Physics of Atomic Nuclei, Vol. 67, No. 10, 2004, pp. 1846–1850. From Yadernaya Fizika, Vol. 67, No. 10, 2004, pp. 1872–1876.

Proceedings of the International Conference "Nuclear Structure and Related Topics"

New Data on Nuclear Subshells Obtained from the Analysis of the Information from the International Database on Nuclear Structure ENSDF*

I. N. Boboshin[1)], B. S. Ishkhanov[1),2)], and V. V. Varlamov[1)]**

Received January 21, 2004

Abstract—In the last decade, a large amount of experimental nuclear spectroscopy data was obtained. This is good progress really, but a new very serious problem appears. Due to significant systematic errors of the data, one is often forced to deal with very discrepant data and often it is difficult to obtain reliable information from them. To solve this problem and to remove the systematic errors, new technologies in working with the data were developed. Using these new technologies, one can obtain information with a high accuracy and reliability, and in many cases, new information has not been or could not be obtained experimentally. Below, an approach of this kind is presented concerning spectroscopic data on Ca and Zr isotopes. It is shown that the behavior of the energy of the first 2^+ level in Zr isotopes can be explained in the framework of a shell-model approach. A separation of the $2d_{5/2}$ subshell in ^{96}Zr (as is for the $1f_{7/2}$ subshell in ^{48}Ca) is found, so that the neutron number $N = 56$ becomes like a magic number for $Z = 40$. To explain a similarity in decaying properties of ^{48}Ca and ^{96}Zr, an additional interaction between closed structures consisting of 20 and 28 nucleons is proposed. Irregularities of the ground-state spin values in the K isotopic chain are explained in the framework of the shell-model approach by the inversion of the proton $1d_{3/2}$ and $2s_{1/2}$ orbitals. *© 2004 MAIK "Nauka/Interperiodica".*

1. DATABASE ENSDF

Contemporary large and complete databanks give real possibilities to solve the problem mentioned in the abstract. The oldest, large, and complete data bank on nuclear spectroscopy is the ENSDF (Evaluated Nuclear Structure Data File) [1]. This file contains nuclear structure and decay data for all known nuclides. For each nucleus, there is an adopted data set containing the recommended values of characteristics of the levels and gamma rays observed and data sets containing the "best" values obtained from various types of experiments. It has to be pointed out that new physical information can appear even at the stage of forming an evaluated "data set." For example, if an experiment gives two possible spin values $1/2$ or $3/2$ for a given level and another experiment gives $3/2$ or $5/2$ for the same level, an evaluator assigns unambiguously to this level the spin value $3/2$, etc.

An important feature of nucleon stripping and pickup experiments is that, as a rule, the total transferred momentum value j cannot be measured. The only exception is experiments with polarized particles. However, if spin and parity of the initial nucleus are equal to 0^+, the total transferred angular momentum is equal to that of a level feeding in the final nucleus. So it is very important to have accurate, reliable, and full data on spins of nuclides, and ENSDF provides this possibility.

2. THE METHOD OF PUTTING DATA ON NUCLEON PICKUP AND STRIPPING EXPERIMENTS IN ACCORDANCE TO EACH OTHER

The main idea of the method [2] is to correct the experimental data so that the constraints

$$S^+_{nlj} + S^-_{nlj} = 2j + 1 \qquad (1)$$

will be fulfilled for three single-particle orbitals closest to the Fermi energy, for which experimental data are presented with a maximum of completeness [3]. Moreover, the constraint

$$S^+_{nlj} + S^-_{nlj} \le 2j + 1 \qquad (2)$$

should hold for the remaining subshells, and

$$\left| \sum_{nlj} S^-_{nlj} - \sum_{nlj} S^+_{nlj} - A \right| \to 0 \qquad (3)$$

*This article was submitted by the authors in English.

1)Institute of Nuclear Physics, Moscow State University, Moscow, Russia.
2)Physics Faculty, Moscow State University, Moscow, Russia.
**e-mail: boboshin@depni.sinp.msu.ru

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Table 1. Energies of the first 2^+ states in even–even Zr isotopes

Nucleus	^{90}Zr	^{92}Zr	^{94}Zr	^{96}Zr
Number of neutrons N	50	52	54	56
$E(2^+, 1)$ [keV]	2186.50	934.48	918.75	1750.47

Table 2. Energies of the first 2^+ states in even–even Ca isotopes

Nucleus	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca
Number of neutrons N	20	22	24	26	28
$E(2^+,1)$ [keV]	3904.50	1524.61	1157.02	1346.00	3831.72

for all the subshells. Here, $S^{\mp}_{nlj}$ are sums of the individual spectroscopic factors $S^{\mp}_{nlj}(E_x)$ of levels with energies E_x; the upper signs "+" and "−" denote nucleon stripping and pickup, respectively; the sum in (3) is taken over valent and upper subshells in the first term and over the lower subshells in the second one; A is a total number of corresponding nucleons (protons or neutrons) in a nucleus. The essence of Eq. (3) is that a residual interaction does not change the total number of nucleons in a nucleus. To this aim, two degrees of freedom are used: (i) a new normalization condition for experimental data is introduced ($S^+_{nlj}(E_x) \to n^+ S^+_{nlj}(E_x)$, $S^-_{nlj}(E_x) \to n^- S^-_{nlj}(E_x)$); (ii) the whole known information about spins of the final states is taken into account, and moreover, all possibilities should be investigated for states with unknown spins.

The codes ARES were developed on the basis of the described procedures.

As a result, intervals for factors n^+ and n^- as well as for j values are determined. More reliable values of spectroscopic factors allow one to avoid a discrepancy between various experimental data, both pickup data and stripping data. Nucleon occupation probabilities of single-particle orbitals

$$N_{nlj} = \frac{[S^-_{nlj} + (2j+1-S^+_{nlj})]}{2(2j+1)} \tag{4}$$

and single-particle energies

$$-E_{nlj} = (1-N_{nlj})[B(A+1) - e^+_{nlj}] + N_{nlj}[B(A) + e^-_{nlj}] \tag{5}$$

are determined by using the improved spectroscopic factors. In Eq. (5), $B(A)$ and $B(A+1)$ are separation energies of a corresponding nucleon in a target nucleus and in a nucleus with one added nucleon; $e^{\pm}_{nlj}$ are centroids of the spectroscopic factor distributions.

Such kinds of results were obtained for nuclides ^{40,42,44,46,48}Ca, ^{46,48,50}Ti, ^{50,52,54}Cr, ^{54,56,58}Fe, ^{58,60,62,64}Ni, ^{64,66,68,70}Zn, ^{90,92,94,96}Zr, and ^{116,118,120}Sn, both for neutron and proton orbitals.

3. IS ^{96}Zr A MAGIC NUCLEUS?

In Table 1, we show the energies of the first 2^+ states in ^{90,92,94,96}Zr isotopes. Their maximal values for $N = 50$ and $N = 56$ are seen very clearly. The maximum at $N = 50$ has an ordinary explanation, because $N = 50$ is a well-known magic number. However, the maximum at the neutron number $N = 56$ requires a special explanation.

Both neutron and proton subshells were a subject of investigation from the point of view of one-nucleon transfer reaction data with the method described above. Neutron single-particle energies are displayed in Fig. 1. With increasing in N, one can see a lowering of the $2d_{5/2}$ subshell from the upper shell $N = 50$–82, so that, in ^{96}Zr, the subshell becomes well separated from it. Since in ^{96}Zr the neutron subshell $2d_{5/2}$ is closed, $N = 56$ becomes somewhat like a magic number. It is necessary to note that a similar

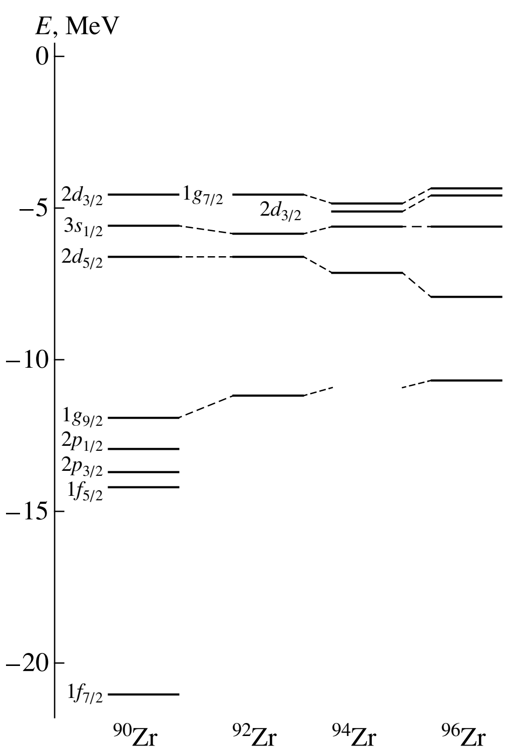

Fig. 1. Neutron subshells in ^{90,92,94,96}Zr isotopes.

Table 3. Nucleon occupation probabilities N_{nlj} and single-particle energies $-E_{nlj}$ (in MeV) of proton orbits in nuclei ^{90,92,94,96}Zr

nlj		^{90}Zr	^{92}Zr	^{94}Zr	^{96}Zr
$1g_{9/2}$	N_{nlj}	0.06(5)	0.08(5)	0.09(5)	0.00(0)
	$-E_{nlj}$	5.41(54)	4.98(142)	6.74(80)	7.48(75)
$2p_{1/2}$	N_{nlj}	0.58(5)	0.49(3)	0.75(5)	0.81(5)
	$-E_{nlj}$	6.97(70)	7.66(77)	9.37(94)	10.59(106)
$1f_{5/2}$	N_{nlj}	1.00(2)	1.00(2)	1.00(2)	0.94(5)
	$-E_{nlj}$	10.37(110)	10.93(110)	11.49(115)	12.17(122)
$2p_{3/2}$	N_{nlj}	–	–	0.87(5)	–
	$-E_{nlj}$	–	–	11.11(112)	–

picture of a separation of the subshell $1f_{7/2}$ in Ca isotopes was found earlier [4]. The neutron number $N = 28$ was suggested for consideration as a magic one (Fig. 2). Correspondingly, the two maxima of the energies of the first 2^+ states at the neutron numbers $N = 20$ and $N = 28$ are observed in Ca isotopes as well (see Table 2).

In Table 3, we present results of our investigations of proton subshells in Zr isotopes. Here, the essential peculiarity is seen in occupation probabilities of the proton $1g_{9/2}$ orbital. Whereas the occupation probabilities in ^{90,92,94}Zr are close to 0.1 (thus corresponding to one proton in the $1g_{9/2}$ orbital), this probability appears to be exactly zero in ^{96}Zr. This follows from distributions of single-proton spectroscopic factors over final states in Y isotopes. While in ^{89,91,93}Y one can observe one-proton transfers with $l = 4$, $j = 9/2$ and spectroscopic factors $S^-(E_x) = 0.9$–1.3 to levels in the excitation energy range 0.5–0.9 MeV, similar transfers to the states of ^{95}Y are not observed at all. It means that a rearrangement of nuclear structure takes place in ^{96}Zr so that this nucleus becomes stiffer and, probably, its shape becomes closer to a spherical one. This feature is typical for a magic nucleus; thus, we conclude that $N = 56$ is a magic number in the nucleus with $Z = 40$.

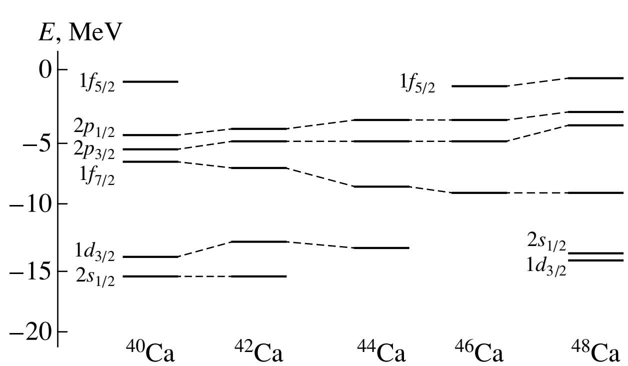

Fig. 2. Neutron subshells in ^{40,42,44,46,48}Ca isotopes.

It is worthwhile to stress that the number $N = 56$ is not a magic one combining with other Z values, i.e., in Mo, Ru isotopes, etc. This fact forces us to pay attention to a relation between numbers 40 and 56. Let us note that 56 is equal to 2×28, and 40 is equal to 2×20, and then we follow along the way of an analogy between ^{96}Zr and ^{48}Ca. Indeed, the analogy goes quite far if we consider data on decays of these two nuclei. For example, both nuclei, ^{48}Ca and ^{96}Zr, decay via the $2\beta^-$ mode—quite rare decay—which exhausts less than 1% of all types of decay, and $T_{1/2}(^{48}\mathrm{Ca}) = (4.2^{+3.3}_{-1.3}) \times 10^{19}$ yr [5] and $T_{1/2}(^{96}\mathrm{Zr}) = (2.1^{+0.8(\mathrm{stat.})}_{-0.4(\mathrm{stat.})} \pm 0.2(\mathrm{syst.})) \times 10^{19}$ yr [6]. This is really a fantastic coincidence: one nucleus is twice as large as the other one, and both of them decay via the same rare mode. Moreover, the half-life of the heavier nucleus is exactly equal to one-half of the lighter.

All these facts can be explained if one supposes the existence of an additional interaction between closed structures $Z = 20$ and $N = 28$ in the nuclei ^{48}Ca and ^{96}Zr. The nucleus ^{48}Ca is known as a neutron-rich nucleus, although it is quite stable. Interaction between the proton $Z = 20$ and the neutron $N = 28$ closed structures can be responsible for this specific stability.

At least two heuristic schemes of a coupling between proton and neutron subsystems can be proposed in the framework of the above assumption: a compound cluster model and a "nuclear crystal" model. The first model (see Fig. 3) supposes two levels of interactions of cluster-like structures. The interaction $\mathcal{A}$ couples $Z = 20$ and $N = 28$ structures to ^{48}Ca, and its destruction leads to $2\beta^-$ decay with

Table 4. Nucleon occupation probabilities N_{nlj} (upper numbers) and single-particle energies $-E_{nlj}$ (in MeV) (lower numbers) of proton subshells in nuclei ^{40,42,44,46,48}Ca

nlj	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca
$1f_{5/2}$	–	–	–	–	0.00
	–	–	–	–	3.81 (12)
$2p_{1/2}$	0.00	–	–	–	0.01 (1)
	−2.38 (24)	–	–	–	2.35 (68)
$2p_{3/2}$	0.09 (0.02)	0.02 (1)	0.05 (2)	–	0.01 (1)
	0.73 (29)	1.30 (18)	4.99 (51)	–	3.95 (53)
$1f_{7/2}$	0.06 (2)	0.08 (3)	0.13 (3)	0.02 (2)	0.02 (2)
	1.67 (22)	4.09 (45)	7.68 (78)	7.89 (99)	8.62 (100)
$1d_{3/2}$	0.97 (3)	0.76 (7)	0.72 (7)	0.94 (4)	0.94 (5)
	9.52 (152)	10.03 (150)	10.81 (108)	13.53 (138)	15.96 (100)
$2s_{1/2}$	1.00	0.90 (5)	0.77 (7)	0.93 (4)	0.84 (9)
	10.94 (109)	>11.29	11.39 (114)	13.94 (139)	14.41 (158)
$1d_{5/2}$	0.96 (2)	–	–	–	–
	14.32 (143)	–	–	–	–

the half-life 4.2×10^{19} yr. The interaction $\mathcal{B}$ couples "clusters" ^{48}Ca to the ^{96}Zr nucleus. The interaction $\mathcal{B}$ is supposed to be stronger than the interaction $\mathcal{A}$, and destroying one of the two $\mathcal{A}$ interactions leads to destruction of the whole system and to $2\beta^-$ decay with the total half-life 2.1×10^{19} yr. The second model supposes a two-valent coupling between $Z = 20$ and $N = 28$ structures in ^{48}Ca (Fig. 4*a*). The ^{96}Zr nucleus is constructed from these two-valent structures like a molecule (Fig. 4*b*). Thus, in both cases, ^{48}Ca and ^{96}Zr, one gets systems with additional stiffness that could be characterized as "nuclear crystal."

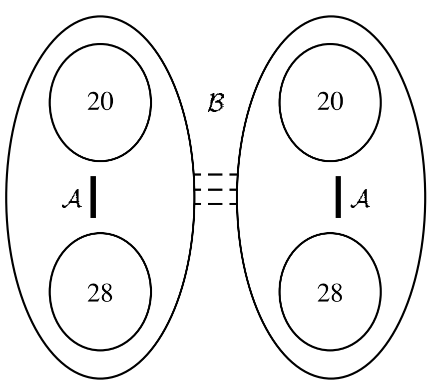

Fig. 3. A compound cluster model of ^{96}Zr.

4. PROTON SUBSHELLS IN Ca ISOTOPES

In Table 4, one-nucleon occupation probabilities as well as single-particle energies of proton orbitals in nuclides ^{40,42,44,46,48}Ca are displayed. One can observe the inversion of the $1d_{3/2}$ and $2s_{1/2}$ subshells in the ^{48}Ca isotope. This peculiarity explains irregularities in spin-parity values of the ground states of K isotopes: in nuclei ^{39,41,43,45}K, the ground states have $J^\pi = 3/2^+$, whereas in ^{47}K the ground state has $J^\pi = 1/2^+$. To describe the placement of proton subshells in ^{48}Ca and, in particular, the inversion of

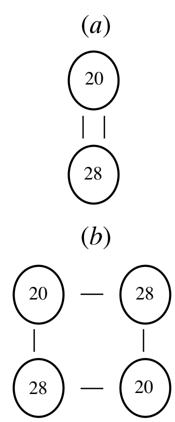

Fig. 4. A two-valent coupling model: (*a*) ^{48}Ca and (*b*) ^{96}Zr.

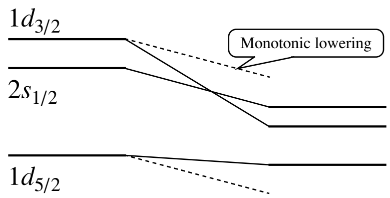

Fig. 5. For the explanation of the inversion of proton $1d_{3/2}$ and $2s_{1/2}$ orbitals in ^{48}Ca.

$1d_{3/2}$–$2s_{1/2}$ subshells, it was assumed that proton spin–orbit splitting decreases in this nucleus (see Fig. 5). This hypothesis was tested by calculations within a dispersion optical model for ^{40,42,44,46,48}Ca [7] and it was shown that this assumption allows one to describe the inversion adequately.

5. CONCLUSIONS

On the basis of the nuclear spectroscopy data bank ENSDF, new interesting information about the single-particle structure of Zr and Ca isotopes is obtained.

The most important conclusions are the following:

(i) The behavior of the energies of the first 2^+ levels in Zr isotopes is explained in the framework of a shell-model approach. A strong separation of the neutron $2d_{5/2}$ subshell in ^{96}Zr (as is with the $1f_{7/2}$ subshell in ^{48}Ca) is found, so that the neutron number $N = 56$ can be considered as a magic one in the nucleus with $Z = 40$. To explain some correlations in decay properties of ^{48}Ca and ^{96}Zr, an additional interaction between closed structures of 20 and 28 nucleons is proposed.

(ii) Irregularities of the ground-state spins along the K isotopic chain are explained in the framework of a shell-model approach by the inversion of the $1d_{3/2}$ and $2s_{1/2}$ proton orbitals.

ACKNOWLEDGMENTS

We acknowledge fruitful discussions with and help from Prof. E.A. Romanovsky and Dr. O.V. Bespalova.

Our research was carried out at the MSU SINP Department of Electromagnetic Processes and Atomic Nuclei Interaction and supported in part by the President of Russia grant no. SS-1619.2003.2 and the Russian Foundation for Basic Research, project no. 03-07-90431.

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