Electromagnetic transition strengths in $^{155}$Dy

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Abstract.

Lifetimes of excited states in $^{155}$Dy were measured by means of the Recoil Distance Doppler-shift technique in the coincidence mode. The experiment was performed at the Laboratori Nazionali di Legnaro with the GASP array and the Cologne plunger using the reaction $^{124}$Sn($^{36}$S,5n)$^{155}$Dy at a beam energy of 155 MeV. The Differential decay-curve method was applied for the lifetime determination. The measured transition probabilities in $^{155}$Dy and the energy spectrum are compared to the predictions of the Particle plus rotor model. The comparison indicates slightly different quadrupole deformations characterizing the low-lying one-quasineutron bands which may point to a shape coexistence.

1. Introduction

Critical point symmetries are a fundamental problem in the study of nuclear structure. The X(5) symmetry$^1$ characterizes the critical point of the phase transition between spherical and axially deformed shape in atomic nuclei. The first example of this symmetry has been found in $^{152}$Sm by Casten and Zamfir$^2$. Later, other examples of X(5) nuclei have been found at N=90. The effect of the shape transition on the single particle degrees of freedom is best studied in odd-A nuclei. The mass region A$\sim$150 is characterized by a rapid shape transition. The nucleus $^{155}$Dy lies in this region. The level-scheme of $^{155}$Dy is well known$^3$, $^4$ but information on the collectivity was known only at high spins$^5$. The first aim of the present work was to measure electromagnetic transition strengths at low and intermediate spins in the one-quasineutron bands. The second aim was to perform particle plus triaxial rotor model (PTRM) calculations for comparison with the data in order to get information on the quadrupole deformation ($\epsilon$, $\gamma$) of the bands studied. To determine lifetimes in these bands we performed Recoil Distance Doppler-shift (RDDS)(cf. e.g. Ref$^6$ and references therein) measurements.

2. Experiment

To populate excited states in $^{155}$Dy we used the reaction $^{124}$Sn($^{36}$S,5n)$^{155}$Dy at a beam energy of 155 MeV. The beam was supplied by the XTU tandem of the Laboratori Nazionali di Legnaro,
Italy. The target and stopper foils were mounted in the Cologne coincidence plunger[7]. The target-to-stopper distance was changed by moving the target holder. The target consisted of 0.9 mg/cm$^2$ tin, enriched to 97.7% in $^{124}$Sn, which was evaporated onto a 1.8 mg/cm$^2$ $^{181}$Ta foil serving as a backing and facing the beam. A 12.0 mg/cm$^2$ Au foil was used to stop the recoils leaving the target with a mean velocity $v$ of 1.83(2)% of the velocity of light $c$. The deexciting $\gamma$-rays were registered with the GASP array[8]. This array consists of 40 germanium detectors, grouped into seven rings. The rings of interest for our RDDS experiment are those where significant Doppler shifts are observed. Namely, these are ring 0 (mean angle with respect to the beam axis of 34.6$^\circ$), ring 1 (59.4$^\circ$), ring 5 (120.6$^\circ$) and ring 6 (145.4$^\circ$). They consist of six detectors each. Spectra for the analysis of the RDDS data were obtained by setting a gate from above on the shifted component of a transition feeding directly the level of interest. In Fig.1, an example of spectra at different distances is shown to illustrate the quality of the data.

![Spectra example](image)

**Figure 1.** Gated $\gamma$-ray spectra of $^{155}$Dy taken at four different distances. The spectra are measured at the indicated distances with the detectors positioned at 34.6$^\circ$ (ring 0) and 145.4$^\circ$ (ring 6) with respect to the beam axis.

3. Data analysis and results
For the data analysis the Differential decay curve method (DDCM)[9, 10] was employed. According to this method, at each target-to-stopper distance $x$, the lifetime $\tau(x)$ of the level of interest is calculated as

$$\tau(x) = \frac{\{B_s, A_s\}}{\frac{d}{dx}\{B_s, A_s\} v}$$ (1)
Here \( v \) is the mean velocity of the recoiling nuclei. The quantities in braces are the number of coincident events corresponding to detection of the Doppler-shifted (s) or the unshifted (u) components of the \( \gamma \) -ray transitions. \( \{B_s, A_u\} \) is the area of the unshifted peak of the transition A while the derivative \( \frac{d}{dx}\{B_s, A_u\} \) is the derivative of the area of the shifted component. The gate is set on the shifted component of a directly feeding transition B. Using Eq.1, a set of lifetime values (the \( \tau \)-curve) is obtained which should naturally lie on a straight line when plotted versus the distance \( x \). Deviations from such behavior point to the presence of systematics errors in the analysis. Gating from above eliminates the unobserved feeders and gating only on the shifted component cancels out completely the effect of nuclear deorientation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.pdf}
\caption{Example of a lifetime determination for the 25/2\(^+\) level using gated spectra measured with the detectors positioned at 145.4\(^\circ\). The left part of the figure presents fits[11] of the line-shape of the 425 keV \( \gamma \) -ray transition measured at different distances with the detectors of ring 6. The gate is set on the top of the shifted component of the 520 keV transition, which feeds directly the level of interest. The right part illustrates the lifetime determination according to Eq.(1). The \( \tau \)-curve derived for the \( I^z=25/2^+ \) level in \(^{155}\)Dy is displayed on top of the figure. The mean value \( \tau=4.35\ (26)\ \text{ps} \) is obtained as an average of the data points shown.}
\end{figure}

For the investigation of a given level we have set gates on the shifted component of a directly feeding transition in the \( \gamma-\gamma \) matrices corresponding to all rings where appreciable Doppler-shifts are observed. The spectra for every gated ring were summed up to increase the statistics. The resulting spectrum was analyzed. There are two forward and two backward rings, which means that four values for the lifetime have been determined independently.

As a result from our analysis 16 lifetimes of exited states in \(^{155}\)Dy were determined for the first
time. The relative uncertainties of the lifetimes are of the order of maximum 10%. By gating from above the problem of the unknown feeding is eliminated which ensures a high degree of reliability for the results. More details on the lifetime analysis and the results will be given in a forthcoming paper [12]. The reduced transition probabilities $B(\sigma \lambda)$ deduced from the lifetime data are presented in Fig.3 in units of $e^2 b^\lambda$ for electric transitions and $\mu_N b^{\lambda-1}$ for magnetic ones.

Figure 3. Experimental level scheme of $^{155}$Dy from Refs.[3, 4] compared to PTRM calculations. The Nilsson configurations of the theoretical bands are indicated. See also text.

4. Discussion
To describe the reduced transition probabilities $B(\sigma \lambda)$ and the level scheme in $^{155}$Dy we performed particle plus triaxial rotor model (PTRM) calculations within the approach of Ref.[13]. For this purpose, we used the codes GAMPN, ASYRMO PROBAMO and E1PROBAM[14] supplied by the authors of the model. First, the single particle orbitals for a fixed quadrupole deformation ($\epsilon, \gamma$) are found as a solution of the Hamiltonian problem with the Modified Harmonic Oscillator potential. Then, a standard BCS calculation is performed to take into account pairing and a set of orbitals close to the Fermi surface (in our case 15) is chosen which participate in the diagonalization of the Particle-Rotor Hamiltonian in the strongly coupled basis. At the last stage, reduced transition probabilities are calculated with the resulting wave functions. Different values of the deformation parameters $\epsilon$ and $\gamma$ were used to provide best PTRM fit of the level energies and the transition strengths. A value of the quadrupole deformation parameter $\epsilon=0.24$ and a value of the asymmetry shape parameter $\gamma=0^\circ$ were found.
to be optimal. The results of the calculations for the $B(E2)$ transition strengths show a very good agreement with the experimental ones. There are some differences between the theoretically determined values in the bands and the experimental data. Some of the transition probabilities are bigger and other are smaller. This suggests that the different bands are characterized by a different quadrupole deformation in shape-transitional $^{155}$Dy.

5. Summary and conclusions
Using the Recoil Distance Doppler-shift method we have determined 16 lifetimes in $^{155}$Dy. For the data analysis the Differential decay-curve method was used. The experimentally determined excitation energies are in a good agreement with the particle plus rotor model. There is a good agreement also between the experimentally determined and theoretically calculated within the particle plus rotor model electromagnetic transition strengths $B(E2)$. The differences between the theoretically determined values in the bands and the experimental data suggest that the different bands are characterized by a different quadrupole deformation in $^{155}$Dy.

References
[1] Iachello F 2001 Phys. Rev. Lett. 87 052502
[2] Casten R F and Zamfir N V 2001 Phys. Rev. Lett. 87 052503
[3] Reich C W 2005 Nuclear Data Sheets 104 1
[4] Vlastou R et al. 1994 Nucl. Phys. A 580 133
[5] Emling H et al. 1989 Phys. Lett. B 217 33
[6] Alexander T K and Forster J S 1978 Adv. Nucl. Phys. 10 197
[7] Dewald A et al. 1992 Nucl. Phys. A 545 822
[8] Bazzacco D 1992 in Proceeding of the International Conference on Nuclear Structure at High Angular Momentum, Ottawa, Chalk River Report, AECL 10613 p.386
[9] Dewald A, Harissopoulos S and von Brentano P 1989 Z. Phys. A 334 163
[10] Böhm G et al. Nucl. Instr. Meth. Phys. Res. A 329 248
[11] Petkov P et al. Nucl. Instr. Meth. Phys. Res. A 431 208
[12] Petkov P et al. to be published
[13] Larsson S E, Leander G and Ragnarsson I 1978 Nucl. Phys. A 307 189
[14] Semmes P B 1991 Computer manual, presented at Nuclear structure theory workshop, Oak Ridge, TN (August 5-16, 1991)