A HIGH-SPIN ISOMER AT HIGH EXCITATION ENERGY IN THE NEUTRON DEFICIENT NUCLEUS $^{152}$Dy

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Abstract: A $^{152}$Dy isomer at $E_x = 5$ MeV is found in the $^{150}$Gd(a,6n)$^{152}$Dy reaction. The possible spin values are $15 < J < 18$. Cascades of relatively strong transitions populating the isomer are observed. The isomer may be interpreted as a four-quasi-particle state situated on the yrast line. The regular level sequence above the isomer may then be an evidence for a decoupled rotational band built on top of this state.

1. Introduction

The excitation and decay of high-spin states with $(a,xyn)$ or $(b,xiny)$ reactions has been a subject of intensive study for several years. In many nuclei, especially in the deformed mass region, the ground state (rotational) band is preferentially excited and other bands show up only weakly. However, in other even-even nuclei, e.g. in the regions of so-called "transitional" nuclei, the yrast line is often not or only partially identical with the ground state band. As a result, bands of other nature and sometimes isolated long-lived (isomeric) states with high spin are observed. Interpretation of the observed high-spin states in the transitional nucleus is often difficult since such states may either have a collective or a (quasi-)particle character. Strong admixtures are possible and may prevent a clear understanding of the actual situation. Interest for nuclei in this region has increased during the past few years as a result of the development of the Interacting Boson Approximation Model of Iachello and Arima and the model for decoupled bands in odd-mass nuclei by Stephens et al.

The investigations of $^{152}$Dy, presented here, is part of a study of high spin states in the neutron deficient Dysprosium isotopes with A=154 with the intention (i) to test the validity of the I.B.A. model for these nuclei, (ii) to investigate the relation between even and adjacent odd-A nuclei in terms of decoupled bands, and (iii) to follow the transition in the structure of the even-even nuclei from the closed shell $^{152}$Dy nucleus to the rotational type $^{150}$Gd$^{+}$.

2. Experimental technique

Alpha beams at six energies between $E_\alpha = 67$ and 100 MeV and beam currents in the order of a few nA from the K.V.I. cyclotron were used in the present in-beam experiment. The targets consisted of $^{154,155,156}$GdO$_2$ with thicknesses in the order of 1-2mg/cm$^2$ on a Kapton backing and enriched to 95, 92 and 94% respectively.

After identification of the main gamma rays by cross bombardments and the measurement of excitation functions, mainly $(a,6n)$ reactions at $E_\alpha = 80$ and 84 MeV were used for coincidence measurements. Three parameter $\gamma$-$\gamma$-t coincidence experiments, prompt and delayed angular distributions in two parameter $t$-$t'(0)$ experiments at seven angles between 90° and 160° were carried out with Ge(Li) detectors and in the latter experiment with the cyclotron RF-signal as time reference. Monitoring of the EX-rays was compromised by an intrinsic Ge detector placed at a fixed angle. Correction of deadtime losses were based on the contents of a pulser peak. The data were digitized using a TERELEC ADC ("PACE") system. Through a K.V.I. designed CAMAC interface and by means of a PDP-15 computer the data were stored event by event on magnetic tape and analysed off-line with the programs GAMI and GATIGA for two and three parameters, respectively. Additional information was obtained from an in-beam measurement of conversion electrons at $E_\alpha = 80$ MeV. In this experiment the target consisted of a self-supporting $^{150}$Gd target (thickness = 1 mg/cm$^2$). The electrons were observed with a Si(Li) detector in the mini-orange spectrometer of Van Klinken and Feenstra.

3. Results

The resulting level scheme of $^{152}$Dy is presented in fig.1. Our data for the transitions between the positive parity states with $E_x < 2700$ keV are in agreement with $^{152}$Ho$^{+}$ decay data.

\[\text{(793B + x)}\]

\[\text{KVI66b}\]

\[\text{KV665b}\]

\[\text{15C6.3} + x\]

\[\text{5290 + x}\]

\[\text{Gy 5090}\]

\[\text{5036} + x\]

\[\text{5094}\]

\[\text{3969}\]

\[\text{1900}\]

\[\text{1090}\]

\[\text{870}\]

\[\text{5046.38}\]

\[\text{3821}\]

\[\text{1261.2}\]

\[\text{613.9} + (100)\]

\[\text{152}\]

\[\text{66 Dy}\]

\[\text{86}\]

\[\text{152}\]

\[\text{66 Dy}\]

\[\text{86}\]

Fig.1. Level scheme of $^{152}$Dy populated in $(a,6n)$ reactions at $E_\alpha = 80$ MeV. Numbers in brackets denote intensities (errors 10-20%). Dashed lines for levels or transitions are introduced in cases where the coincidence evidence is incomplete or order of transitions uncertain.
Fig. 2. Time spectra with respect to the beam for γ-rays in $^{152}\text{Gd}$, taken at $E_b = 71$ MeV. The prompt time distributions of γ-rays in $^{152}\text{Gd}$ and $^{154}\text{Gd}$ are presented for comparison. The time scale for all spectra is 3.7 ns/channel.

Fig. 3. Coincidence γ-ray spectra for $^{152}\text{Gd}$. Spectrum a) shows the projection of all γ-γ-\(\gamma\) events on one energy axis. Spectra b) and c) show the transitions deexciting and feeding the 60 ns isomer, respectively, obtained by setting appropriate gates in the time spectrum of both Ge(Li) detectors, as indicated.

Fig. 4. Conversion electron spectrum of $^{152}\text{Gd}$ observed in-beam with a mini-orange spectrometer. The insert shows the transmission curve measured for the used magnet configuration.
Several previously unobserved levels are proposed. Those marked with dashed lines in fig.1 are tentative in as much as the order of the feeding and deexciting transitions may be reversed. The experimental data do not allow to determine their proper position in the level scheme. The time spectra with respect to the beam bursts(fig.2) show delayed components with $T_{1/2} = 60.25$ ns for all γ-rays decaying from the $E_x = 5.036$ MeV level. For comparison the prompt time distributions of γ-rays in $^{153}$ Dy and $^{154}$ Dm are also presented in fig.2. The actual position of the isomer might be at $E_x = 5036 + x$ keV because it most probably decays by an unobserved transition. The existence of this transition is based on the fact that both the 605 and 610 keV transitions show prompt components in their time distributions. In the case of the 605 keV line, however, the prompt component partially results from an unresolved line presumably belonging to $^{151}$ Dy.

The energy of the unobserved transition must be < 54 keV (X-binding energy of Dy) since no K X-rays have been observed in (delayed) coincidence spectra.

Fig.3 shows examples of γ-γ-t coincidence spectra for $^{152}$ Dm. Nine γ-rays feeding the 60 ns isomer were found in the γ-γ-t coincidence experiment by setting a time gate at 60-200 ns before the prompt time peak. Only five transitions could be placed firmly in this part of the level scheme; most others (shown as dashed lines in fig.1) were placed on basis of their energy fit only.

The spin assignments are based on the analysis of the angular distributions (fig.5) and the conversion electron measurement (fig.4). All transitions present in the cascade depopulating the isomer show practically isotropic angular distributions. The distribution of the prompt components are consistent with pure E2 character of transitions between states with decreasing spin values. An exception is the 605 keV line, where this distribution is almost isotropic. It should be noted, however, that at these high beam energies used in the angular distribution measurement there is approximately a 30% impurity in the prompt component of the 605 keV line as mentioned above.

Fig.5. Angular distributions for γ-ray transitions in $^{152}$ Dy both for the prompt and the delayed part. The line through the data points represent the best fit of a Legendre polynomial.

An assumption of a mixture of an E2 transition in $^{152}$ Dy and a pure dipole transition in $^{151}$ Dy is a likely explanation of the observed angular distribution of the 605 keV line. The alternative explanation of a mixed M1 + E2 character of the 605 keV transition in $^{152}$ Dy seems to be ruled out by the internal conversion data. The latter are consistent with E2 character for all the transitions in question. Possible M1 admixtures are less than 20% for most of the lines and less than 30% for the 605 keV transition. An admixture of this magnitude does not yield the observed angular distribution even for a rather improbable Jπ = 0 transition. The 637 keV and 647 keV lines are unresolved doublets and no statements about the possible M1 + E2 mixing can be made; the E1 character, however, may be excluded.

The above arguments and the excitation functions data allow one to determine the most probable spin value for the 5036 keV level as Jπ = 16+ or 15+. The possible spin values for the isomeric state are then 17, 16, 15 with parity undetermined, or 18+. The latter value requires an enhanced E2 transition to the 5036 keV level. Such a transition could take place e.g. between members of a four quasi-particle multiplet, and thus cannot be a priori excluded. Besides the parity assignments of the decay scheme of $^{152}$ Dy also shows a set of states with a probably negative parity (fig.1). The parity assignment is based on the result of the conversion coefficient measurement of the 398 keV transition between the $E_x = 2353$ and the 1965 keV states which is most likely an E1 (only an upper limit for the μ value can be given). The decay of levels in this "band" is also seen in the delayed spectra although no feeding transition from the isomer has been identified yet. The spin and parity assignments of the levels at $E_x = 3160$ and 3969 keV levels could not be established because the 254.1 keV transition between the former state and the Jπ = (9+) level at 2906 keV is not resolved from the 253.6 keV transition feeding the isomer, and from the 256 keV γ-ray in the decay of $^{152}$ Dy to $^{152}$ Th.
4. Discussion

The surprising features in the deduced level scheme (fig.1) can be summarized as follows: (i) the 'breaks' in the ground state band (GSB) above the $J=8^+$ state and in the negative parity band (NPB) above the $J=9^+$ state, (ii) the existence of a $1/2^+$ at 60 keV with $J=15$ to 18 and undetermined parity at $E_x = 5$ MeV, (iii) the observation of discrete transitions above the isomer up to $E_x = 8$ MeV.

At the moment one can only speculate about the relationship of the isomer. Its long life-time may be associated with a retardation of a transition between states differing not in the spin value but in some other nuclear property (e.g. collectivity, deformation, etc.). Alternatively, the missing isomeric transition need not be hindered or even may be slightly enhanced, provided that it connects close lying yrast states.

An irregularity in the yrast line of the type mentioned might be reproduced if one assumes that the isomeric state is of a four-quasiparticle nature, while the lower energy yrast states are e.g. collective vibrations.

The yrast line below the isomeric state in $^{152}$Pb does not follow the $J(J+1)$ energy dependence and is characterized for a vibrational rather than rotational nucleus. If one treats the $^{152}$Pb nucleus in its ground state as a vibrational one and uses the parametrization of the I.B.A. model\(^a\) one can reproduce the first three excited states of the ground state band and the negative parity band. The first $8^+$ state, however, is observed for far too low energy and presumably is of a different nature (e.g. mostly two-quasiparticle).

A rough estimate of the energies of four-quasiparticle states may be obtained using the mass tables and the experimental single quasiparticle energies from adjacent odd-A nuclei and neglecting the residual interactions. E.g. the $4 q.p.$ configuration $v_1f_7q^2$, $i_{13/2}^2$ ($J=16^+$) has the unperturbed energy of 3.024 MeV. The unperturbed energy for the lowest $8^+$ two-quasiparticle state, $v_1/i_{13/2}/h_9/2$, is 2.528 MeV, which is close to the observed energy value of the lowest $8^+$ state, 2.438 MeV. The latter assignment is supported by the strong beta-decay feeding with low log ft value of this state from the $J=9^+$; 52 sec. isomer in $^{152}$Nd (ref.7) which presumably has a ($h_9/2$, $v_1f_7/2$) configuration.

Another intriguing problem is the nature of the states observed above the isomeric level. Assuming the four-quasiparticle nature of the latter, one may consider the possibility of the core polarization, caused by these quasiparticles and resulting in the core deformation. This could explain the observed 270 keV $\rightarrow$ 525 keV $\rightarrow$ 254 keV gamma-ray cascade populating the isomer as corresponding to the $B = 6^+ \rightarrow 4^+ \rightarrow 2^+$ transitions in the deformed core, with the four-quasiparticle not participating in the rotation ("Coriolis decoupled", or "rotation aligned"). One notes the near R(R+1) dependence of the energy spacing in fig.1. The apparent moment of inertia $I_{44}$ point at the "64" point is $2I_h^2/27MeV^2", very similar to that in the ground state bands of the more rotational $N=88$ or $N=90$ isotones.

The existence of rotation aligned bands in odd-A nuclei seems to be a well recognized feature of collective nuclear motion\(^2\). In particular, such bands involving the $1/2^+$ neutron or $3/2^+$ proton orbitals have been regularly observed in the light rare earth region\(^3\). The same decoupling mechanism has also been suggested to explain spectra of even nuclei at high spins in terms of decoupled two-quasiparticles\(^4\).

The yrast line in a transitional nucleus may also be constructed by summing the angular momenta of individual quasiparticles moving in a spherical or slightly oblate (e.g. $\epsilon = -0.15$) potential.

A rather irregular pattern may be obtained in this way. It is interesting to note that in a preliminary calculation of this kind\(^10\) a dip in the yrast line of $^{152}$Pb has been obtained at $J=16$, while no such dip has been found for the adjacent $^{150}$Pb. The calculation did not include pairing and yielded too low energies. It may be argued, however, that the pairing correction might increase the energies without destroying the irregularities.

5. Conclusion

The 60 ns $^{152}$Pb-Py offers a rather unique possibility of further study of the effects relevant to the current discussion of the nuclear properties in the high-excitation-energy high-spin region.

Isomers similar to that in $^{152}$Pb are likely to be found also in other transitional nuclei. Though the isomerism as such is not essential for the formation of rotation aligned bands, it greatly facilitates the experimental study at high excitation energy, allowing one to use the timing technique as a sort of sieve to single out the interesting transitions.

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