The inverted odd-even staggering of the differential radii of the Eu isotopes, the presence of close lying parity doublet bands, E1 enhanced transition probabilities between parity doublet bands and a very similar magnetic moment of the 3\(^{-}\) ground state with the magnetic moment of the 3\(^{-}\) ground state in the known octupole deformed nucleus \(^{154}\)Eu all suggest possible octupole deformation in \(^{152}\)Eu.

Just beyond \(^{132}\)Sn, both the sets of the \(d_{5/2}\) and \(h_{11/2}\) proton orbitals and also the \(f_{7/2}\) and \(i_{13/2}\) neutron orbitals lie close together and near the fermi surface. This should result in particle-hole states with \(J^z=3^-\), which can form the basis for octupole deformation in this region. However, the \(d_{5/2}\) and \(g_{7/2}\) proton orbitals are degenerate at \(A=135\).\(^{1}\) This could mean that octupole correlation effects would be seen over a considerable proton region of the nuclear periodic table and/or might result in a dilution of the octupole effect from the proton orbitals. Indeed, experimental evidence now exists\(^{2,\ldots,8}\) for octupole deformation from \(^{85}\)Cs to \(^{86}\)Eu and probably also for \(^{85}\)Tb.

In this paper, we investigate octupole deformation for the detailed spectroscopic properties of the odd-odd nucleus \(^{152}\)Eu. This is the only odd-odd nucleus other than the isotopic \(^{154}\)Eu in which octupole deformation has been suggested.\(^{8}\)

For most nuclei differential nuclear radii (differences between radii of nuclei and their isotopic neighbor with one less neutron--\(\delta(r^2)=r_{N,N-1}^2-r_{N}^2\)) are smaller for odd-A than for even-A nuclei. However, in the Rn,\(^{9}\) Fr\(^{10}\) and Ra\(^{11,12}\) nuclei with neutron number from 132 to 139 (except 134 for Fr), this odd-even effect is reversed and has been qualitatively related to octupole deformation.\(^{10-13}\)

Recently, a similar reversal of this odd-even effect has been observed in the Cs and Ba nuclei\(^{7}\) and in the Eu isotopes.\(^{8}\) The differential radii for the Eu isotopes are plotted in Fig. 1, using the data of Dörschel et al.,\(^{14}\) Ahmad et al.\(^{15}\) and Alkhazov et al.\(^{16}\) Normal odd-even staggering is observed for neutron number 78 through 88, except at the 82 neutron shell closure. However, from neutron number 88 through 93, including \(^{152}\)Eu, the odd-even staggering is reversed. The sudden onset of quadrupole deformation\(^{18}\) precisely at neutron number 89 in \(^{152}\)Eu makes it difficult to differentiate between the effects of quadrupole and octupole deformation of \(^{152}\)Eu. Nonetheless, the differential radii of Fig. 1 are a first step in suggesting evidence for octupole deformation. In the following we examine the more detailed spectroscopic evidence to determine whether or not \(^{152}\)Eu is in fact octupole deformed.

One of the important characteristics of octupole deformed nuclei is the presence of parity doublets (PDs) in the level structure. In the limit of stable octupole
deformation, these PDs (states of the same spin but opposite parity) would be degenerate. In the odd-A actinides, they are not degenerate, but the PD splittings vary from \(0.1\) to \(200\) keV.

A detailed level diagram of \(^{152}\)Eu up to 500 keV excitation energy, presenting only that part of the level structure\(^{18}\) of \(^{152}\)Eu, which can be interpreted in terms of PDs, is shown in Fig. 2. Shaded vertical columns show Gallagher-Moszkowski (GM) doublet bands with their major Nilsson two quasi-particle assignments below the bands. Band heads are shown bold. The E1 transitions with measured transition probabilities are shown with bold/solid/dashed diagonal lines for the bands involving PDs/mixed/non-PDs respectively. PD band heads are shown connected in Fig. 2 in unshaded boxes. It is quite remarkable that there are sixteen bands which involve eight sets of PDs. It should be noted that the \(K=1^+\) and \(4^+\) bands lying at 78.2 and 196.9 keV respectively are interpreted in Fig. 2 as a mixture of the \(p5/2;532^+ n3/2;532\) and \(p5/2;413^+ n3/2;651\) Nilsson configurations, in the usual asymptotic quantum numbers representation, \(\Omega;Nn\lambda\), as suggested in Ref. 18). On the basis of the expected band head energies and GM splittings of the available twoparticle Nilsson configurations in comparison with the excitation energies, spin-parities and decay patterns of the observed levels,\(^{18\text{--}24}\) we suggest\(^{25}\) the 158.1 keV \(1^+\) 1.8 ns isomeric state and the 227.7 keV \(4^+\) state (not shown in Fig. 2) as the GM doublet with the reversed Nilsson configurations \(p5/2;413^+ n3/2;651\) admixed with \(p5/2;532^+ n3/2;532\). The configuration assignment for the 180.6 keV \(5^-\) has been revised from that given in Ref. 18) to conform with the established\(^{21}\) \(p(h_{11/2})n(i_{13/2})\) character of the highly decoupled rotation aligned band based on this state. The 148.7 keV level is assigned\(^{21}\) \(J^\pi=6^+\) on the basis of a 62.8 keV, \(\Delta I=0\), E1 transition de-exciting the 211.6 keV \(6^-\) level of the \(h_{11/2} i_{13/2}\) band. The 160.9 keV level is assigned\(^{21}\) \(J^\pi=5^+\) on the basis of its feeding by 50.7 keV transition from the 211.6 keV \(6^-\) level. The observed E1 decay rates\(^{20}\) from the 180.6 keV \(2.1\) ns \(5^-\) isomer into the 148.7 keV \(6^+\), the 108.1 keV \(5^+\), and the 89.9 keV \(4^+\) levels suggest a significant \(i_{13/2}\) neutron component in these levels.
Fig. 2. Partial level scheme of $^{152}\text{Eu}$ below 500 keV. Shaded vertical boxes give Gallagher-Moszkowski doublet bands together with their major Nilsson two quasi-particle components. Unshaded joined boxes show parity doublets (PDs). Diagonal arrows show El transitions for which transition probabilities have been measured.

Occurrence Deformation in the Odd-Odd Nucleus $^{152}\text{Eu}$
This factor, taken together with the decays\textsuperscript{21) from the higher spin negative parity levels, suggests the 108.1 keV 5\(^+\) and the 160.9 keV 5\(^+\) to be highly admixed with the former having a higher \(i_{3/2}\) neutron component on the basis of the observed\textsuperscript{20) small hindrance factor for the E1 transition into it from the 180.6 keV 5\(^-\) isomer. These strong configuration admixtures in the various levels of the transitional nucleus \(^{152}\text{Eu}\) had been indicated in the earlier lifetime measurement studies,\textsuperscript{20) and, as discussed above, are borne out in the more recent high spin investigations.\textsuperscript{21)\n}

The eight sets of PD band heads and their energy differences are compiled in Table I. The average energy splitting for all eight PD band heads is 71.2 keV. This compares with a value\textsuperscript{8) of 84.5 keV in the case of the 15 PD band heads in \(^{154}\text{Eu}\). It is also clear that the energy splitting in the PD bands of \(^{152}\text{Eu}\) would be considerably less if the \(K=\pm 2\) splitting were excluded from the average. Also the GM pair comprising the 249.0 keV 2\(^+\) and the 483.3 keV 3\(^+\) levels shown in Fig. 2 is rather uncertain, firstly because of the speculative placement\textsuperscript{19) of a 2\(^+\) level at 249.0 keV and more so because of the very large GM splitting in comparison with the calculated (75 \pm 20) keV value. As seen in Table I, this pair also brings in rather large PD splitting. It does, however, seem to be a general feature of the odd-odd octupole deformed nuclei.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Table I. Parity doublets in the band heads of \(^{152}\text{Eu}.\)} & & & \\
\hline
\textbf{Energy} & \textbf{Major Nilsson} & \textbf{Energy} & \textbf{Major Nilsson} & \textbf{Energy} & \textbf{Energy} \\
\textbf{(keV)} & \textbf{Conf.} \(K^\pi\) & \textbf{Major Nilsson} & \textbf{Conf.} \(K^\pi\) & \textbf{Splittings in} & \textbf{Parity Doublet} \\
\textbf{\(p \pm n\)} & \textbf{\(p \pm n\)} & \textbf{\(p \pm n\)} & \textbf{\(p \pm n\)} & \textbf{(keV)} & \\
\hline
0 & 3\(^-\) & 221.2 & 3\(^+\) & 221.2 & \\
\(p5/2;413\) & \(n11/2;505\) & & & & \\
& & & & & \\
65.3 & 1\(^-\) & 78.2 & 1\(^+\) & 12.9 & \\
\(p5/2;413\) & \(n3/2;521\) & & & & \\
& & & & & \\
203.2 & 4\(^-\) & 196.9 & 4\(^+\) & 6.3 & \\
\(p5/2;413\) & \(n3/2;521\) & & & & \\
& & & & & \\
141.8 & 4\(^-\) & 89.9 & 4\(^+\) & 51.9 & \\
\(p5/2;413\) & \(n3/2;532\) & & & & \\
& & & & & \\
203.1 & 1\(^-\) & 249.3 & 1\(^+\) & 46.2 & \\
\(p5/2;413\) & \(n3/2;532\) & & & & \\
& & & & & \\
180.6 & 5\(^-\) & 108.1 & 5\(^+\) & 72.5 & \\
\(p5/2;532\) & \(n5/2;642\) & & & & \\
& & & & & \\
283.7 & 2\(^-\) & 249.0 & 2\(^+\) & 34.7 & \\
\(p5/2;413\) & \(n1/2;530\) & & & & \\
& & & & & \\
359.3 & 3\(^-\) & 483.3 & 3\(^+\) & 124.0 & \\
\(p5/2;413\) & \(n1/2;530\) & & & & \\
& & & & & \\
\hline
\textbf{Average Parity Doublet Splitting} & & & 71.2 & & \\
\hline
\end{tabular}
\end{table}
that a much larger number of PDs is observed than in the odd-A nuclei. This may be simply the result of greater complexity in the low energy spectroscopy, and/or it may be connected with the fact that larger octupole deformations are expected for odd-odd nuclei than for odd-A nuclei.

One of the more interesting facets of this research involves the $0^-$ 9.3 $h$ isomer observed at 45.599 keV. This state is less deformed$^{3,16}$ ($\beta \leq 0.2$) than the ground state and other states with $\beta \sim 0.3$. An additional anomaly involving this $0^-$ state is connected with the very different hindrance factors of a transition populating the state and a transition depopulating it. A 32.634 keV E1 transition with a hindrance factor of $8.8 \times 10^4$ relative to the Weisskopf limit populates this state from the 78.2 keV $1^+$ state. This is a surprisingly low hindrance factor for an E1 transition. On the other hand, no 45.599 keV transition is observed depopulating the $0^-$ state to the $3^-$ ground state. The limit on the hindrance factor is $>2.0 \times 10^7$ relative to the Weisskopf limit for this M3 transition. Since both the $1^+$ state at 78.2 keV and the $3^-$ ground state are deformed, it is difficult to understand this discrepancy in the transition probabilities.

An additional feature which strongly suggests octupole deformation in $^{152}$Eu is its magnetic moment. It has been measured$^{14-17}$ to be $-1.94$ nm which is remarkably close to the figure $-2.02$ nm in $^{154}$Eu. This implies that the configurations, including the octupole deformation which has been established in $^{154}$Eu, are very similar in $^{152}$Eu.

An additional method to look for octupole deformation is to compare E1 transition probabilities for transitions between PDs and transitions not involving PDs. E1 transition probabilities between PDs are often enhanced by a factor of $\sim 10^2$ in the odd-A actinides when compared with those not involving PDs. Although this en-

<table>
<thead>
<tr>
<th>Initial State</th>
<th>Final State</th>
<th>$E_r$ (keV)</th>
<th>$F_w^{a)}$</th>
<th>PD Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.23 keV $1^+$</td>
<td>65.30 keV $1^-$</td>
<td>12.97</td>
<td>$5.3 \times 10^4$</td>
<td>MIXED</td>
</tr>
<tr>
<td>$p5/2;532$ $n3/2;532$</td>
<td>$p5/2;413$ $n3/2;521$</td>
<td>89.85 keV $4^-$</td>
<td>$2.9 \times 10^5$</td>
<td>NO</td>
</tr>
<tr>
<td>$p5/2;413$ $n3/2;651$</td>
<td>0.0 keV $3^-$</td>
<td>$89.85$</td>
<td>$2.9 \times 10^5$</td>
<td>NO</td>
</tr>
<tr>
<td>$p5/2;413$ $n3/2;402$</td>
<td>$p5/2;413$ $n11/2;505$</td>
<td>$160.88$ keV $5^+4$</td>
<td>$3.5 \times 10^4$</td>
<td>NO</td>
</tr>
<tr>
<td>+$p3/2;411$ $n5/2;642$</td>
<td>$89.85$ keV $4^-$</td>
<td>71.27</td>
<td>$1.4 \times 10^4$</td>
<td>MIXED</td>
</tr>
<tr>
<td>$p5/2;413$ $n3/2;532$</td>
<td>$141.83$ keV $4^-$</td>
<td>89.85 keV $4^-$</td>
<td>51.98</td>
<td>YES</td>
</tr>
<tr>
<td>$p5/2;413$ $n5/2;642$</td>
<td>108.11 keV $5^+4$</td>
<td>33.71</td>
<td>$1.4 \times 10^4$</td>
<td>MIXED</td>
</tr>
<tr>
<td>+$p3/2;411$ $n5/2;642$</td>
<td>180.63 keV $5^-$</td>
<td>$89.85$ keV $4^-$</td>
<td>90.78</td>
<td>NO</td>
</tr>
<tr>
<td>180.63 keV $5^-$</td>
<td>$90.78$</td>
<td>$1.8 \times 10^4$</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>$p5/2;532$ $n5/2;642$</td>
<td>180.63 keV $5^-$</td>
<td>108.11 keV $5^-$</td>
<td>72.52</td>
<td>YES</td>
</tr>
<tr>
<td>$p5/2;532$ $n5/2;642$</td>
<td>$p5/2;413$ $n5/2;642$</td>
<td>180.63 keV $5^-$</td>
<td>148.74 keV $6^+5$</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table II. E1 transitions in $^{152}$Eu and their hindrance factors$^{20}$ for transitions from Fig. 1. In column 2, we use the notation $I^K$ for labelling the states for which $I \neq K$.

a) The hindrance factor $F_w$. 

Downloaded from https://academic.oup.com/ptp/article-abstract/81/5/1057/1854125 by guest on 02 March 2019
hancement is somewhat less in the two known odd-A rare earth octupole deformed nuclei, the factor is again $\sim 10^2$ in the only odd-odd case, $^{154}$Eu. Fortunately the E1 transition probabilities have been determined\(^1\) for a number of transitions in $^{152}$Eu; the relevant data are listed in Table II and shown in Fig. 2. It is well documented that the states in the transitional nucleus $^{152}$Eu are strongly mixed. This is reflected in the orbital assignments in Table II and makes it difficult to make clear cut distinctions between transitions involving PDs and those not involving PDs. Just as in the case of $^{154}$ Eu we find it necessary to consider, in addition, transitions between states only part of which involve PDs. We have designated the PD character of these states “mixed”. Using there three designations, we find that the relative values for the hindrance factors (Fws) fit reasonably well. Thus generally the lowest hindrance factors involve transitions between PDs, intermediate hindrance factors between mixed states, and highest hindrance factors between states not involving PDs. There is however an exception—the 90.78 keV transition between the 180.63 keV and 89.85 keV states, which are not PDs, has a hindrance factor $1.8 \times 10^4$ similar to the 32.63 keV transitions between the 78.23 keV $1^+$ and the 45.60 keV $0^-$ states mentioned above. Yet there is no mechanism for mixing to produce PDs in these $\Delta K=1$ transitions. We have no explanation for these exceptions.

It is also interesting that, as in the case of $^{154}$Eu, each of the eight sets of PD bands involve major Nilsson two quasi-particle configurations in which either the proton or the neutron orbital is identical while the other orbital has $\Delta N=\pm1$ and opposite parity.

In summary, eight PDs have been observed below 500 keV, encompassing a considerable fraction of the known spectroscopy of $^{153}$Eu. The greatest hindrance to observing additional PDs is the identification/assignment of additional positive parity states in the low energy spectrum particularly involving the $i_{13/2}$ neutron states to go with the already observed negative parity bands. No positive parity states are presently identified involving the $p3/2$ or $411$ orbital. Thus one of the challenges for experimentalists is to look for these additional positive parity bands. In addition, the evidence for octupole deformation in $^{152}$Eu is enhanced by the very similar magnetic moments in the ground states of $^{152}$Eu and $^{154}$ Eu and by the observed reversal of the odd-even staggering of the nuclear radii in the region covering these nuclei. Finally, there is enhancement in the E1 transitions between PD bands when compared to E1 transitions not between PD bands.

**Acknowledgements**

Support of the National Science Foundation under contract number PHY86-05032 with Florida State University is gratefully acknowledged.

**References**

Octupole Deformation in the Odd-odd Nucleus $^{152}$Eu