Chapter 6

High spin states in $^{178}$Os

6.1 Introduction

The Os nuclei lies in the beginning of the transitional region between the well-deformed rare earth and spherical lead isotopes. The nuclei in this region are believed to be soft to changes in deformation due to the softness of nuclear potential, and consequently may result in the shape coexistence. The neutron Fermi level in Os nuclei from $A=170$ to $A=186$ lie in the middle of the $i_{3/2}$ orbitals, so their shape tend to take an appreciable prolate deformation ($\beta_2 = 0.2-0.3$). Hence collective bands with well-defined moment of inertia and quadrupole moments occur and the effect of the different proton orbitals is observed as a modulation of the prolate structure.

6.1.1 Anomalies

The anomalies in the yrast sequence, an effect attributed to change in moment of inertia of the ground state rotational band and the band crossing phenomena are very important and vary strongly with the mass number in case of the Os nuclei. In $^{172}$Os two low frequency anomaly are observed, one at $\hbar \omega = 0.24$ MeV at spin $I = 8^+$ and another at $\hbar \omega =0.27$ MeV at spin $I = 16^+$. These are however not apparent in $^{170}$Os. In $^{174}$Os also, the anomaly is absent and its yrast curve is smooth up to a high frequency $\hbar \omega = 0.40$ MeV [1] in contrast to $^{170}$Os to $^{182}$Os isotopes in which anomalies are observed at frequency ranging from 0.31 MeV to 0.26 MeV. In this range i.e., from $^{182}$Os to $^{176}$Os the magnitude of anomaly decreases with decreasing neutron number. In case of $^{178}$Os, $^{178}$Os, the anomalies in the yrast band spacing are observed, as is evident from the plot of
6.1 Introduction

Figure 6.1: Plot of the aligned angular momentum $(I_x)$ against the rotational frequency $\hbar \omega$ deduced from the experimental level schemes. Both yrast and yrare states are included (from ref. [9]).

the aligned angular momentum $(I_x)$ against the rotational frequency $\hbar \omega$ shown in figure 6.1. From figure it is evident that the backbending anomaly changes smoothly from an S-shape curve in $^{182}$Os to a weak but well-defined upbending in $^{176}$Os. Further, since the yrast states above the backbending anomaly are at similar excitation energies, the ground state band moment of inertia varies rapidly in this region, the band crossing and hence the backbending anomaly occurs progressively at higher frequencies with decreasing neutron number. The magnitude of the anomaly depends in details on the difference between the S-band and the ground state band and the strength of the interaction between these bands. In this range of isotopes, the slopes of the curves differ substantially at low frequencies. This difference in behaviour which is equivalent to a more rapid increase in moment of inertia with spin for the lighter isotopes, can be attributed to Coriolis anti-pairing (CAP) or the others effects such as changes in deformation.

The rotational bands of the osmium isotopes display very interesting properties that vary with the neutron number [2-5]. These have approximately constant quadrupole deformation $\beta_2$, and varying hexadecapole deformation, $\beta_4$ [6]. The yrast bands of the nuclei
High spin states in $^{178}\text{Os}$

$^{182,184,186}\text{Os}$ also display a rather sudden and strong gain in aligned angular momentum at rotational frequencies of $\hbar \omega = 0.26$ to 0.30 MeV [2, 7]. Their interaction has been interpreted in terms of rotational alignment of $i_{13/2}$ quasi neutron pair with fairly weak interaction between the crossing bands [8]. The nuclei $^{176,178,180}\text{Os}$ on the contrary, experience crossings with strong interactions characterized by an irregular but gradual increase of alignment [3, 9]. Deformation susceptibility (softness) and triaxial shapes are also expected for the Os nuclei since they are located at the upper edge of the deformed region. In this region three high-j shells lie close to the Fermi surface viz. the $i_{13/2}$ neutron and the $h_{9/2}$ and $h_{11/2}$ proton shells. A search for band crossings due to rotation-alignment of quasiproton pairs requires an extension of rotational bands to large angular momenta.

The nucleus $^{178}\text{Os}$ has been studied earlier by Dracoulis et al. [10] using $^{162}\text{Er}(^{16}O, 4n)^{178}\text{Os}$ reaction, Kibedi et al. [11] using the $\beta$-decay of $^{178}\text{Ir}$ and Burde et al. [12] using $^{154}\text{Sm}(^{28}\text{Si}, 5n)^{178}\text{Os}$ reaction. They have however reported contradictory results. Dracoulis et al. have reported tentatively a $\beta$-band, with the band head at 1167 keV ($4^+$ state). They have also reported a few weak negative parity bands but no $\gamma$-band was reported by them. Kibedi et al. on the other hand have reported a strong $\gamma$-band with band head at 864.3 keV ($2^+$ state) and also a $\beta$-band with band head at 650.4 keV ($0^+$ state). They have however reported only one weak negative parity band with band head at 1302 keV ($3^-$ state). Burde et al. [12] on the other hand have reported an unusual most likely a superdeformed band at 6956 keV ($26^+$ state). It consist of seven regularly spaced transitions of 36 keV apart, which corresponds closely to that of the super-deformed band in $^{152}\text{Dy}$ after an $A^{5/2}$ normalization. The presence of anomalies in osmium isotopes, and observation of unusual rotational band in $^{178}\text{Os}$ motivated us to further investigate the nucleus at high spin. Another motivating factor is to look for the features associated with the collective rotation bands, e.g., shape transition, band crossing and proton alignment at higher excitation.
6.2 Experiment and Data Analysis

High spin states in the $^{178}$Os nucleus have been studied using the $^{165}$Ho($^{20}$Ne, p6n)$^{178}$Os fusion evaporation reaction at beam energy of 150 MeV. The $^{20}$Ne beam was delivered by the Variable Energy Cyclotron Centre (VECC), Calcutta. A self-supporting enriched $^{165}$Ho target of thickness $\approx 4 \text{mg/cm}^2$ was used in the experiment. The emitted $\gamma$-rays from the residual nuclei were detected using the Indian National Gamma Array (INGA), stationed at Variable Energy Cyclotron Centre, Calcutta. For this experiment, the INGA comprised of six Compton-suppressed Clover detectors, two each at angles 40°, 90° and 125°, with respect to the beam direction. In total about 300 million two- and higher fold $\gamma-\gamma$ coincidence events were collected in the experiment. Efficiency and energy calibration were performed with the standard $\gamma$-ray $^{152}$Eu and $^{133}$Ba radioactive sources. After gain-matching, the coincidence events were sorted off-line to obtain symmetric and asymmetric (angle dependent) matrices. The data were analyzed using both RADWARE [13] and IUCSORT [14] computer software package.

A method based on the observation of the direction correlation of $\gamma$-rays de-exciting oriented states (DCO ratios) [15,16] was adopted to determine the $\gamma$-ray multipolarities and spins of the nuclear levels. For this purpose, a $\gamma-\gamma$ asymmetric matrix was created where one axis corresponded to a $\gamma$-ray recorded by the detectors at 90° while the other axis corresponded to the $\gamma$-ray recorded by the detectors at 40°. A gate corresponding to a $\gamma$-ray of known multipolarity was taken on one axis (say, x-axis) and the coincident spectrum was projected on the other axis. Next the same gate was set on the y axis and the projection was made along the x axis. Using gates of known quadrupole transitions, we define $R_{DCO}$ as

$$R_{DCO} = \frac{I_{\gamma_1} \text{ at } 40^\circ, \text{ gated with } \gamma_2 \text{ at } 90^\circ}{I_{\gamma_1} \text{ at } 90^\circ, \text{ gated with } \gamma_2 \text{ at } 40^\circ}$$

(6.1)

Usually the gate is chosen to set on a stretched quadrupole (E2) transition, then theoretically $R_{DCO}=1.0$ is expected for stretched E2 transitions and $\approx 0.6$ for $\Delta = 1$ transitions. Assuming stretched transitions, the intensities of the transitions which had the same multipolarity as the gated $\gamma$-ray was approximately the same in both spectra. For $\gamma$-rays of different multipolarity, the intensities differed by a factor of almost 2. In the present ex-
periment, $R_{DCO}$ value is $\approx 0.5$ for the dipole transitions and $\approx 1.1$ for quadrupoles, using gate on quadrupole transitions. The multipolarity assignments were further supported by extracting the electromagnetic character of the gamma transitions by determining the asymmetry parameter $\Delta_{IPDCO}$. This method of evaluating the asymmetry is known as Integrated Polarization-Directional Correlation from Oriented nuclei (IPDCO). Details of this procedure has been discussed in chapter 2.

6.3 Results and Discussion

From the analysis of the $\gamma - \gamma$ matrix, intensities of transitions, DCO ratios and proper gating, we have established the level scheme of $^{178}$Os, as shown in figure 6.2. The bands are labelled 1-4 to facilitate the discussion. Spins of the levels have been determined from the $R_{DCO}$ ratios and the parity assignments are based on polarization measurements. In addition to the transitions reported by Dracoulis et al. [10], seventeen transitions viz. 144, 185, 271, 355, 398, 502, 532, 546, 562, 633, 750, 1200, 1513, 1563, 1576, 1589 and 1778 keV have been newly identified and one additional new side band (band 4) has been observed in the present work. These transitions are marked by asterisk in the level scheme. The representative spectra, gated on transitions 132 keV and 144 keV are shown in figures 6.3 and 6.4. The $\gamma$-rays identified with this nucleus are summarized in Table 6.1 according to their energies, relative intensities, spin and multipolarity assignments. The results of polarization measurements are shown in figure 6.5. The levels of the ground state band (band 1) up to $16^+$ state, band 1a up to $24^+$ and band 1b up to $22^+$ are confirmed as reported by Dracoulis et al. [10]. We did not see the transition of 834 keV ($26^+ \rightarrow 24^+$) of band 1a as reported by Dracoulis et al. earlier in coincidence with 643, 719 and 772 keV $\gamma$-lines. But in present data the transition of 834 keV ($24^+ \rightarrow 22^+$) has been seen in coincidence with the 722 keV doublet gamma transition of the yrare band (band 1b) in place of 743 keV transition tentatively placed earlier by Dracoulis et al. [10] in this band. The $\beta$-band placed tentatively earlier by Dracoulis et al., at 1167 keV, $4^+$ state has not been observed in this study. The unusual rotational band reported by Burde et al. and the linking transition of 803 keV from band 1a to this unusual rotational band
Figure 6.2: Level scheme for $^{178}$Os populated in $^{176}$Ho($^{20}$Ne, p$^6$n)$^{178}$Os reaction. Newly observed transitions are marked with an asterisk. The energies are marked within ±1 keV. The spin and parity assignments, given in parentheses, are tentative.
High spin states in $^{178}$Os

Figure 6.3: $\gamma - \gamma$ coincidence spectrum with gate on 132 keV transition.

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<th>$E_f$ (keV)</th>
<th>Counts</th>
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</tr>
<tr>
<td>150</td>
<td>732</td>
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<tr>
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<td>1050</td>
<td>1130</td>
</tr>
<tr>
<td>1150</td>
<td>1200</td>
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Gate 132 keV
6.3 Results and Discussion

Figure 6.4: \(\gamma - \gamma\) coincidence spectrum with gate on 144 keV transition.
Table 6.1: Excitation energies in keV, initial and final spins for the transitions, γ-ray energies in keV, relative intensities, DCO ratio and the multipolarity of the transitions belonging to $^{178}$Os nucleus

<table>
<thead>
<tr>
<th>$E_i$</th>
<th>$J_i^a \rightarrow J_f^a$</th>
<th>$E_\gamma$</th>
<th>$I_\gamma^a$</th>
<th>$R_{DCO}$</th>
<th>Mult.</th>
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<td>132</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>132</td>
<td>100</td>
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<td>2054</td>
<td>$5^+ \rightarrow 2^+$</td>
<td>144</td>
<td>7.0</td>
<td>1.2 (0.031)$^c$</td>
<td>E2</td>
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<tr>
<td>2239</td>
<td>$7^+ \rightarrow 5^+$</td>
<td>185</td>
<td>6.4</td>
<td>1.1 (0.038)$^c$</td>
<td>E2</td>
</tr>
<tr>
<td>1706</td>
<td>$6^- \rightarrow 4^-$</td>
<td>238</td>
<td></td>
<td></td>
<td>E2</td>
</tr>
<tr>
<td>1780</td>
<td>$7^- \rightarrow 5^-$</td>
<td>242</td>
<td>4.0</td>
<td></td>
<td>E2</td>
</tr>
<tr>
<td>1023</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>252</td>
<td>1.6</td>
<td>0.98 (0.022)$^c$</td>
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</tr>
<tr>
<td>398</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>266</td>
<td>&gt;140</td>
<td>1.1 (0.026)$^c$</td>
<td>E2</td>
</tr>
<tr>
<td>2510</td>
<td>$(8^+) \rightarrow (6^+)$</td>
<td>271</td>
<td>9.5</td>
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<td>2018</td>
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<tr>
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<td>317</td>
<td>5.3</td>
<td>1.32 (0.06)$^b$</td>
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<tr>
<td>1213</td>
<td>$(4^+) \rightarrow (2^+)$</td>
<td>349</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2865</td>
<td>$(11^+) \rightarrow (9^+)$</td>
<td>355</td>
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<tr>
<td>761</td>
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<td>1.1 (0.012)$^b$</td>
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<td>3.6</td>
<td>1.3 (0.080)$^b$</td>
<td>E2</td>
</tr>
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<td>432</td>
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<td>432</td>
<td></td>
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<td>E2</td>
</tr>
<tr>
<td>2817</td>
<td>$12^- \rightarrow 10^-$</td>
<td>433</td>
<td></td>
<td></td>
<td>E2</td>
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</table>

$^a$Errors on the relative intensities are estimated to be less than 5% of the quoted values for strong transitions ($I_\gamma > 10$) and less than 20% for the weaker transitions ($I_\gamma < 10$). The values are normalized to 100% for the 132 keV transition of the ground state band.

$^b$R$_{DCO}$ ratio from the gate on 266 keV quadrupole transition.

$^c$R$_{DCO}$ ratio from the gate on 132 keV quadrupole transition.
6.3 Results and Discussion

Table I continued

<table>
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<tr>
<th>$E_i$</th>
<th>$J^e_i \rightarrow J_f^e$</th>
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<th>$I_\gamma$</th>
<th>$R_{DCO}$</th>
<th>Mult.</th>
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<td>624</td>
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<td>$4^+ \rightarrow 4^+$</td>
<td>625</td>
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<td>(E2)</td>
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<td>633</td>
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<td>E2</td>
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<td>E2</td>
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<td>1.25 (0.05)$^b$</td>
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<td>5290</td>
<td>$21^- \rightarrow 19^-$</td>
<td>650</td>
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$^{d}R_{DCO}$ ratio from the gate on 363 keV quadrupole transition.
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<th>$I_\gamma$</th>
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<td>6418</td>
<td>$24^+ \rightarrow 22^+$</td>
<td>834</td>
<td>1.7</td>
<td></td>
<td>E2</td>
</tr>
<tr>
<td>1031</td>
<td>$3^+ \rightarrow 2^+$</td>
<td>899</td>
<td>12</td>
<td>0.64 (0.06)$^e$</td>
<td>M1/E2</td>
</tr>
<tr>
<td>2097</td>
<td>$9^- \rightarrow 8^+$</td>
<td>904</td>
<td>1.8</td>
<td>0.46 (0.029)$^d$</td>
<td>E1</td>
</tr>
<tr>
<td>1706</td>
<td>$6^- \rightarrow 6^+$</td>
<td>945</td>
<td>2.8</td>
<td>0.47 (0.026)$^b$</td>
<td>E1</td>
</tr>
<tr>
<td>1416</td>
<td>$(5^+) \rightarrow 4^+$</td>
<td>1018</td>
<td>7.0</td>
<td>0.59 (0.020)$^b$</td>
<td>M1/E2</td>
</tr>
<tr>
<td>1780</td>
<td>$7^- \rightarrow 6^+$</td>
<td>1019</td>
<td></td>
<td></td>
<td>E1</td>
</tr>
<tr>
<td>1468</td>
<td>$4^- \rightarrow 4^+$</td>
<td>1070</td>
<td>0.84</td>
<td>0.45 (0.032)$^b$</td>
<td>E1</td>
</tr>
<tr>
<td>1213</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>1080</td>
<td>3.2</td>
<td>1.1 (0.050)$^c$</td>
<td>E2</td>
</tr>
<tr>
<td>1961</td>
<td>$8^+ \rightarrow 6^+$</td>
<td>1200</td>
<td>10.2</td>
<td>1.13 (0.07)$^d$</td>
<td>E2</td>
</tr>
<tr>
<td>1911</td>
<td>$(5^+) \rightarrow 4^+$</td>
<td>1513</td>
<td>1.8</td>
<td>0.75 (0.047)$^b$</td>
<td>(M1/E2)</td>
</tr>
<tr>
<td>1961</td>
<td>$(5^+) \rightarrow 4^+$</td>
<td>1563</td>
<td>1.9</td>
<td>0.70 (0.039)$^b$</td>
<td>(M1/E2)</td>
</tr>
<tr>
<td>1974</td>
<td>$(5^+) \rightarrow 4^+$</td>
<td>1576</td>
<td>2.2</td>
<td>0.68 (0.043)$^b$</td>
<td>(M1/E2)</td>
</tr>
<tr>
<td>1987</td>
<td>$(5^+) \rightarrow 4^+$</td>
<td>1589</td>
<td>2.3</td>
<td>0.78 (0.045)$^b$</td>
<td>(M1/E2)</td>
</tr>
<tr>
<td>1910</td>
<td>$(3^+) \rightarrow 2^+$</td>
<td>1778</td>
<td>6.0</td>
<td>0.64 (0.047)$^c$</td>
<td>(M1/E2)</td>
</tr>
</tbody>
</table>
6.3 Results and Discussion

Figure 6.5: Experimental γ-ray asymmetry parameter $\Delta_{IPDCO}$, from polarization measurements plotted for γ-ray transitions of $^{178}\text{Os}$. A positive value corresponds to an electric transition and a negative value indicate the magnetic transition. The quoted errors are due to peak fitting and background subtraction.

reported by them is also not seen in the present work. The previously identified bands assigned as negative parity bands (band 2 and band 3) by Dracoulis et al. [10] have been observed in this work. The $\beta$ and $\gamma$-bands observed by Kibedi et al. [11] have also been confirmed with the addition of a few new transitions. On the basis of the DCO and linear polarization analysis, $E2$ character is assigned to the 732 keV ($2^+_2 \rightarrow 2^+_1$) interaband transition. The $\gamma$ transition 899 keV ($3^+ \rightarrow 2^+$) between gamma and ground state band is assigned $M1/E2$ nature from the present DCO and polarization measurements.

A new side band (band 4) in the level scheme based on the band head energy of 1910 keV has been identified for the first time, which feeds ground state band via a linking transitions of 1778 keV. On the basis of DCO value and polarization measurement, we adopted $M1/E2$ multipolarity for the 1778 keV transition, therefore band 4 is assigned
High spin states in $^{178}$Os

the positive parity. On the basis of DCO ratio, nature of the interband transitions in
the new band e.g. 144 keV ($5^+ \rightarrow 3^+$), 185 keV ($7^+ \rightarrow 5^+$) and 271 keV ($9^+ \rightarrow 7^+$)
are assigned as $E2$ transitions. In addition to this we have observed ten new transitions
viz. 398, 532, 546, 633, 750, 1200, 1513, 1563, 1576 and 1589 keV. On the basis of the
DCO measurements, the transitions 398, 532, 546, 1200 are assigned stretched electric
quadrupole ($E2$) while the transitions 1513, 1563, 1576 and 1589 keV are of magnetic
dipole nature ($M1$).

6.3.1 Hartree-Fock calculation with angular momentum projec­
tion

The experimental results have been studied with deformed Hartree-Fock (HF) and Angu­
lar momentum ($J$) projection [17, 18]. The prolate HF calculations for the valence nucleons
lying outside the $^{132}$Sn core were performed for the $^{178}$Os nucleus, using the surface-delta
residual interaction [19, 20] (with strength 0.3 MeV for pp, pn and nn interactions) within
a model space of one major shell each for protons and neutrons. We use spherical Nilsson
single-particle energies [21]. The $3s_{1/2}, 2d_{3/2}, 2d_{5/2}, 1f_{7/2}, 1h_{11/2}$ and $1h_{9/2}$ proton states
have energies 3.654, 3.288, 0.731, 0.0, 1.705 and 7.1 MeV, and the $3p_{1/2}, 3p_{3/2}, 2f_{5/2},$
$2f_{7/2}, 1h_{9/2}$ and $1i_{13/2}$ neutron states have energies 4.462, 2.974, 3.432, 0.0, 0.686 and
1.487 MeV, respectively. The prolate HF orbits for $^{178}$Os are shown in figure 6.6. The
HF orbits shown for are doubly degenerate and are labelled by the $m$ quantum number,
the sum total of which for the occupied orbits gives the $K$ value. The degeneracy (within
30 keV) of the $1/2^-$ and $7/2^-$ orbit near the Fermi level gives rise to few low-$K$ negative
and positive parity bands.

HF orbits provide a realistic deformed intrinsic structure for the study of the high
spin band structure. Angular momentum projection (PHF) from the HF configuration (in
figure 6.6) and excitation based on them reproduce the observed band structures (figure
6.7 for $^{178}$Os). The Fermi level is in between $7/2^-$ and $1/2^-$ orbits which are almost
degenerate (with $1/2^-$ level being 30 keV higher in energy). Since $1/2^-$ is prolate like and
$7/2^-$ is oblate like, the $K = 0^+$ with ($1/2^-$)$_{2n}$ forms the ground band in our calculation.
The $K = 0^+$ band formed (with last two neutrons in $m = 7/2^-$ orbit) lies higher (figure
6.3 Results and Discussion

Figure 6.6: The prolate HF orbits of $^{176}$Os are given with $m$ represented by the length of each line. The neutron Fermi level is between $1/2^-$ and $7/2^-$ and that of proton is in between $9/2^-$ and $7/2^+$. 

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Figure 6.6: The prolate HF orbits of $^{176}$Os are given with $m$ represented by the length of each line. The neutron Fermi level is between $1/2^-$ and $7/2^-$ and that of proton is in between $9/2^-$ and $7/2^+$. 

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157
Figure 6.7: The band crossing in the yrast spectra of $^{178}$Os are compared with experiment.

6.7) angular momentum projection (AMP) from the $K = 1^+ (5/2^+, 7/2^+) i_{13/2}$ neutron rotation aligned (RAL) configuration gives rise to the $s$-band which is shown in figure 6.7. The $s$-band crosses the $g$-band at $I = 10\hbar$. The second band crossing occurs around $I = 18\hbar$ due to alignment of $(i_{13/2})^4$ neutrons ($K = 2^+$ band in figure 6.7). As is evident from the figure 6.7 the proton aligned band occurs higher in energy. The experimental spectra compares well with theory. At $I = 16\hbar$ two side bands appear in the experimental spectra. Interestingly from among the three $16^+$ states observed the lowest two states are $20$ keV apart and the other at about $100$ keV from the yrast $16^+$ state. At the neutron Fermi level the degeneracy of the two negative parity orbits (the oblate driving $m = 7/2^-$ and prolate driving with $m = 1/2^-$) greatly influence the band structure. The theoretical results for the negative parity bands are compared with experiment in figure 6.8. Excitation of a neutron from $7/2^-$ to $7/2^+$ gives a $K = 7^-$ structure occurring at 0.8261 MeV. This structure is observed in other osmium isotopes also and have been suggested by Dracoulis et al. [10] in $^{178}$Os but at higher energy (2.096 MeV). Importantly the degeneracy (within $30$ keV) of the $1/2^-$ and the $7/2^-$ level at the Fermi level favours a $K = 4^-$ structure with
neutrons in $7/2^+$ to $m = 1/2^-$ at an excitation of 0.618 MeV. This structure is found to be lower in our calculation and is observed in $^{180}$Os. The energy of the $1/2^-$ orbit lie lower to $7/2^-$ by 250 keV). This lowering is due to increase in occupancy in the neutron $f_{7/2}$ shell and is a reflection of $T = 0$ pairing property of the HF calculation. Hence in $^{180}$Os the $K = 7^-$ structure appears lower. Interestingly a $K = 3^-$ band with neutron excited from $5/2^+$ to $1/2^-$ crosses the $K = 4^-$ band at $I = 15^-$ changing the intrinsic structure.

### 6.3.2 Alignment behaviour of bands in $^{178}$Os

Additional important properties of the bands can be obtained by examining the experimental Routhian and aligned angular momentum. The experimental Routhians and aligned angular momenta extracted for different bands are shown in figures 6.9 and 6.10, respectively, as a function of rotational frequency. They have been deduced from the excitation energies $E$ and the spins $I$ of the observed levels and are obtained by subtracting the energy and angular momentum of the collective rotation. The Harris parameters [22], used to extract the quasiparticle energy and the alignment are $J_0 = 25\hbar^2 MeV^{-1}$ and
High spin states in $^{178}$Os

$J_1 = 60h^4MeV^{-3}$. As shown in figure 6.10 the band 1a shows the first band crossing at a rotational frequency of $\hbar\omega = 0.29$ MeV which is somewhat higher than the predicted frequency by Bengtsson et al. [23] of 0.24 MeV. The theoretical proton and neutron Routhians have been plotted for the even-A ($^{178-180}$Os) isotopes [23]. It has initial align-

ment of 9.5h as shown in figure 6.10 and is caused due to the rotation alignment of an $i_{13/2}$ quasineutron pair. The similar trend has been observed by Lieder et al. [24] in $^{180}$Os. The band crossing is associated with a deformation change from $\beta_2 = 0.24$, $\beta_4 = 0.025$ and $\gamma = -1^\circ$ for the ground band to $\beta_2 = 0.21$, $\beta_4 = 0.045$ and $\gamma = -12^\circ$ for the crossing band of $(\nu_{13/2})^2$ configuration according to the calculations of Wyss et al. [25]. The similar trend has been predicted by our Total Routhian Surface (TRS) calculations, performed within Wood-Saxon cranking formalism [26,27]. For these calculations the average mean field is taken to be a rotating Wood-Saxon potential [28,29] with monopole type of pairing interaction. The TRS results are plotted in figure 6.11 for the frequencies $\hbar\omega = 0.0$ and $\hbar\omega = 0.22$ MeV respectively. We have seen that the TRS plot shows a minimum at $(\hbar\omega = 0.0)$ with $\gamma = 0^\circ$ (figure 6.11(a)) and this minima is shifted towards $\gamma = -15^\circ$ at

Figure 6.9: Experimental Routhians in MeV as a function of rotational frequency $\hbar\omega$ for the bands in $^{178}$Os using $J_0 = 25h^2MeV^{-1}$ and $J_1 = 60h^4MeV^{-3}$ as reference core parameters.
rotational frequency of $\hbar \omega = 0.22$ MeV as shown in figure 6.11(b). This indicates that the nucleus is prolate deformed in the ground state and has a tendency towards $\gamma$-softness at higher excitation which give rise to $\gamma$-band. The value of $\gamma$ calculated from the energies of $2^1_1$ & $2^1_2$ states using asymmetric rotor model [30] as given below

$$\frac{E_2(2)}{E_1(2)} = \frac{1 + \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}}{1 - \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}} = \frac{864}{132},$$

(6.2)

also predicts $\gamma = 15^\circ$ which is close to the value indicated by TRS calculation. The band 1b starts with an initial alignment of $\approx 6\hbar$ at $\hbar \omega = 0.36$ MeV and increases to a value of $\approx 10\hbar$ at rotational frequency of $\hbar \omega = 0.37$ MeV. The band 1b seems to be the continuation of the ground state band (band 1) which crosses with the band 1a at 0.37 MeV. From the experimental Routhian plots one can see that above the $\hbar \omega = 0.35$ MeV the band 1b is approximately parallel to band 1a as expected for the BC band from theoretical calculations [23]. The negative parity bands (band 2 and band 3) have relatively large aligned angular momentum and display a similar frequency dependence of the aligned angular momentum. Both the bands show a crossing in the frequency range

\[161\]
0.15 \leq \hbar \omega \leq 0.25 \text{ MeV} \text{ with an alignment gain of } \approx 3h \text{ corresponding to an alignment of an } i_{13/2} \text{ quasineutron pair. The new band 4 starts with an aligned angular momentum of } 1.8h \text{ and shows no crossing and goes up to the aligned angular momentum of } 7h \text{ at } \hbar \omega = 0.27 \text{ MeV. This band may have the configuration similar to the } (+, 1)_{7} \text{ band in } ^{180}\text{Os [24].}

Figure 6.11: Total Routhian surface plots in } \beta_{2} - \gamma \text{ plane for the positive parity band in } ^{178}\text{Os at the rotational frequencies } \hbar \omega = 0.0 \text{ MeV, and } \hbar \omega = 0.22 \text{ MeV are shown in (a) and (b) respectively.}
6.4 Conclusion

The level structure of even-even nucleus $^{178}$Os has been studied with the six Clover detectors array using heavy ion fusion evaporation reaction. Several new transitions belonging to this nucleus have been identified and one side band have been newly observed. The level scheme has been substantially enhanced and a number of ambiguities in level structure reported earlier have been resolved. The experimental results are compared with the projected angular momentum deformed Hartree-fock model calculations and cranked Woods-Saxon model calculations. This nucleus is found to be prolate deformed in the ground state but it has tendency towards $\gamma$-softness at higher excitation as revealed by the cranked Woods-Saxon model and geometrical asymmetric rotor model.
Bibliography


BIBLIOGRAPHY


