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ISOTONIC CHANGES OF NUCLEAR CHARGE RADII

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Изотонические изменения зарядовых радиусов ядер

Метод наименьших квадратов использован для комбинированного анализа экспериментальных данных по зарядовым радиусам из мюонных атомных спектров и по разностям зарядовых радиусов из лазерной спектроскопии. На его основе определены с большой точностью абсолютные величины зарядовых радиусов. Использована систематика для изотопных цепочек 26 элементов от $_{36}\mathrm{Kr}$ до $_{92}\mathrm{U}$ и получена информация об изотонических сдвигах в широкой области ядер.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1992

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Isotonic Changes of Nuclear Charge Radii

A least square fit method for combined analysis of experimental data for nuclear radii from muonic atom spectra and for charge radii changes from laser spectroscopy has been developed. On its basis absolute values of charge radii have been evaluated with high degree of accuracy A systematics for the isotope chains of 26 elements from $_{36}\mathrm{Kr}$ to $_{92}\mathrm{U}$ is created and information on isotonic shifts spanning over large nuclear chart distances is deduced.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1992

1. Introduction

The charge radius is one of the most important nuclear parameters. It depends on the effective nuclear interaction and thus can give some information about it. At present there is vast information about the nuclear charge radii changes with varying neutron number at constant proton number (isotopic shifts) extending far from stability line. This is achieved predominantly by application of laser spectroscopic methods in optical spectra measurements. These investigations allow to obtain information on isotopic shifts of other nuclear parameters as well: nuclear deformation, compressibility and thickness of surface layers.

It is of great interest to obtain also the data about changes of the above-mentioned parameters with varying proton number at constant neutron number (isotonic shifts). This is however difficult due to the lack of precision methods, which permit the determination of nuclear charge radii changes of neighbouring elements at variance with those of neighbouring isotopes. The information about isotonic shifts might be obtained from absolute values of charge radii $\langle r^2 \rangle$. But these values of $\langle r^2 \rangle$, deduced from spectra of muonic atoms as well as from electron scattering experiments, have as a rule insufficient accuracy, which may lead to some distortions of the evaluated $\langle r^2 \rangle$. Only for light elements ($Z<30$) the accuracy of measurements is good enough, and some definite conclusions about isotonic shifts have been obtained /1/.

In the present work a method is developed, based on the combined analysis of optical spectra and spectra of muonic atoms, which allows to determine $\langle r^2 \rangle$ values with high accuracy. A systematics of nuclear charge radii of a number of elements in a wide proton and neutron region has been performed. More definite conclusions on isotonic changes for charge radii have been obtained.

2. Analysis and results

For evaluating isotonic shifts one needs besides the optical isotopic shifts, an absolute $\langle r^2 \rangle$ value for at least one isotope in each chain, as an additional input parameter that serves as a link between different elements.

The accuracy of isotonic shifts determination might be improved, if $\langle r^2 \rangle$ values are known for a number of isotopes. Therefore a method for least square fit of charge radii and their isotopic shifts of the ground and isometric states of an element nuclear chain has been developed. The experimental data for nuclear charge radii from spectra of muonic atoms and for isotopic mean square charge radii changes from laser spectroscopy have been used. The fit for any radius and isotopic shift has not been performed with respect to one nucleus by taking into account one shift. It has been done by finding the optimal variant with the least error averaging the data for the radii of all isotopes and for the shifts of all isotopic pairs of the element. It gives the greatest possible number of shifts, i.e. between any isotope pair, with their errors with highest accuracy, even when only a part of the possible experimental data exists.

The method is realized in a programme version for personal computers. A systematics for the isotope chains of 26 elements from ${}_{36}$Kr to ${}_{92}$U is created.

Table 1 displays the obtained results for $\langle r^2 \rangle^{1/2}$ in the interesting regions about Z=40, 50, 64 and 82. The experimental $\langle r^2 \rangle^{1/2}$ data, used in the calculations, are given, too for comparison. Fuller table of $\langle r^2 \rangle^{1/2}$ values for wide region of nuclei will be presented in later publication.

The main peculiarities of the numerical results are the following:

a) The χ^2 - value, normalized to an average value of unity, is near to unity in most cases. The only exception is the very low χ^2 for Cd isotopes, which might be connected with the random errors for this case being nuclear lower than the reference errors (see ref. 4), since the last ones might include much larger systematic errors.

b) The calculated errors are more than $\sqrt{M}$ times (M is the number of the experimental $\langle r^2 \rangle^{1/2}$ - values used) lower than the experimental ones. This is related with the averaging procedure for $\langle r^2 \rangle$.

c) The differences between the fitted and the experimental values of $\langle r^2 \rangle^{1/2}$ are lower than errors.

3. Conclusion

The long chains of $\langle r^2 \rangle$ values extending far from stability which have been computed here in several regions of the nuclear chart provided us for the first time with a possibility of obtaining

Table 1

Values of charge radii

Element	Z	A	$\langle r^2 \rangle^{1/2}$ fit fm	$\langle r^2 \rangle^{1/2}$ exp fm	references $\langle r^2 \rangle^{1/2}$	$\Delta\langle r^2 \rangle$
Zr	40	90	4,2749(65)	4,623(8)	/2/	/3/
		91	4,2863(65)	4,309(22)		
		92	4,3021(67)	4,300(22)		
		94	4,3224(68)	4,332(22)		
		96	4,4362(60)	4,396(22)		
Mo	42	92	4,3319(18)	4,317(4)	/2/	/4/
		94	4,3589(16)	4,352(4)		
		95	4,3660(16)	4,362(4)		
		96	4,3819(16)	4,383(4)		
		97	4,3850(16)	4,387(4)		
		98	4,3997(17)	4,407(4)		
		100	4,4265(18)	4,443(4)		
Cd	48	106	4,5057(14)	4,566(3)	/2/	/5/
		108	4,5813(14)	4,581(3)		
		110	4,5961(14)	4,596(3)		
		112	4,6103(14)	4,611(3)		
		113	4,6131(14)			
		114	4,6238(14)	4,624(8)		
		115	4,6264(25)			
		116	4,6340(13)	4,634(3)		
Sn	50	112	4,5969(2)	4,5958(5)	/6/	/5/
		113	4,6032(2)			
		114	4,6113(2)	4,6103(5)		
		115	4,6157(2)			
		116	4,6261(1)	4,6261(5)		
		117	4,6309(1)	4,6320(6)		
		118	4,6399(1)	4,6395(5)		
		119	4,6439(1)	4,6448(6)		
		120	4,6521(1)	4,6522(6)		
		122	4,6630(2)	4,6633(6)		
		124	4,6723(2)	4,6736(6)		

Table 1 (continuation)

1	2	3	4	5	6	7
Ba	56	132	4,8280(6)		/2/	/5/
		133	4,8264(8)			
		134	4,8296(6)	4,8315(14)		
		135	4,8269(6)	4,8223(18)		
		136	4,8308(6)	4,8320(11)		
		137	4,8289(6)	4,8252(21)		
		138	4,8351(6)	4,8354(10)		
		140	468640(6)			
Sm	62	144	4,9581(36)	4,947(9)	/1/	/4/
		145	4,9705(36)			
		146	4,9848(36)			
		147	4,9947(39)			
		148	5,0091(36)	5,002(6)		
		149	5,0191(39)			
		150	5,0407(36)	5,045(6)		
		151	5,0559(40)			
		152	5,0837(37)	5,093(6)		
		153	5,0914(35)			
		154	5,1044(40)			
Cd	64	146	4,9835(51)		/1/,	/6/,/7/
		152	5,0791(13)			
		154	5,1227(12)	5,1221(41)		
		155	5,1320(12)	5,1265(35)		
		156	5,1418(12)	5,1413(30)		
		157	5,1446(12)	5,1431(35)		
		158	5,1562(12)	5,1583(23)		
		160	5,1710(12)	5,1723(21)		
Pb	82	204	5,4869(6)	5,486(1)	/1/	/4/
		205	5,4893(6)			
		206	5,4965(6)	5,4939(29)		
		207	5,5005(6)	5,504(1)		
		208	5,5072(6)	5,503(2)		
U	92	233	5,8230(27)	5,8158(66)	/8/	/9/
		234	5,8308(20)	5,8289(31)		
		235	5,8353(19)	5,8343(28)		
		236	5,8446(19)			
		238	5,8576(17)	5,8604(23)		

also isotonic shifts over large nuclear chart distances. Examples are presented for constant neutron number N about three proton number regions: Z=36-50 (fig. 1); Z=48-70 (fig. 2) and Z=72-82 (fig.3). No corrections for deformation contributions are included. The dependence of $\langle r^2\rangle^Z$ on Z in all the figures is with respect to a conveniently chosen reference value $\langle r^2\rangle^{Z_0}$. The following conclusions on the general trends of this dependence can be drawn:

1. The slope of the $\langle r^2\rangle^Z$ - dependence on Z is more abrupt than the slope of the $\langle r^2\rangle^N$ - dependence on N. The $\Delta\langle r^2\rangle^Z/$ Z slope varies from 0.1 fm² for heavy nuclei to 0.3 fm² for medium nuclei. On the other hand the $\langle r^2\rangle^N/$ N slope is around 0.06 fm².

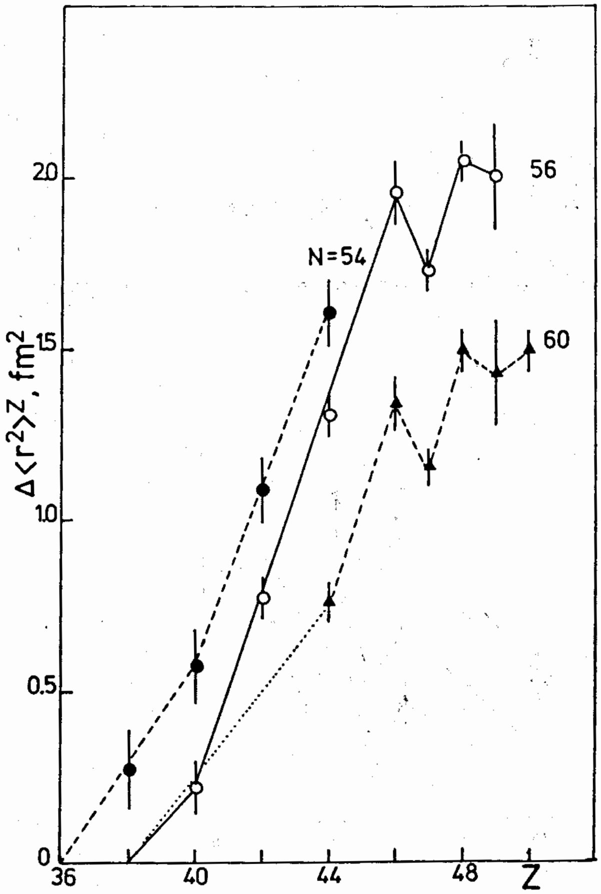

Fig. 1. $\Delta\langle r^2\rangle$ in the isotonic series N=54, 56, 60.

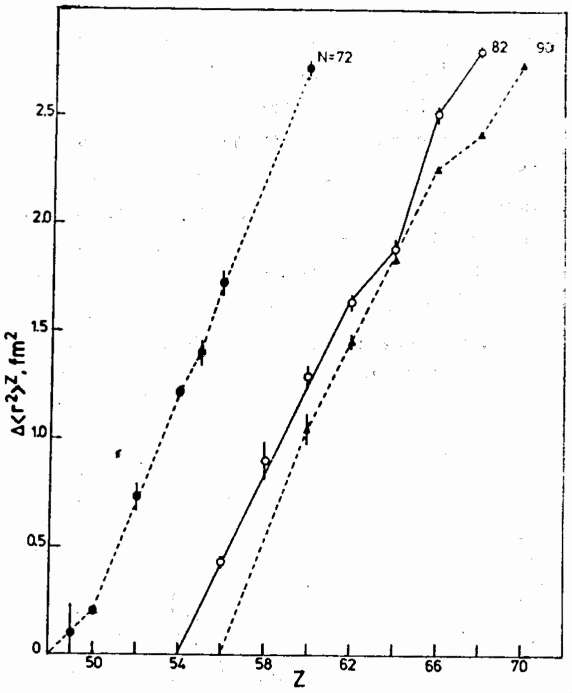

Fig. 2. $\Delta\langle r^2\rangle$ in the isotonic series N=72, 82, 90.

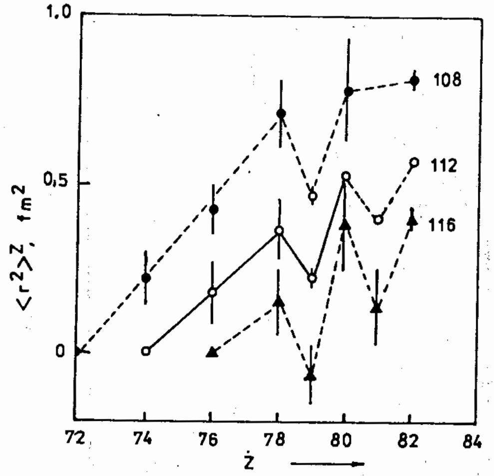

Fig. 3. $\Delta\langle r^2\rangle$ in the isotonic series N=108, 112, 116.

2. The behaviour of $\langle r^2\rangle^Z$ with increasing Z near to proton magic numbers (50, 82) is analogous to the behaviour of $\langle r^2\rangle^N$ near to neutron magic numbers: $\langle r^2\rangle$ is nearly constant.

3. The odd-even staggering of $\langle r^2\rangle^Z$ with respect to proton number Z has the same character as the odd-even staggering of $\langle r^2\rangle^N$ with respect to neutron number N: the adding of an odd proton causes a smaller increase of the charge radius than the adding of an even proton.

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