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Are nuclei with $N \sim 43$ deformed?

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Abstract. The level schemes of ^{75}Se and ^{79}Kr have been established through gamma ray and conversion electron spectroscopy following ^{75}As (p, n γ^-e) and ^{79}Br (p, nγe$^-$) reactions. The data on these nuclei and the nuclei in the neighbourhood of this mass region are discussed and evidence is presented to show that the nuclei with $N \sim 43$ are deformed.

Keywords. (p, n γ e$^-$) reactions; Coriolis coupling; deformed nuclei.

1. Introduction

The recent observation of Bonn *et al* (1972), that the root mean square radius of ^{185}Hg in its ground state is more than that of ^{187}Hg, raised the question as to whether ^{185}Hg is deformed. In this connection the high spin levels of ^{186}Hg and ^{184}Hg were studied by Proetel *et al* (1973) and Rud *et al* (1973) respectively by means of heavy-ion induced reactions. Proetel *et al* (1973) found that while the $2^+ \to 0^+$ and $4^+ \to 2^+$ level-spacings are equal, the levels of even spin from 6^+ to 14^+, which they studied, showed level spacings that can be fitted into a rotational band with an inertial parameter $\hbar^2/2\mathcal{J} = 12$ keV. Rud *et al.* similarly concluded that ^{184}Hg is deformed from levels of spin $\geqslant 6^+$ and supported their conclusion by measuring the B(E2) values of the transitions between some of the levels of the rotational band. The inertial parameter as well as the measured B(E2) values lead to a deformation parameter $\beta_2 = 0{\cdot}28$. These results can be explained if the potential energy as a function of deformation has a second minimum at $\beta_2 = 0{\cdot}3$ in these nuclei (Proetel *et al* 1973), the first minimum being at either $\beta_2 = 0$ or a small negative value. Dickmann and Dietrich (1973) calculated such a potential energy curve on the Strutinsky-Nilsson model and found that the potential energy for light even Hg isotopes indeed has minima at $\beta_2 \sim -0{\cdot}15$ and $\beta_2 \sim 0{\cdot}28$. They also calculated the zero point energy and the most probable shape for these nuclei and concluded that the light even Hg isotopes have a stable deformation. The odd mass nuclei in this region may further stabilize the deformation and thus the observation of Bonn *et al* (1972) can be understood in terms of a deformation.

A similar situation seems to occur in the ^{76}Se, ^{78}Kr region. Recently Wyckoff and Draper (1973) have studied the high spin levels in $^{72\text{-}78}$Se and $^{78\text{-}84}$Kr. In

$^{74-78}$Se and ^{78,80}Kr, the $0^+ \to 2^+$ and $2^+ \to 4^+$ spacings are roughly equal but the levels with spin 6^+ to 10^+ can be fitted into a rotational band with the inertial parameter $\hbar^2/2\mathfrak{J} \approx 35$ keV. Further, the B(E2) values for $2^+ \to 0^+$ transitions in $^{74-78}$Se and ^{78,80}Kr are enhanced by a factor of ~ 45 compared to the single particle estimate. If one calculates the deformation parameter β_2 for these nuclei on the rotational model, namely by using the relation

$$B\,(\mathrm{E2})_{2^+ \to 0^+} = e^2 Q_0{}^2/16\pi \tag{1}$$

with

$$Q_0 = \frac{3}{\sqrt{5\pi}} Z R_0{}^2 \beta_2 (1 + 0\cdot 16\beta_2) \tag{2}$$

one obtains $\beta_2 = 0\cdot 35$ (Stelson and Grodzins 1965). Thus even though the level energies up to spin 4^+ show a 'vibrational' character, the B(E2) values and the energy spacings of the higher spin levels suggest that these nuclei are deformed with $\beta_2 \sim 0\cdot 35$ at least at higher excitation energy and angular momentum. Recently Tanaka and Tomoda (1973) have calculated the potential energy as a function of deformation for ^{76}Se and ^{76}Kr and found potential energy minima for $\beta_2 \sim -0\cdot 2$ and $\beta_2 \sim 0\cdot 35$, the latter being $\sim 1\cdot 5$ MeV lower than the former. Thus the situation here is similar to the one obtaining in the light Hg isotopes.

Since these even nuclei show characteristics of being deformed, the neighbouring odd mass nuclei may also be deformed. In fact, the ground state of ^{75}Se ($I = 5/2^+$) and ^{79}Se ($I = 7/2^+$) have large electric quadrupole moments ($Q \sim 1$ barn), corresponding to $\beta_2 \sim 0\cdot 35$ on the basis of eq. (2), if one assumes that $I = K$. Engels (1967) has already suggested that ^{77}Se is deformed on the basis of the B (E_2) values. We furnish here further evidence for the deformed nature of the odd neutron nuclei in this region.

2. Experimental procedure and results

We have studied the excited states of ^{75}Se and ^{79}Kr through (p, n) reactions on ^{75}As and ^{79}Br respectively (Agarwal *et al* 1973, 1974 *a*, *b*) using the $5\cdot 5$ MeV Van de Graaff accelerator at B.A.R.C., Trombay. The energies, the spins and parities and lifetimes of the levels were measured using a variety of techniques which included in-beam γ-ray, internal conversion electron spectroscopy and angular distributions of γ-rays. The details of the experiments together with the complete level schemes for ^{75}Se and ^{79}Kr will be published elsewhere. Here, we present the data only on a few levels which are relevant in the present context. Partial level schemes of ^{75}Se, ^{77}Se and ^{79}Kr are shown in figure 1. The levels in ^{77}Se are taken from the existing data (Nuclear Data 1966). Also shown in the figure are some of the high spin excited states in ^{75}Se studied recently by Protop *et al* (1973) by (α, xn) reactions on Ge isotopes.

3. Discussion

From figure 1, one observes that in all the three nuclei, three levels of spin $1/2^-$, $3/2^-$ and $5/2^-$, which can be fitted into a $K = 1/2^-$ rotational band, are seen. The inertial parameters $\hbar^2/2\mathfrak{J}$ and the decoupling parameter a are also shown in the

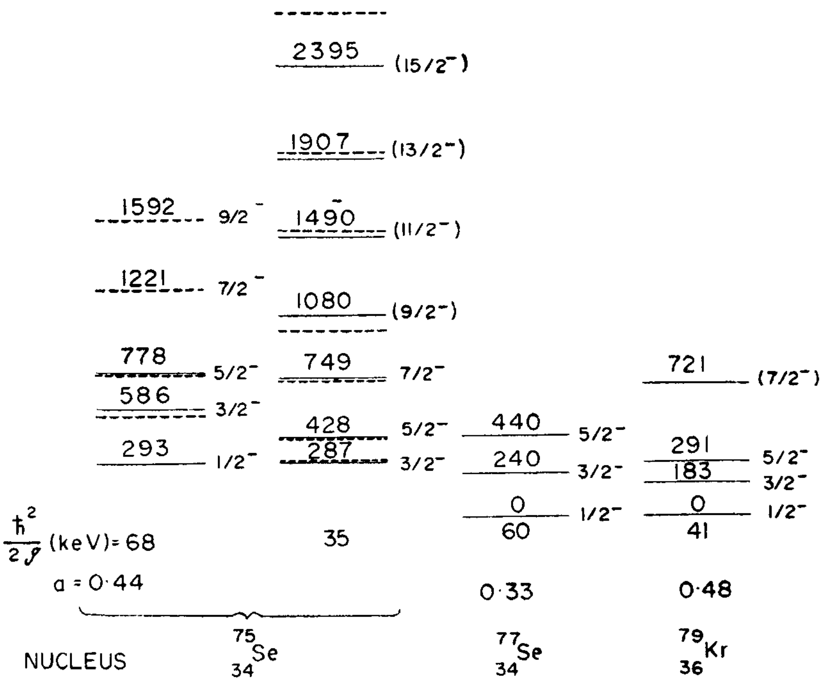

Figure 1. Partial level schemes of ^{75}Se, ^{77}Se and ^{79}Kr. The energy in keV and the spin and parity of each of the levels are marked. The $K = 1/2^-$ band in these nuclei and the $K = 3/2^-$ band in ^{75}Se are separately presented. The moment of inertia parameter $\hbar^2/2\mathcal{J}$ and the decoupling parameter, a, for these bands are shown. The results of a band mixing calculation between the $K = 1/2^-$ and $3/2^-$ bandsin ^{75}Se are shown by dotted lines. The calculation was made using the parameters $\hbar^2/2\mathcal{J} = 45$ keV, $a = 0{\cdot}4$ and the Coriolis coupling strength (Kerman 1956) $A_k = 60$keV.

figure. In ^{79}Kr, there is also a level at 721 keV, which has tentatively been assigned a spin of $7/2^-$. This level fits into the $K = 1/2^-$ band. The levels at 287 ($3/2^-$), 428 ($5/2^-$), 749 ($7/2^-$), 1080 ($9/2^-$), 1490 ($11/2^-$), 1907 ($13/2^-$) and 2395 ($15/2^-$) in ^{75}Se can also be fitted into a rotational band with $K = 3/2^-$, as has been noted by Protop *et al* (1973). However, the inertial parameter $\hbar^2/2\mathcal{J}$ has a value of 65 keV for the $K = 1/2^-$ band while it is 35 keV for the $3/2^-$ band. This large difference in the moment of inertia for the two bands in the same nucleus can be understood on the basis of mixing of these two bands through a Coriolis interaction. A Coriolis coupling calculation with a common value of $\hbar^2/2\mathcal{J} = 45$ keV and $a = 0{\cdot}4$ for the decoupling parameter for the $1/2^-$ band, reproduces the observed level energies reasonably well. The calculated energies of the levels are shown by dotted lines in figure 1. The moment of inertia and the decoupling parameter for the $K = 1/2^-$ bands in ^{77}Se and ^{79}Kr are similar (figure 1).

The $K = 1/2^-$ band assigned in these three nuclei can further be identified with the (301 ↓) $1/2^-$ Nilsson orbit. The decoupling parameter for this band can be calculated from the Nilsson wave functions (Nilsson 1955) to be $0{\cdot}7$ to $0{\cdot}8$ for deformation ranging from $\beta_2 = 0{\cdot}2$ to $0{\cdot}4$. The experimental value is in reasonable agreement with the calculated one. Similarly, the $K = 3/2^-$ band in ^{75}Se can be identified with the (301 ↑) $3/2^-$ Nilsson orbital.

4. Conclusions

The following piece of evidence exist for concluding that the nuclei in the region with $N \sim 43$ are deformed:

(i) The energy spacings for levels with spin $I \geqslant 6^+$ for the even Kr and Se isotopes can be fitted into a rotational band.

(ii) The large B (E2) values for the $2^+ \rightarrow 0^+$ transitions in the even Kr and Se isotopes and the large quadrupole moments for the ground states of $^{75, 79}$Se.

(iii) The observation of three $K = 1/2^-$ rotational bands with consistent moments of inertia and decoupling parameters.

(iv) The $K = 3/2^-$ band observed by Protop *et al.* (1973) in ^{75}Se.

(v) The potential energy curve calculation by Tanaka and Tomoda (1973) which shows a potential minimum for $\beta_2 = +0{\cdot}35$.

It will be interesting to study the high spin levels in the odd mass Se and Kr isotopes in order to see whether more rotational bands could be identified.

The positive parity levels have not been discussed in the present work. They will be discussed elsewhere (Agarwal *et al* 1974 *a*, *b*). However, it may be mentioned that Sanderson (1973) has recently made a Coriolis coupling calculation for the positive parity levels and concluded that the energy levels could be fitted well by a deformation parameter $\beta_2 \sim 0{\cdot}3$ in agreement with the conclusion of the present work. Scholz and Malik (1968) made similar Coriolis coupling calculations for the odd proton nuclei in this region and found reasonable agreement between the calculated and the observed levels.

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