br from Ref. [10].

In summary, the results of a study of high-spin states of ^{77}Br with the ^{75}As(α,2n)^{77}Br and ^{73,74}Ge(^{7}Li,xn)^{77}Br reactions were presented. For the first time a cascade of $\Delta I = 1$ transitions was identified on top of the $(\frac{17}{2}^-)$ state at 2931.6 keV. This structure, which has counterparts in ^{79,81}Br as shown in Fig. 6, is interpreted as arising from a 3-qp configuration. Moreover, the moments of inertia found in the negative-parity sequences revealed alignment effects of high-j $g_{9/2}$ quasiprotons at a rotational frequency of about $\hbar\omega \approx 0.4$ MeV in accordance with similar phenomena observed in other odd-mass Br isotopes.

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