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Short note

Shapes of the neutron-rich $^{88\text{-}94}$Kr nuclei

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Abstract. Neutron-rich, $^{88\text{-}94}$Kr nuclei, populated in spontaneous fission of ^{248}Cm, have been studied with EUROGAM 2, by measuring prompt γ-rays. Many new excited states in even-even Kr isotopes have been identified. For the first time spins and parities were determined experimentally in these nuclei. Our results indicate that the quadrupole deformation of Kr isotopes will appear only above $N = 58$, as observed in Sr and Zr nuclei. The newly found 3^- level at 1506.4 keV in ^{90}Kr suggests the exsistence of a new region of increased octupole correlations, probably associated with the $\nu(d_{5/2}h_{11/2})$ pair of $\Delta l = \Delta j = 3$ orbitals.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.Lv Gamma transitions and level energies – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

Neutron-rich nuclei with masses $A \sim 100$ exhibit several interesting features, and the strong dependence of the observed spectroscopic properties on the number of protons and neutrons makes these nuclei a very good testing ground for various theoretical models. For the Sr ($Z = 38$) and Zr ($Z = 40$) nuclei a sudden shape transition from spherical to strongly-deformed ground states ($\beta_2 \sim 0.40$) around N=59 has been reported [1]. Recent laser measurements of isotope shifts on krypton ($Z = 36$) isotopes extended considerably the experimental information about the electromagnetic, ground-state properties for the neutron-rich Kr isotopes up to $N = 60$ [2]. The mean charge radii, measured there, may suggest that the ground-state deformation of Kr isotopes increases gradually from $\beta_2 \approx 0.1$ at $N = 50$ to $\beta_2 \approx 0.3$ at $N = 58$. Less is known about excited states in these Kr isotopes since such states in nuclei from this region are difficult to reach. Until now only low spin-states have been identified in ^{88,90,92}Kr nuclei from investigations of β-decay properties of neutron-rich Br isotopes [3–5] and the knowledge about the ^{94}Kr nucleus [6] is limited to the suggestion that the transition of 665 keV belongs to this nucleus and de-excites the 2_1^+ state.

The present work reports partial results of our medium-spin studies of $^{88\text{-}94}$Kr isotopes, which were undertaken in order to observe structural changes in these nuclei as a function of increasing neutron number. In particular, we were interested to check what is the dependence of the ground state deformation in Kr isotopes on the neutron number. Is it increasing gradually from $N = 50$, as observed for the mean charge radii ref. [2], or does it set in rapidly above $N = 58$ as observed in the corresponding Sr and Zr nuclei [1,7]. The knowledge of nuclear deformation in these nuclei is of prime importance for the predictions of the astrophysical r-process flow in this region. As illustrated in fig. 1, the $N = 58$, Ge Se and Kr isotones are positioned at the critical point, where the predicted [8] r-process path (dashed line) crosses the region of the expected sudden change of ground-state deformation between $N = 58$ and $N = 60$ (shaded area).

Neither spins nor parities have been measured in the discussed Kr isotopes before. Such data are necessary for any serious discussion of nuclear structure of these nuclei. One of the main goals of this work was therefore an experimental determination of spins and parities in these nuclei.

To study excited states in the neutron-rich, even-even Kr nuclei we have exploited the power of modern instrumentation for γ-ray spectroscopy. Excited states in Kr isotopes were populated in the spontaneous fission of ^{248}Cm

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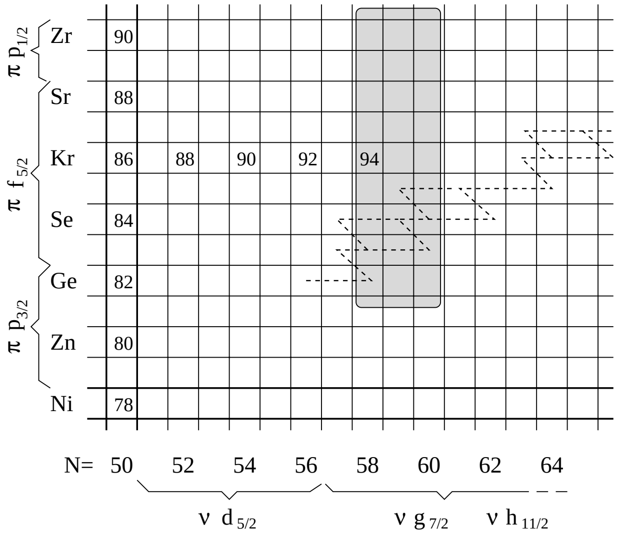

Fig. 1. Schematic drawing of the region of nuclei studied in the present work. The dashed line marks the expected path of the astrophysical r-process.

and multiple coincidences between prompt-γ rays following fission were measured with the EUROGAM2 array of Anti-Compton Spectrometers. Details about the experiment and data analysis techniques have been described previously [7].

A γ transition in a given Kr nucleus will appear in coincidence with transitions in a number of neodymium isotopes, which are complementary fission fragments to Kr isotopes in spontaneous fission of ^{248}Cm. New γ transitions in Kr and Nd nuclei were identified in the present work by implementing double gates on know γ transitions in $^{150-156}$Nd and ^{88,90,92}Kr nuclei, respectively. The newly found transitions in Nd isotopes were then used further as gates to identify additional new transitions in Kr nuclei. Level schemes of ^{88,90,92}Kr have been considerably extended in excited energy and spin with respect to schemes previous published.

To identify excited states in ^{94}Kr, the heaviest of the observed Kr isotopes, we gated on the known transitions in Nd isotopes. Three γ-rays were found to be consistently in prompt coincidence with known transitions in $^{150-154}$Nd isotopes and therefore were assigned to a krypton isotope. The relevant, double-gated spectra are shown in fig. 2.

To identify the mass of this Kr isotope, we used the technique of mass correlation proposed in ref. [9] and described recently in detail in ref. [10]. The method is based on the observation that in spontaneous fission of ^{248}Cm no proton and an average number of three neutrons are emmited from fission fragments. Gating on the newly identified krypton γ-transitions it was found, that the mean mass of the complementary Nd fragments is $\langle A(Nd)\rangle$= 151.5±0.2. This value correlates very well with the krypton mass $A(\mathrm{Kr}) = 94$, as shown in fig. 3, where the correlation between Kr masses and the corresponding, average masses of complementary Nd isotopes is displayed.

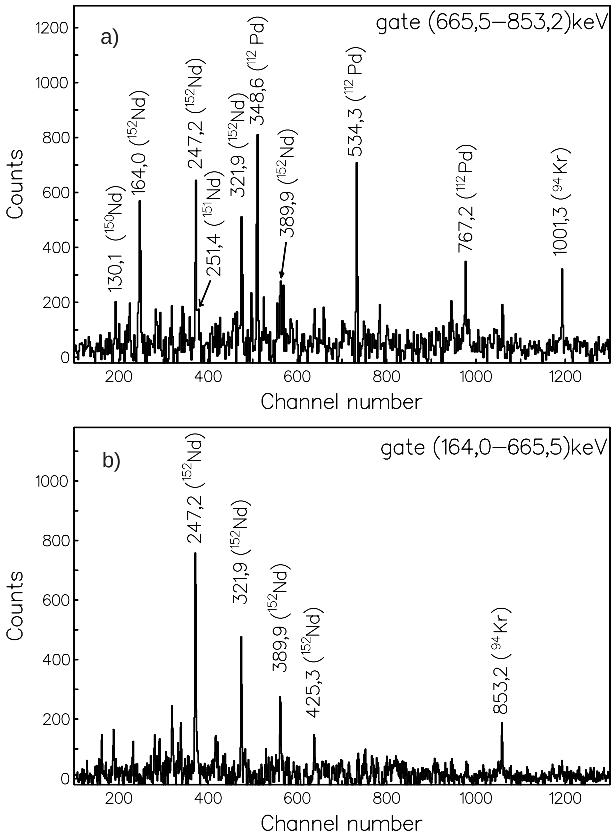

Fig. 2. Coincidence spectra, doubled-gated on γ lines in ^{94}Kr and ^{152}Nd (upper panel) and on two γ transitions in ^{94}Kr (lower panel). Lines from ^{112}Pd are due to overlapping gates.

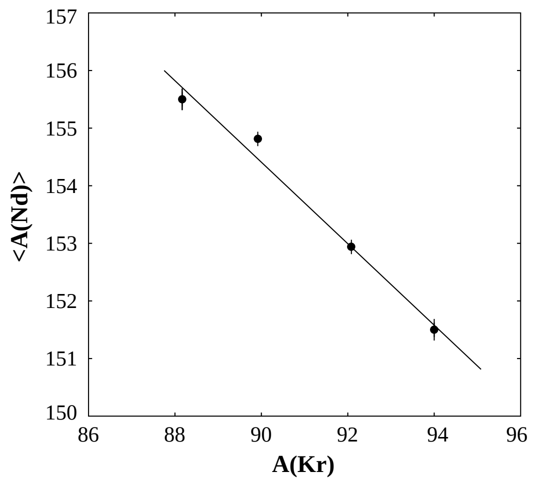

Fig. 3. Correlation between masses of Kr isotopes and the mean mass of complementary Nd isotopes.

Multipolarities of γ transitions in Kr nuclei were determined experimentally by measuring angular correlations and directional-polarisation of corresponding γ-rays, as described in ref. [7]. In table 1 we show values of angular correlation coefficients for pairs of consecutive transitions in $^{88\text{-}94}$Kr isotopes together with the deduced multipolarities for these transitions. Linear polarisation values ob-

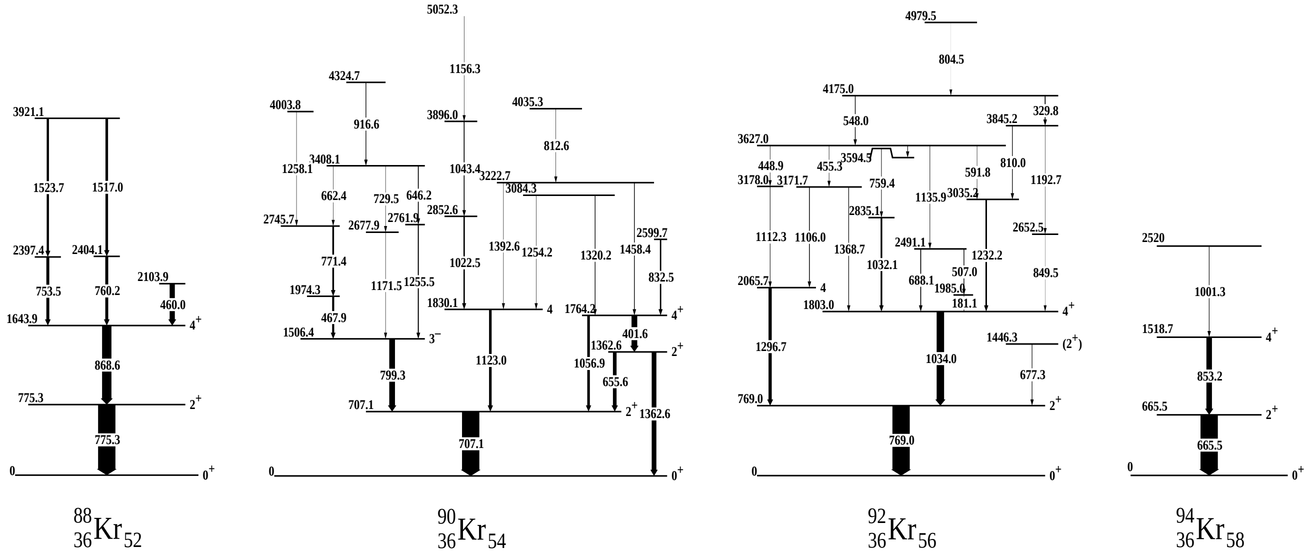

Fig. 4. Partial level schemes of $^{88\text{-}94}$Kr nuclei, as obtained in the present work.

tained are $P = +0.7(4)$ for the 799.3 keV transition in ^{90}Kr and $P = +1.0(5)$ for the 1034.0 keV transition in ^{92}Kr, indicating the electric character of both transitions.

Table 1. Angular correlations for pairs of transitions in Kr nuclei as obtained in the present work.The deduced transition multipolarities for transitions are shown in the last column.

Nucleus	Cascade (E_1 – E_2)	A_{22}/A_{00}	A_{44}/A_{00}	Multipolarity
^{88}Kr	775–868	0.13 ± 0.03	-0.09 ± 0.01	Q-Q
^{90}Kr	707–1056	0.08 ± 0.03	0.02 ± 0.01	Q-Q
	707–799	-0.20 ± 0.02	-0.02 ± 0.01	Q-D
	707–1123	0.10 ± 0.02	0.04 ± 0.01	Q-Q
	707–655	-0.23 ± 0.04	0.13 ± 0.02	Q-D
	799–468	0.12 ± 0.02	0.07 ± 0.01	D-D
	799–1255	0.13 ± 0.04	0.07 ± 0.02	D-D
	401–1362	0.13 ± 0.02	0.03 ± 0.01	Q-Q
	401–655	-0.03 ± 0.02	-0.03 ± 0.01	Q-D
^{92}Kr	769-1269	0.06 ± 0.03	0.07 ± 0.01	Q-Q
	769-1034	0.12 ± 0.01	0.03 ± 0.01	Q-Q
	769-677	-0.20 ± 0.06	0.07 ± 0.02	Q-D
^{94}Kr	666-854	0.09 ± 0.03	-0.11 ± 0.01	Q-Q

Partial level schemes of $^{88\text{-}94}$Kr nuclei, as obtained in the present work based on the coincidence data and multipolarity measurements, are shown in fig. 4.

The first excited states in $^{88\text{-}92}$Kr nuclei were previously assigned spin and parity 2^+ [3–6], which is consistent with our angular correlation data.

In the ^{88}Kr nucleus the two lowest transitions, of a stretched quadrupole character, define the 2^+ and 4^+ excitations at 775.3 keV and 1643.9 keV, respectively. Spins and parities of higher-lying states were not determined. A tentative 3^- spin and parity assignment to the 2103.9 keV level, proposed previously [3], is not very likely. In this work we observe the 460.0 keV transition in ^{88}Kr but it overlaps with the 459.3 keV transition in the complementary ^{156}Nd fragment, preventing angular correlation measurement for this transition. However, if the spin of the 2103.9 keV level was 3^-, one should observe a strong $E1$ transition to the 775.3 keV level, which is not seen in our data. A more likely spin and parity assignment for the 2103.9 keV level is 4^+.

In the ^{90}Kr nucleus we assign spin 4^+ to the 1764.2 keV level, for which a new, 1056.9 keV decay branch is found. We also confirm the 2^+ assignment to the 1362.6 keV level. The 1506.4 keV level is assigned spin and parity 3^-, due to the stretched $E1$ character of the 799.3 keV transition. The 1830.1 keV level is assigned spin $I = 4$.

In the ^{92}Kr one observes an excitation pattern similar to the one in ^{90}Kr, although no octupole excitation is seen here. Previous assignment of 3^- spin and parity to the 1803.0 keV level [5] is not correct since the 1034.0 keV transition is of a stretched E2 character, as shown by our angular correlation and linear polarisation data. We assign spin and parity 4^+ to the 1803.0 keV level. The 2065.7 keV level is also assigned spin $I = 4$ based on angular correlations data.

Finally, in the ^{94}Kr nucleus, for the lower two transitions angular correlations indicate stretched quadrupole character, thus fixing spin and parity 2^+ and 4^+ for the 665.5 keV and 1518.7 keV levels, respectively.

The study of the ground-state properties of Kr isotopes has been performed in the framework of relativistic mean-field (RMF) theory [11] and using the Nilsson-Strutinsky method, with the cranked Woods-Saxon average potential [12]. Both calculations suggest that quadrupole deformation for heavy Kr isotopes increases gradually from β_2 $\approx$0.06 for ^{88}Kr to $\beta_2 \approx 0.3$ for ^{94}Kr. This results agree with values of the quadrupole deformation parameter β_2, deduced from the mean charge radii ref. [2], using the droplet model [13]. However, as pointed out in refs. [2, 14], such model does not apply in spherical and weakly de-

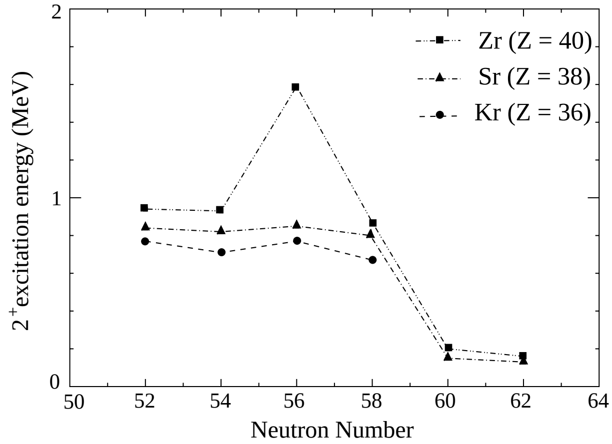

Fig. 5. Energies of the first excited, 2_1^+ state in the neutron-rich, even-even isotopes of Sr, Zr and Kr.

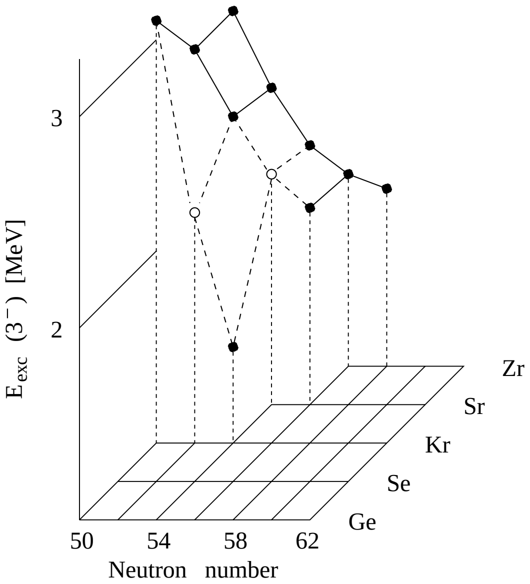

Fig. 6. Energies of the, 3^- excitation energies in the neutron-rich, even-even isotopes of Sr, Zr and Kr. Open circles mark the expected energies of 3^- excitations in ^{88}Kr and ^{92}Sr.

formed nuclei. Our results show that ^{88,90,92,94}Kr isotopes sustain a stable spherical shape, as illustrated in fig. 5, where the energies of the first 2^+ state are plotted versus neutron number for the even-even isotopes with $Z = 36$–40.

This conclusion is supported by by the overall excitation patterns observed in the ^{88,90,92,94}Kr nuclei, and in particular the $E(4_1^+)/E(2_1^+)$ energy ratios for these nuclei, which vary between 2.1 and 2.5, values characteristic of spherical vibrators.

Excitation energies of the 2_1^+ levels in Kr isotopes are very similar to those in the corresponding Sr and Zr nuclei. An exception is the 2_1^+ excitation energy in ^{96}Zr, which is significantly higher. High 2_1^+ excitation in ^{96}Zr has been interpreted as due to the combined effect of the $Z = 40$ and $N = 56$ subshell closures. These closures are often quoted in the literature. In fig. 5, however, there is no clear indication of the presence of the $Z = 40$, $Z = 38$ or $N = 56$ subshell closures, apart from the ^{96}Zr point. Neither are the 2_1^+ energies significantly higer at $N = 56$ than at $N = 54$ or $N = 58$ nor are they significantly higher in Sr nuclei than in their Kr isotones.

In this context it is interesting to look at the systematics of excitation energies of 3^- levels in these nuclei, now enriched by the newly found 3^- level at 1506.4 keV in ^{90}Kr, and the noticed absence of such level among near-yrast excitations in ^{92}Kr. In fig. 6 we show known 3^- excitation energies in nuclei from this region. In the ^{86}Kr nucleus the 3^- level has a rather high excitation energy of 3099 keV, which is due to the $N = 50$ shell closure. A rapid decrease of this energy with increasing neutron number to 1506 keV in ^{90}Kr can be interpreted as due to the growing $\nu(d_{5/2}h_{11/2})_{3^-}$ contribution to the octupole phonon. The non-observation of the 3^- level in ^{92}Kr, in the present work, suggests a significant increase of the 3^- energy at $N = 56$. This observation may indicate that the $N = 56$ subshell closure exists. In fig. 6 one can also notice features indicating the existence of the $Z = 40$ and, most likely, also the $Z = 38$ subshell closures. Despite the $\nu(d_{5/2}h_{11/2})_{3^-}$ contribution to the octupole phonon, the 3^- level is placed high in energy in Sr and Zr nuclei.

The newly found 3^- level in ^{90}Kr, with excitation energy significantly lower than in the neighbouring nuclei is a possible indication of a new region of increased octupole correlations, connected here with the mentioned $\nu(d_{5/2}h_{11/2})$ pair of $\Delta l = \Delta j = 3$ orbitals. It would be interesting to find the 3^- excitation energies in the neighbouring $N = 54$ isotones, ^{88}Se and ^{92}Sr. If the above interpretation is correct, the 3^- excitation energy in ^{92}Sr should be as high as in ^{94}Zr, while in ^{88}Se it should be as low as in ^{90}Kr.

In the $^{88\text{-}94}$Kr nuclei valence neutrons occupy the $\nu d_{5/2}$ and $\nu g_{7/2}$ orbitals, while eight valence protons fill the $\pi p_{3/2}$ and $\pi f_{5/2}$ orbitals. The yrast 2^+ as well as 4^+ excitations are observed at similar energies in these nuclei. This suggests that their structure is probably due to valence protons, since their excitation energies are not sensitive to changes in neutron number. The observed 2^+ and 4^+ excitations could be then members of the $(\pi f_{5/2}^4)_{0^+,2^+,4^+}$ multiplet. On the other hand, the valence neutrons on the $\nu d_{5/2}$ orbital, can produce a similar pattern. In the studied nuclei, one observes systematically non-yrast, 2_2^+ as well as 4_2^+ levels, which may correspond to neutron excitations. To answer what is the nature of these, as well as higher lying levels, requires further work, which is being conducted. More information about these nuclei will be published in forthcomming papers.

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