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LEVEL STRUCTURE OF ^{80}Rb STUDIED WITH THE ^{79}Br(α, 3n) REACTION †

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Abstract: States of ^{80}Rb were excited through the ^{79}Br(α, 3n) reaction at bombarding energies between 30 and 55 MeV. Excitation functions, γ-ray angular distributions, γ-γ coincidences and γ-time distributions with respect to the beam bursts were determined. Levels with the following excitation energies (in keV) and spin-parity values are proposed: 175.6 2, 334.9 $3^{(-)}$, 375.9 3^+, 418.6 (4), 423.1 (4), 470.5, 472.5 4, 486.1 (5) and 496.4 (5). The 175.6, 375.9 and 472.5 keV levels together with the ground state exhibit a $K^\pi = 1^+$ quasi-rotational structure, regarding the energy spacings and the mixing ratios of the γ-rays. It is shown that this structure is quite similar to bands known in ^{68}Ga and ^{64}Cu. A description of these bands in terms of the Nilsson model gives satisfactory results.

E | NUCLEAR REACTION ^{79}Br(α, 3n), $E = 30$ to 55 MeV; measured E_γ, I_γ, $\gamma(\theta)$, γγ-coin. ^{80}Rb deduced levels, J, π, δ, Q. Enriched target. Ge(Li) detectors.

1. Introduction

The present study of levels of ^{80}Rb populated through the (α, 3nγ) reaction on ^{79}Br has been undertaken as part of a program to investigate doubly odd neutron-deficient nuclei in the $28 \leqq N, Z \leqq 50$ region.

Our knowledge of $^{80}_{37}$Rb$_{43}$ has until now been limited to the results obtained from the radioactive decay of ^{80}Sr [ref. [1])]. The information about spins and other properties of the levels populated in this decay is scarce. From the decay of ^{80}Rb the ground state is known to be 1^+ [ref. [1])].

This spin and parity can be understood in terms of the known data from neighboring odd-A nuclei. The ground state of the $N = 43$ isotones ^{75}Ge, ^{77}Se, ^{79}Kr and ^{81}Sr have $I^\pi = \frac{1}{2}^-$ while the isotope ^{81}Rb has an $I^\pi = \frac{3}{2}^-$ ground state. It is known that intermediate deformations are found in this region of the periodic table. This is, for instance, reflected in the marked variation of the $\frac{9}{2}^+$ state energies with neutron number in the odd-Z Rb isotopes. The maximum deformation is known to occur for $N \approx 44$ [refs. [2, 3])]. Also, the $\frac{9}{2}^+$ ground states found in the odd-N Ge, Se, Kr and Sr isotopes have been interpreted as deformed states. Hence it seems natural to expect ^{80}Rb to share this property. Recent results also show [4]) that deformed bands are found in

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doubly odd nuclei in this region of the periodic table. So it is interesting to find out if such bands are also seen in ^{80}Rb.

Since the (α, xn) reaction favors the population of high-spin levels, we have used the ^{79}Br(α, 3nγ) reaction in order to reach excited states of ^{80}Rb.

In the following, the experimental procedures are outlined and the results are given. These are discussed in the last section.

2. Experimental procedure

2.1. EXPERIMENTAL SET UP

A 55 MeV α-particle beam was obtained from the Buenos Aires Synchrocyclotron, which was subsequently degraded so that energies between 30 and 55 MeV were attained.

The target was made of sodium bromide enriched to 98.5 % in ^{79}Br. The NaBr powder was uniformily distributed on a Melinex strip and bound to it with spray lacquer. The target area was about 2 cm^2 and the thickness was 5 mg/cm^2.

The γ-radiation was detected with a coaxial Ge(Li) detector of 7 % efficiency and 2.3 keV energy resolution. In order to see the low-energy spectra with better resolution a small X-ray Ge(Li) detector, with a resolution of 280 eV for a 5 keV γ-transition, was used.

The analysis of the γ-spectra was performed with the aid of the computer program SAMPO [5]). Sources of ^{152}Eu and ^{133}Ba were used for energy and efficiency calibration of the Ge(Li) detector in the experimental geometry. All the γ-ray energies are estimated to be accurate to about 0.3 keV. The overall error of our efficiency calibration can be estimated as ± 5 %.

2.2. EXPERIMENTAL RESULTS

The ^{80}Rb isotope was investigated through the ^{79}Br(α, 3n)^{80}Rb reaction. The single γ-ray spectrum taken at E_α = 45 MeV is shown in fig. 1. There are several lines which belong to other reactions like (α, 2n), (α, np) and (α, 2np).

The isotopic assignment of the γ-rays was done on the basis of the relative excitation functions. The α-beam energy was varied between 30 and 55 MeV in steps of 5 MeV. In fig. 2 the excitation functions for representative γ-rays from the (α, 2nγ), (α, npγ), (α, 3nγ), (α, 2npγ) and (α, 3npγ) reactions are shown. As can be seen, reactions involving two, three and four particles can be easily distinguished from each other.

In order to distinguish between (α, 3nγ) and (α, 2npγ), two criteria were applied:

(i) A 175.0 keV γ-transition is known from ref. [1]) to correspond to the deexcitation of the first excited state of ^{80}Rb. Similar relative excitation functions and coincidences with the 175.6 keV transition make it possible to assign the other γ-rays to the ^{80}Rb isotope.

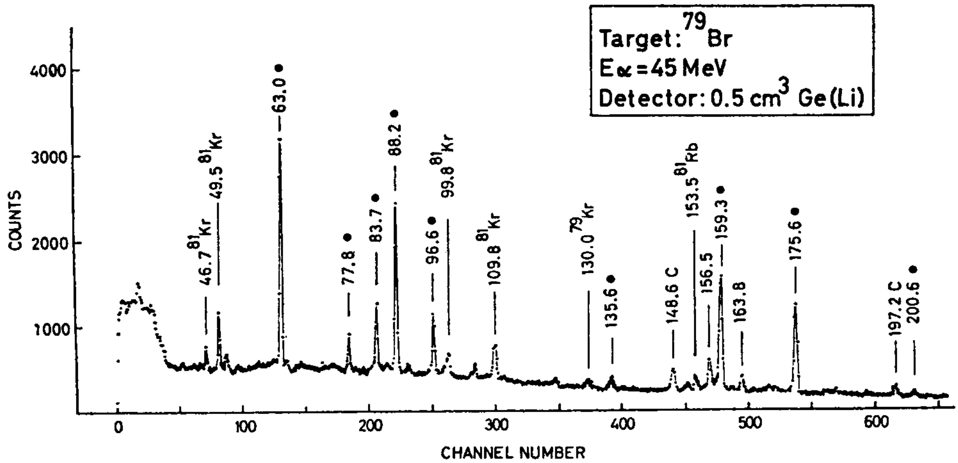

Fig. 1. Single γ-ray spectrum from the ^{79}Br(α, 3n)^{80}Rb reaction at 45 MeV, obtained with a small Ge(Li) X-ray detector. The γ-rays assigned to ^{80}Rb are labeled with solid dots and the lines originating in the target backing with the letter C.

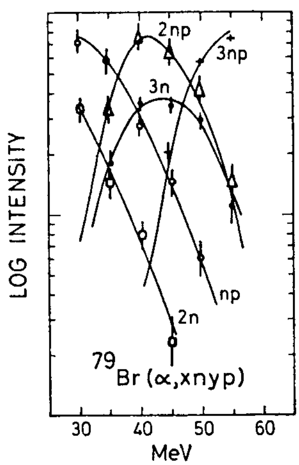

Fig. 2. Excitation functions for the different reactions observed from the bombardment of ^{79}Br with α-particles of energies between 30 and 55 MeV. The curves correspond to the most intense γ-rays in each reaction, np: 49.5 keV for ^{81}Kr; 2n: 153.5 keV for ^{81}Rb; 3n: 63.0 for ^{76}Br; 2np: 616.2 keV for ^{80}Kr; 3np: 130.0 keV for ^{79}Kr. The relative intensities are arbitrary. The dependence of the shape on the level spins is negligible compared to the difference bewteen the curves involving two, three and four particles.

(ii) The decay scheme of ^{80}Kr is known not only from radioactive decay, but also from the (α, 2nγ) reaction, so that the γ-transitions which belong to ^{80}Kr could be readily identified.

On this basis, the lines at 63.0, 77.8, 83.7, 88.2, 96.6, 135.6, 159.3, 175.6, 200.6 and 375.9 keV were assigned as transitions in ^{80}Rb. The energies and intensities are given

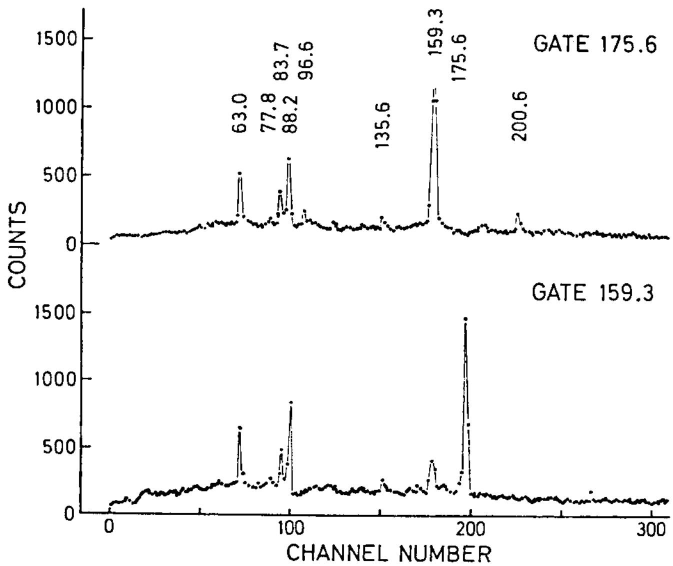

Fig. 3. The γ-ray spectra in coincidence with the 159.3 and 175.6 keV transitions, as observed with the (7 %) Ge(Li) detector.

TABLE 1

Summary of results of the present experiment

Energy (keV) (±0.3)	Intensity (±10 %)	Spin sequence	A_2
63.0	4.3	(5)–(4)	−0.44±0.10
77.8	1.1	(5)–(4)	
83.7	2.2	(4)–3	−0.02±0.14
88.2	6.2	(4)–3	−0.30±0.06
96.6	3.5	4–3	−0.32±0.07
135.6	1		
159.3	28.0	3–2	−0.63±0.05
175.6	30.0	2–1	−0.51±0.08
200.6	3.1	3–2	−0.25±0.04
297.3	≦0.5	4–2	
375.9	4.1	3–1	0.40±0.15

in table 1. These γ-rays were fitted into a level scheme on the basis of γ-ray energy combinations, γ-intensity balance, γ-γ coincidence relationships and γ-ray angular distributions.

2.3. COINCIDENCE MEASUREMENTS

The coincidence spectrometer consisted of one Ge(Li) detector of 7 % effiiency and a small X-ray detector. A conventional coincidence circuit of $2\tau = 40$ nsec resolution time, was used in conjunction with a 4096 Intertechnique multichannel analyzer. Gates, were set on all the γ-rays with the exception of the weak 135.6 keV γ-transition.

The coincidence spectra with the gates set on the 175.6 and 159.3 keV line are shown in fig. 3.

2.4. ANGULAR DISTRIBUTION MEASUREMENTS

Gamma-ray spectra were taken at seven angles (75°, 90°, 100°, 110°, 120°, 130° and 140°) with respect to the beam direction. The movable detector was placed 15 cm from the target. To normalize the spectra taken at different angles, the output of a pulser, triggered by the pulses from a monitor detector, was fed into the preamplifier of the moving detector. The normalized peak areas were fitted to the usual angular correlation function $W(\theta) = 1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$. The parameters A_2 and A_4 determined in this way are related to the tabulated coefficients [6] $A_2^{\max}$ and $A_4^{\max}$, which correspond to total alignment by the attenuation coefficients $\alpha_K = A_K/A_K^{\max}$. However, within errors, in all cases A_4 was consistent with zero, and a second fit with A_2 as the only free parameter and $A_4 = 0$ was carried out. The result of this second fit is shown in table 1.

2.5. TIMING MEASUREMENTS

To investigate the existence of isomeric states with lifetimes longer than a few nsec, the small X-ray detector was used, and the time interval between its pulses and the synchrocyclotron radiofrequency was recorded following the method of Yamazaki and Ewan [7]. The data were accumulated in a 64 × 64 channel format in the analyzer memory, spanning the energy range $40 < E_\gamma < 200$ keV. The system time resolution was about 15 nsec and the slope of the prompt distribution was 4 nsec. All the γ-rays with the exception of the 77.8 and 83.7 keV transitions show a prompt distribution over a flat time background. The 77.8 and 83.7 keV transitions show a half-life of 8 ± 2 nsec, without any long lifetime contribution.

3. Analysis and discussion

3.1. ENERGY LEVELS AND DECAY SCHEME

The energy levels of ^{80}Rb and their decay scheme are shown in fig. 4. The scheme was constructed on the basis of the relative γ-intensities, energy combinations and coincidence experiments.

Comparing our results with those from the decay work [1], only the level at 175.6 is common to both studies. The coincidence results confirm without ambiguity the placement of all the γ-rays except the 297.3 keV transition which is placed in the decay scheme based only on the energy fit and the excitation function.

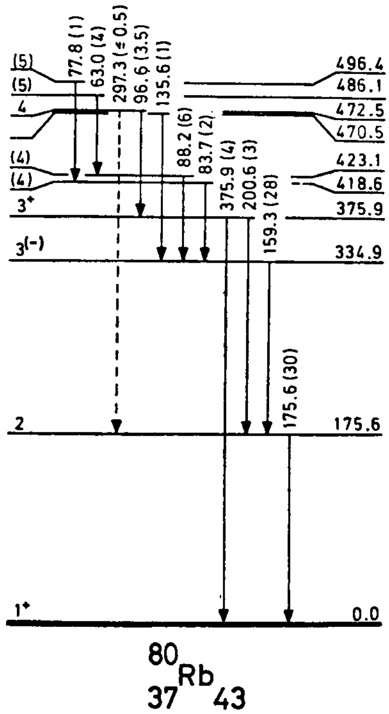

Fig. 4. Level scheme of ^{80}Rb obtained in the present work.

3.2. SPIN ASSIGNMENTS AND MULTIPOLARITY OF THE γ-TRANSITIONS

In the present case, the results of the angular distribution measurements allow us to determine the spin of the following levels, assuming that the spin-parity of the ground state is $I^\pi = 1^+$.

The 375.9 keV level. This level deexcites to the 175.6 keV and ground states through the 200.6 and 375.9 keV transitions respectively. The angular distribution of the latter is typical of a $\Delta I = 2$ stretched transition. The lack of any long lifetime involving this level, inferred from the coincidence results, shows that the 375.9 keV γ-ray must have E2 character. Therefore $I^\pi = 3^+$ is assigned to this level.

The 175.6 keV level. This level is fed by the 200.6 keV transition from the $I^\pi = 3^+$, 375.9 keV state and deexcites to the ground state by the 175.6 keV transition. Since the angular distribution of both γ-rays is characteristic of $\Delta I = 1$ transitions, the only spin compatible with both measurements is $I = 2$.

The 472.5 keV level. This level deexcites to the 375.9 keV level by the 96.6 keV transition. The angular distribution of this transition is only compatible with $\Delta I = 0, 1$. However, $\Delta I = 0$ can be ruled out because it implies a large negative A_4 (≤ -0.25), which is not the case, and a large mixing ratio which should yield a measurable half-life for this transition ($T_{\frac{1}{2}} > 0.1$ μs) while the experimental value is $T_{\frac{1}{2}} < 5$ ns. Hence $I = 4$ is assigned to this level.

The 334.9 keV level. This level deexcites to the 175.6 keV level through the 159.3 keV transition. The angular distribution of this transition is only compatible with $\Delta I = 1$. Therefore $I = 3$ is assigned to this level. The lack of a crossover transition suggests that this level has negative parity.

The 423.1 and 486.1 keV levels. Both levels are deexcited by the 88.2 and 63.0 keV transitions, respectively. Their angular distributions favour $\Delta I = 1$. The lack of crossovers suggests that the spins increase with energy, therefore spins $I = 4$ and 5 are tentatively assigned to these levels.

The 418.6 and 496.4 keV levels. The 418.6 keV level is deexcited by the 83.7 keV γ-ray. The angular distribution corresponding to this transition is consistent with $\Delta I = 0, 1$. However, the lack of a crossover to the $I = 2$, 175.6 keV level, favours spin $I = 4$. The time distribution ($T_{\frac{1}{2}} = 8 \pm 2$ ns) of the 77.8 keV line, which depopulates the 496.4 keV level, limits its multipolarity to dipole character. This result, together with the absence of a crossover transition to the $I = 3$ lower levels, suggests that the spin of the 496.4 keV level is $I = 5$.

4. Discussion

As was mentioned in sect. 1, the spin and parity of the ground state of ^{80}Rb can be understood in terms of the ground-state properties of the neighboring odd-A nuclei. Since the latter are known to be deformed one can expect to observe a band structure in ^{80}Rb. In fact an interesting feature of the present level scheme is given by the spin sequence $I = 1, 2, 3$ and 4, energy spacings and decay patterns of the levels situated at 0,175.6, 375.9 and 472.5 keV.

Assuming that the 175.6 and 472.5 keV levels have positive parity, this sequence can be compared with the predictions of the $I(I+1)$ law, as shown in fig. 5. An overall fit is obtained with a moment of inertia $J_0/\hbar^2 = 0.016 \pm 0.03$ keV^{-1}. It is noteworthy that not only similar moments of inertia are found in the odd-A neighboring nuclei [8, 9]), but also in the doubly odd ^{76}Br isotope, for which the moment of inertia was found to be $J_0/\hbar^2 = 0.014$ keV^{-1} [ref. [4])].

Searching for similar patterns in this region of the periodic table, it is striking to observe that part of the level scheme† of ^{68}Ga is almost identical with the band found in the present work for ^{80}Rb. Also a similar band occurs [10]) for ^{64}Cu††. A comparison of these data is shown in figs. 5 and 6. The shell-model configuration $|\pi p_{\frac{3}{2}}, \nu f_{\frac{5}{2}}|_{I^\pi = 1^+ \dots 4^+}$ could provide a basis in which a description of this band structure could be attempted for ^{64}Cu and ^{68}Ga, but not for the heavier isotope ^{80}Rb.

Alternatively, in view of the similar structures exhibited by the three isotopes one can try a common description in terms of a rotational scheme. As in the case of ^{80}Rb, such an interpretation is supported by the observed rotational bands in the odd-A neighbours of ^{64}Cu and ^{68}Ga, the isotopes ^{63}Cu and ^{67}Ga, respectively.

† The observation of these similarities is due to R. P. J. Perazzo.

†† The possibility of obtaining $K^\pi = 1^+$ states with similar deformations for the three nuclei was pointed out to us by E. E. Maqueda.

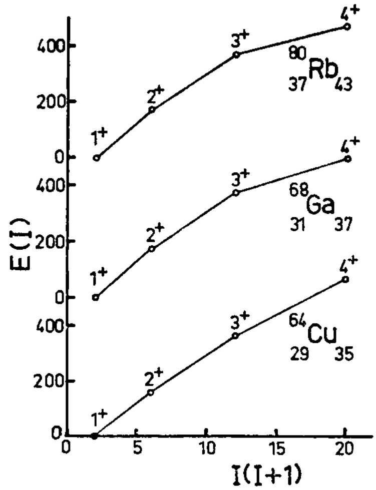

Fig. 5. Plot of the excitation energies $E(I)$ as function of $I(I+1)$ for ^{64}Cu, ^{68}Ga and ^{80}Rb. The data of ^{64}Cu and ^{68}Ga are from ref. [10]).

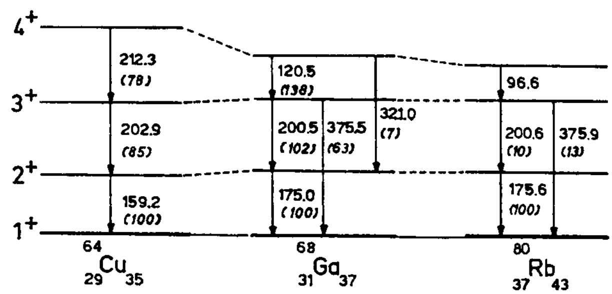

Fig. 6. Partial level schemes for ^{64}Cu, ^{68}Ga and ^{80}Rb. The data of ^{64}Cu and ^{68}Ga are from ref. [10]).

TABLE 2

Deformations and configurations assumed for the $K^\pi = 1^+$ bands in ^{80}Rb, ^{68}Ga and ^{64}Cu and deduced parameters

Isotope	ε	Q_0 (b)	Configuration	g_K	Sign of δ
^{80}Rb	0.2	1.74	$\pi\frac{3}{2}[301]$, $\nu\frac{1}{2}[301]$	5.64	+
^{68}Ga	0.2	1.31	$\pi\frac{1}{2}[310]$, $\nu\frac{3}{2}[301]$	0.12	−
^{64}Cu	0.14	0.82	$\pi\frac{1}{2}[321]$, $\nu\frac{3}{2}[301]$	−0.47	−

It is interesting to find that it is possible to obtain $K^\pi = 1^+$ wave functions with similar deformations for the three nuclei, in spite of their different nucleon numbers.

The ground state of ^{80}Rb can be explained as arising from the Nilsson configuration $\{\pi\frac{3}{2}[301]\}, \nu\frac{1}{2}[301]\}_{1^+}$ with $\varepsilon = 0.2$†. For ^{68}Ga, assuming the same deformation, one

† We use ε instead of δ as Nilsson's deformation parameter to avoid confusion with the symbol used for the mixing ratio.

can construct the $K^{\pi} = 1^+$ ground state with the $\{\pi\frac{1}{2}[310], \nu\frac{3}{2}[301]\}_{1^+}$ configuration. For ^{64}Cu, the $K^{\pi} = 1^+$ band is obtained with the wave function $\{\pi\frac{1}{2}[321], \nu\frac{3}{2}[301]\}_{1^+}$ with slightly less deformation, $\varepsilon = 0.14$.

The validity of these proposed Nilsson configurations can be tested by comparing the predicted mixing ratios, δ, for different transitions of the cascade with those obtained from the angular distribution data.

For $K \neq \frac{1}{2}$ bands, the absolute value of δ is

$$|\delta| = 0.933\times10^{-3}\,\frac{E_\gamma(\text{keV})}{\sqrt{I^2-1}}\,\frac{Q_0(\text{b})}{g_K-g_R},$$

while the sign of δ is given by the sign of the ratio $Q_0/(g_K-g_R)$. Here E_γ is the transition energy and I is the spin of the parent state. The intrinsic quadrupole moment was calculated according to

$$Q_0 = 0.0115\,ZA^{\frac{2}{3}}\,\varepsilon(1+0.66\,\varepsilon),$$

and g_R was set equal to 0.4.

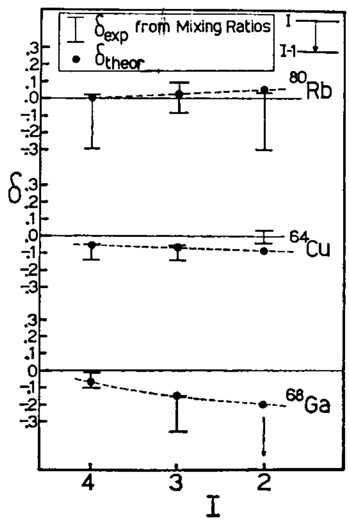

Fig. 7. Predicted and experimental mixing ratios for $I \to (I-1)$ transitions which deexcite levels of quasi-rotational bands in ^{64}Cu, ^{68}Ga and ^{80}Rb, respectively.

The proposed Nilsson wave functions enter in the calculation of the intrinsic gyromagnetic factors g_K. Since the wave functions correspond to positive deformation, Q_0 is positive and the sign of δ is determined by the difference $g_K - g_R$.

A summary of these data for the three nuclei is given in table 2.

The predicted and experimental mixing ratios are compared in fig. 7. The experimental values for ^{80}Rb were obtained from the angular distribution data assuming that the alignment does not vary significantly from one level to the other in the band.

An estimate of the attenuation coefficient was obtained for the stretched $\Delta I = 2$ transition from the 375.9 keV level. The result is $\alpha_2 = 0.80 \pm 0.35$. Using this value for the other levels, the corrected A_2^{max} parameters, and in turn, the mixing ratios were computed. The mixing ratios for ^{68}Ga and ^{64}Cu are extracted from the data of Pomar *et al.* [10]). As in the case of ^{80}Rb, the angular distribution of the stretched quadrupole 375.5 keV $3^+ \rightarrow 1^+$ transition in ^{68}Ga was used to calculate the average attenuation coefficient, while in ^{64}Cu, where the corresponding transition has not been observed, the degree of alignment was deduced from the stretched quadrupole 1019.1 keV $6^{(-)} \rightarrow 4^+$ transition [10]).

Although the error bars are large, particularly for the ^{80}Rb data (owing to the low intensity of the 375.9 keV γ-ray), the results seem to yield a fair indication that the proposed description is basically correct.

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