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Letter

First observation of excited states in the ^{110}Mo nucleus

W. Urban[1,2,a], T. Rząca-Urban[1], J.L. Durell[3], W.R. Phillips[3], A.G. Smith[3], B.J. Varley[3], I. Ahmad[4], and N. Schulz[5]

[1] Faculty of Physics, Warsaw University, ul. Hoża 69, PL-00-681 Warsaw, Poland
[2] Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS/Université Joseph Fourier, F-38026 Grenoble Cedex, France
[3] Schuster Laboratory, Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[4] Argonne National Laboratory, Argonne, IL 60439, USA
[5] Institut de Recherches Subatomiques UMR7500, CNRS-IN2P3 et Université Louis Pasteur, F-67037 Strasbourg, France

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Abstract. The ground-state band in ^{110}Mo has been observed for the first time. The band, comprising six levels, has been populated in the spontaneous fission of ^{248}Cm and studied by means of prompt γ-ray spectroscopy using the EUROGAM2 array. The ratio $E_{\mathrm{exc}}(4^+)/E_{\mathrm{exc}}(2^+)$ suggests that the deformation of ^{110}Mo is smaller than that in ^{108}Mo but may stabilize at higher neutron number, where an oblate shape is expected. The new data suggests that the deformation of Sr and Zr isotopes decreases above neutron number $N = 64$.

PACS. 23.20.Lv γ transitions and level energies – 21.60.Cs Shell model – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

In a recent theoretical study of neutron-rich nuclei from the $A \sim 110$ region [1] it has been stated that around neutron number $N = 70$, these nuclei undergo a deformation change from prolate to an oblate shape. Such a change in neutron-rich palladium isotopes was predicted in 1995 [2]. Subsequent experimental studies of these nuclei [3,4] did not support this expectation. According to ref. [4], up to $N = 72$ (^{118}Pd), palladium isotopes maintain a prolate shape, as indicated by the crossing frequencies in their rotational bands. The picture is similar for ruthenium isotopes, the second easiest chain of neutron-rich isotopes to study around $N = 70$.

The authors of ref. [1] pointed out that the most pronounced prolate-oblate deformation change is expected in the neutron-rich zirconium isotopes. In these nuclei strong prolate deformation develops for $N \geq 62$, while for $N \geq 72$ the oblate minimum in the potential energy becomes yrast and stable up to very high spins. These oblate Zr isotopes are, however, beyond reach at present. The heaviest Zr isotope with known excitations, ^{104}Zr$_{64}$, shows a prolate deformation at the saturation limit.

The prospects of experimental verification are better for molybdenum isotopes. Inspecting the $E(4^+)/E(2^+)$ ratio for isotopes with known excited levels, one sees a clear maximum of the deformation at $N = 64$, two neutrons before the middle of the $50 < N < 82$ shell. Reference [1] predicts that in ^{110}Mo$_{68}$ an oblate minimum in the nuclear potential develops at $\beta_2 \approx 0.22$. This minimum becomes the ground-state configuration in Mo isotopes with $N \geq 70$. It is therefore of interest to search for excited states in the ^{110}Mo nucleus, which till now are not known.

In this Letter we report on the first observation of excited states in ^{110}Mo. These results were obtained form the analysis of multiple coincidences between prompt γ-rays following the spontaneous fission of ^{248}Cm, measured using the EUROGAM2 array of anti-Compton spectrometers in Strasbourg. More informations about the experiment and the analysis methods are given in ref. [5].

Figure 1a) shows a γ-ray spectrum double-gated on the 1313 keV and 381 keV lines in ^{136}Xe, obtained from triple-gamma coincidences. It is expected that ^{136}Xe is the strongest fission-fragment partner to the ^{110}Mo nucleus. Apart from the known lines in ^{136}Xe, and the complementary Mo isotopes, lighter than ^{110}Mo, one can see a line at 213.7 keV. A spectrum double-gated on 213 keV and 1313 keV lines, shown in fig. 1b), indicates that the 213.7 keV transition belongs to a new Mo isotope because only lines of ^{136}Xe and new lines at 385.6 keV, 531.6 keV,

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[a] e-mail: `urban@fuw.edu.pl`

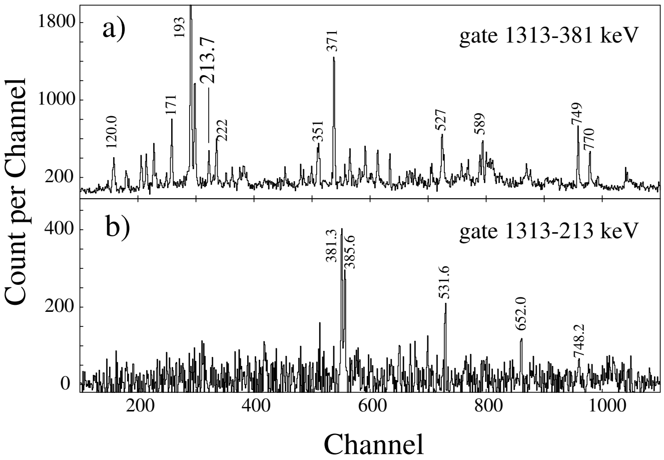

Fig. 1. Coincidence spectra of γ-radiation following the fission of ^{248}Cm, gated on lines in ^{136}Xe and ^{110}Mo. Lines are labeled with their energies in keV.

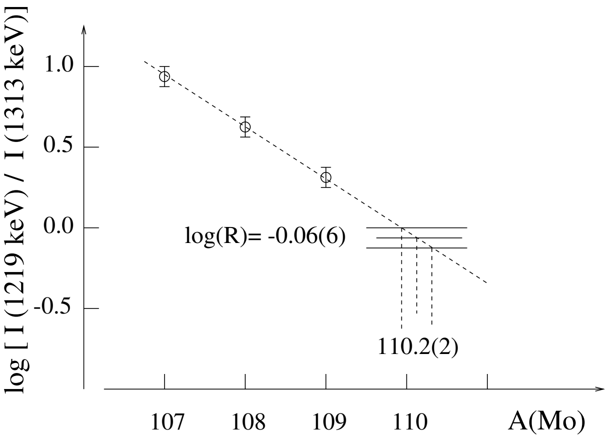

Fig. 2. A correlation between masses of Xe and Mo fission fragments from spontaneous fission of ^{248}Cm. See text for more explanations.

652.0 keV and 748.2 keV are seen in this spectrum. Further gating revealed that all these transitions are in a cascade and in coincidence with the 1313 keV and 381 keV lines in ^{136}Xe.

To identify the mass number of the isotope to which the new cascade belongs, we have calculated the ratio, R, of the intensity of the 1219 keV line in ^{137}Xe to the intensity of the 1313 keV line in ^{136}Xe, as observed in spectra double-gated on gamma lines belonging to various Mo isotopes. Due to the correlation between masses of the complementary fission fragments [6], the ratio R depends on the mass of the gated Mo isotope. In fig. 2 we show the ratio R as a function of mass of the gated Mo isotope. Because of large variation in R, we show $\log(R)$ values. The dependence is nearly linear. The dashed line represents a straight-line fit to the data points available for ^{107,108,109}Mo. We assume that it can be extrapolated to mass $A = 110$. The ratio for the new cascade is represented by a horizontal bar at $\log(R) = -0.06(6)$. The intersection of this value with a straight-line fit determines the mass of the Mo isotope to which the new cascade belongs. The experimental mass of 110.2(2) indicates that the new cascade belongs to the ^{110}Mo nucleus.

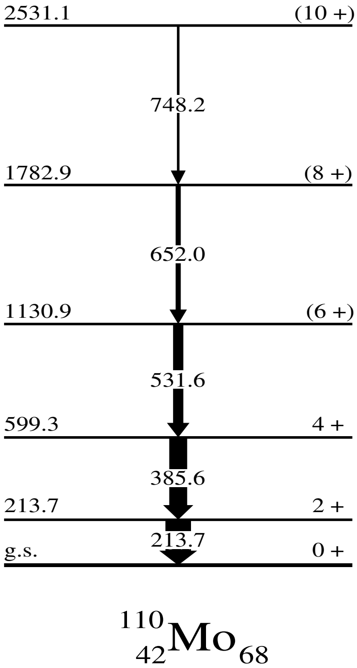

Fig. 3. Partial level scheme of ^{110}Mo, as obtained in the present work.

Table 1. Properties of γ transitions in ^{110}Mo, as observed in this work.

E_γ (keV)	I_γ (rel.)	A_2/A_0	A_4/A_0	Multi-polarity	Ref. E_γ (keV)
213.7	100(5)			$E2$	
385.6	50(5)	0.08(3)	−0.04(3)	$E2$	213.7
531.6	25(5)			($E2$)	
652.0	14(4)			($E2$)	
748.2	6(2)			($E2$)	

The proposed level scheme of ^{110}Mo is shown in fig. 3. We ordered the transitions in the cascade according to their intensities, as seen in the doubly gated spectra, shown in fig. 1. The intensities are given in table 1.

We have determined angular correlations between the lowest two transitions in the ground-state cascade in ^{110}Mo, using techniques described in [5,7]. We assumed that the first-excited state in ^{110}Mo, observed at 213.7 keV, has spin and parity $I^\pi = 2^+$, as commonly observed in even-even nuclei [8]. Consequently, the 213.7 keV transition is taken as the stretched quadrupole reference. The resulting correlation, shown in table 1, indicates that the 385.6 keV transition is also a stretched quadrupole ($\Delta I = 2$). For this transition we adopt an $E2$ multipolarity rather than $M2$, considering its prompt character. From this result we conclude that the second-excited level in ^{110}Mo, observed at 599.3 keV, has spin and parity 4^+.

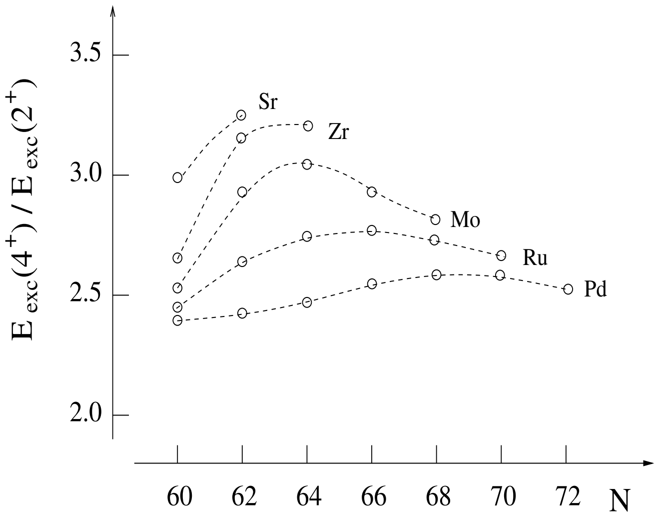

Fig. 4. The $E(4^+)/E(2^+)$ ratio for even-even nuclei of the $A \sim 110$ region. The data are form this work and refs. [3,6,9, 10]. Dashed lines are drawn to guide the eye.

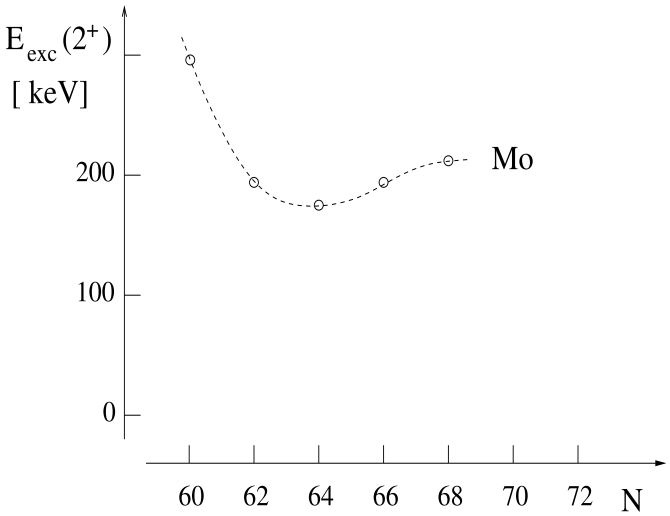

Fig. 5. The $E(2^+)$ excitation energy in even-even Mo nuclei of the $A \sim 110$ region. The data are form this work and refs. [6, 10]. The dashed line is drawn to guide the eye.

In addition, the 748.2 keV line shows some broadening. This is consistent with the assignment of spin 10^+ to the 2531.1 keV level. We refer here to the fact that levels with such spins have half-lives in a range of picoseconds, resulting in a Doppler broadening, as observed in previous analysis [11].

In fig. 4 we show the ratio of the lowest two excitation energies, $E(4^+)/E(2^+)$, in even-even nuclei of the $A \sim 110$ region, as a function of neutron number, N. Such a ratio is related to the deformation of the corresponding ground states. It is generally expected that the deformation should reach its maximum around the middle of the shell, here at $N = 66$. Figure 4 shows a wide maximum around $N = 66$ in Ru isotopes. It is, however, different for other isotopic chains. For Pd isotopes the maximum is centered two-to-four neutrons above the middle of the shell. For Mo isotopes, where we included the new result for ^{110}Mo, the $E(4^+)/E(2^+)$ ratio has a well-defined maximum seen at $N = 64$, two neutrons below the middle of the shell. At present there is no sufficient data to tell where the maximum of the deformation is located for Zr and Sr isotopes. It is possible, looking at fig. 4, that it may be located between $N = 62$ and $N = 64$.

One may interpret different positions of the maxima observed in fig. 4, using the calculations of ref. [1] and the results of other recent studies. In Sr and Zr isotopes with $N < 66$ a strong prolate deformation develops, driven by low-Ω subshells of the $h_{11/2}$ orbital [12–14]. It is well documented that this deformation saturates already at $N \sim 62$ [15–17]. Above the middle of the shell an oblate deformation is expected in Sr, Zr and Mo isotopes with $72 \leq N \leq 76$ [1]. This should be due to the population of high-energy subshells of the $h_{11/2}$ shell, which are driving nuclei towards an oblate shape as well as due to the rotational alignment of these high-j orbitals [1]. In between these two regions, around the middle of the shell, there may be a decrease of the deformation due to the shape transition from prolate to oblate. This may occur in nuclei where both prolate and oblate shapes are well developed, as is expected for Sr, Zr and Mo nuclei. There is a hint that this happens for Mo isotopes. It is seen more clearly on the plot of $E(2^+)$ excitation energy *vs.* N, shown in fig. 5. It is likely that the $E_{\mathrm{exc}}(2^+)$ values stabilize or even have another minimum above $N = 70$.

For ruthenium isotopes, the deformation peaks at the middle of the shell ($N = 66$). These nuclei are known to be triaxial [9], *i.e.* neither prolate nor oblate deformation is expected here.

In palladium nuclei ($Z = 46$), which are soft and weakly deformed due to the proximity of the $Z = 50$ shell, the prolate shape is not well developed at $N < 66$. On the other hand, due to the population of high-energy subshells of both proton $g_{9/2}$ and neutron $h_{11/2}$ shells, an oblate deformation is expected past the middle of the shell [1]. The deformation of even-even Pd isotopes, measured by the $E(4^+)/E(2^+)$ ratio, indeed increases for $N > 66$ reaching the maximum around $N = 68$. It will require more investigations to verify if this is a sign of the predicted oblate shape [1] or if, as claimed in ref. [4], the deformation of these nuclei is prolate also at $N > 66$. We note, that one may expect an increase of prolate deformation for $N > 70$ due to the presence of the deformation-driving, $1/2^-[541]$ intruder orbital, originating from the $f_{7/2}$ subshell (see fig. 1 in ref. [1]).

It is also interesting to look at the changes of the $E(4^+)/E(2^+)$ ratio as a function of the proton number, Z. This is shown in fig. 6 for $N = 60$, 62, 64 and 68 isotones. Figures 4 and 6 are, in a sense, complementary. In fig. 4 one has information for N below the middle of the shell, while in fig. 6 there are data for Z above the middle

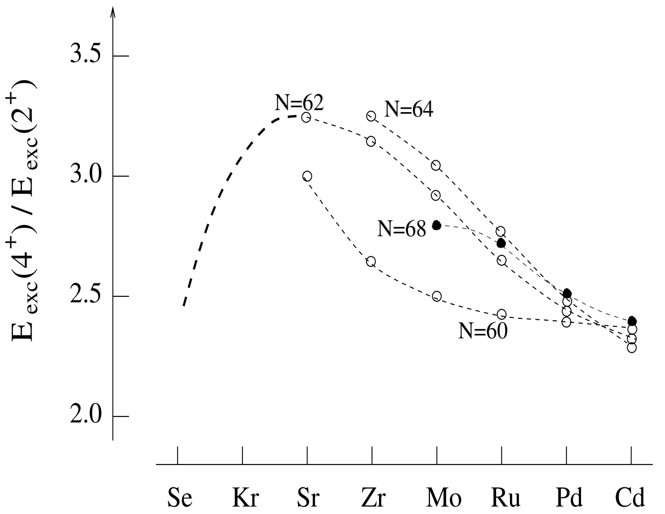

Fig. 6. The $E(4^+)/E(2^+)$ ratio for even-even nuclei of the $A \sim 110$ region. The data are form this work and refs. [3,6,9,10,18]. Dashed lines are drawn to guide the eye.

of the shell. Analogies between the two pictures provide hints about the evolution of the deformation in the region, as discussed below.

There is a pronounced gap at $Z = 34$ in the calculated level scheme of protons and there are no high-j, deformation-driving orbitals just below the $Z = 34$ gap [1,6]. The $Z = 34$ line is thus an analog of the $N = 56$ line. The $N = 56$ isotones are known to be spherical. It is expected, therefore, that selenium isotopes should be spherical or weakly deformed. Consequently, there should be a rather sudden increase of deformation from Se ($Z = 34$) to Sr ($Z = 38$), where the deformation is at its maximum. This is marked by the thick dashed line in fig. 6. The well-studied increase of the deformation between $N = 56$ and $N = 62$ in Sr and Zr isotopes is due to the population of low-Ω subshells of the $h_{11/2}$ neutron shell [15–17]. By analogy, the anticipated sudden onset of the deformation between $Z = 34$ and $Z = 38$ may be associated with the population of the 1/2[440] and 3/2[431] orbitals, originating from the $g_{9/2}$ proton shell, in agreement with the single-proton spectra calculated in refs. [1,6].

Another interesting conclusion from fig. 6, where we included the point for ^{110}Mo, is that for $N = 68$ isotones, the deformation seems to attain its maximum around $Z = 42$. Two interesting predictions can be made, assuming that the $N = 68$ systematics, which is quite regular, can be extrapolated. First, the deformation of $^{106}\mathrm{Sr}_{68}$ and $^{108}\mathrm{Zr}_{68}$ may be significantly lower than that observed for Sr and Zr nuclei at $N = 62$ and $N = 64$. This is in accord with our suggestion above that in Sr and Zr isotopes the deformation has its maximum between $N = 62$ and $N = 64$. The second, more general suggestion is that in the discussed region the maximum of the deformation extends along the line from ^{98}Sr up to ^{116}Pd. We note that this line coincides with the simultaneous filling of the $g_{9/2}$ proton and $h_{11/2}$ neutron shells. It is a challenge for the future studies to verify this picture.

We note at the end, that the newly found scheme of ^{110}Mo should help the future β^--decay studies of the yet unknown nucleus ^{110}Nb.

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