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Analysis of Single-Particle Energies of the Neutron States in the ^{64,66,68,70}Zn Isotopes within a Mean Field Model with Dispersive Optical Potential

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Abstract—The dynamics of the shell parameters of $^{64, 66, 68, 70}$Zn nuclei close to the Fermi energy, obtained by the joint evaluation of data from the stripping and pick-up reaction of a nucleon on one and the same nucleus, demonstrates how the difference between the neutron single-particle spectra of the levels of ^{70}Zn and ^{68}Ni nuclei with the number $N = 40$ arises. The experimental data are analyzed within a mean field model with dispersive optical potential. The calculation results describe very well the dimunution of the energy gap between the $1g_{9/2}$ and $2p_{1/2}$ levels in Zn isotopes, in comparison with Ni isotopes.

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INTRODUCTION

Studies of the manifestation and disappearance of the magic properties of nuclei with a change of their nucleon number are one line of current interest in modern nuclear physics. It has thus been discovered that in addition to magic nuclei with the classical numbers $N, Z = 2, 8, 20, 40, 50, 126$, nuclei (both stable and unstable) with new, non-classical magic numbers (e.g., ^{54}Ca with $N = 34$ and ^{96}Zr with $N = 56$) have the property of magicity as well. Such nuclei are often isolated; i.e., the magic properties of the nucleus with a new magic number N are revealed only in combination with a definite Z value (a so-called "magic pair") [1].

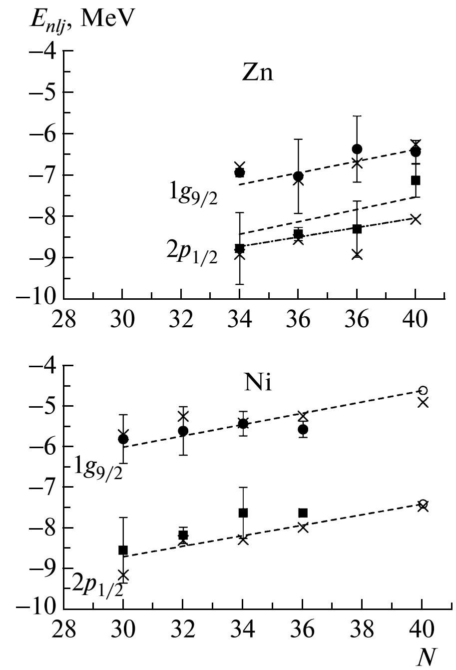
The number $N = 40$ corresponds to a filled shell in the oscillator potential, and the ^{90}Zr and ^{68}Ni nuclei exhibit magic properties. The ^{70}Zn nucleus has no such properties (see Fig. 12 in [1]). One of the characteristic features of magic nuclei is the larger gap Δ between the last occupied and the first free single-particle levels, compared to that of neighboring nuclei. The ^{70}Zn nucleus has 40 neutrons and differs from ^{68}Ni by two protons. The question therefore arises of how the addition of two protons to the even-even nickel isotopes affects the dynamics of the single-particle neutron spectra.

The experimental shell parameters, occupation probabilities $N_{nlj}^{\exp}$, and single-particle energies $E_{nlj}^{\exp}$ of the neutron states close to the Fermi energy E_F of the $^{64, 66, 68, 70}$Zn isotopes are given in [2]. An analysis of the obtained shell parameters allowed us to determine the characteristics of the neutron filling of the subshells of these nuclei, and to demonstrate their relationship using the available data on the energies of the first excited 2^+ states and on the deformation parameters. According to the shell model without configuration mixing, the neutron $2p_{1/2}$ state in ^{70}Zn should be completely filled and the $1g_{9/2}$ state should be completely free. According to [2], the considerable increase in the spectroscopic factors of the $9/2^+$ states in $^{63, 65, 67, 69}$Zn isotopes indicates that the occupation of the $1g_{9/2}$ subshell in $^{64, 66, 68, 70}$Zn increases and in the ^{70}Zn nucleus reaches a value of around two neutrons. It was found that the gap between the neutron $2p_{1/2}$ and $1g_{9/2}$ states was far less than that in $^{70}_{30}$Zn$_{40}$. It was concluded that the number $N = 40$ in the $^{70}_{30}$Zn$_{40}$ nucleus is not magic, while the $^{68}_{28}$Ni$_{40}$ nucleus exhibits magic properties.

This work is devoted to a comparative analysis of the single-particle energies of the $2p_{1/2}$ and $1g_{9/2}$ states and the energy gap between them in the $^{58, 60, 62, 64, 68}$Ni and $^{64, 66, 68, 70}$Zn isotopes. The analysis is performed within a mean field model with a dispersive optical potential constructed according to the method in [3].

EXPERIMENTAL

To date, the most reliable ranges of the change in $E_{nlj}^{\exp}$ energies and $N_{nlj}^{\exp}$ occupation probabilities, allowing for the incompleteness of experimental information on the spins and parities of the excited nuclear states, were obtained in [2] for Zn isotopes and in [4] for Ni isotopes, thanks to the upgrading [5] of the software component in the joint evaluation of data from the stripping and pick-up reaction of a nucleon. The figure shows the $E_{1g_{9/2}}^{\mathrm{exp}}$ and $E_{2p_{1/2}}^{\mathrm{exp}}$ energies of the neutron states of Zn and Ni isotopes from [2, 4]. Only the errors due to the uncertainty of the spin and parity values are shown in the figure (the errors in the renormalized spectroscopic factors of the states are about ≈10%). We performed a linear extrapolation of the $E_{1g_{9/2}}^{\mathrm{exp}}$ and $E_{2p_{1/2}}^{\mathrm{exp}}$ energies under the assumption that the slopes of their mass dependences in Zn and Ni isotopes were close, and obtained an estimate more reliable than the one in [6] of the energies of these states in the unstable ^{68}Ni nucleus: $E_{1g_{9/2}}^{\mathrm{calc}} = -4.6(5)$ MeV (the value remained the same as in [6]), and $E_{2p_{1/2}}^{\mathrm{calc}} = -7.4(5)$ MeV ($E_{2p_{1/2}}^{\mathrm{calc}} = -7.8(8)$ MeV [6]). It should be noted we were able to perform this extrapolation within the errors due to the uncertainty of spin and parity values.



Single-particle energies of the $1g_{9/2}$ and $2p_{1/2}$ subshells of $^{64, 66, 68, 70}$Zn and $^{58, 60, 62, 64, 68}$Ni nuclei. Black dots represent the experimental data; white dots, the estimates of this work. Crosses represent our calculations with the DOP. The dashed line shows the linear approximation at four points; the dashed-dotted line, the linear approximation at three points (see the text).

A mean field model with dispersive optical potential (DOP) [7] was successfully used to describe the single-particle structure of nuclei (see [3]). This model allows one to use a unified approach to describing the single-particle characteristics both of the low-lying states of nucleons and of the states close to E_F, along with the data on the scattering of nucleons by a nucleus. The model offers naturally-arising opportunities for tracing the dynamics of the single-particle structure of nuclei and for extrapolations to the region of unstable nuclei.

In this work, the neutron DOP of the $^{64, 66, 68, 70}$Zn nuclei was determined using the method in [3]. This method is based on the regularities in the imaginary part of the systematics [8] of the global parameters of the traditional (nondispersive) optical potential. The geometric parameters a_d, r_s, a_s, r_{so}, and a_{so} (here and below, we use the notations in [3]) were established in accordance with [8]. The a_{HF} parameter was equal to the a_d value [8] for all of the all studied isotopes.

The r_{HF} and r_d parameters were found by a grid search in order to reach the minimum of the value χ^2 (see expression (8) in [3]). The χ^2 value was calculated with the total error of the E_{nlj}^{exp} values due to the errors in the spectroscopic factors (≈10%) and the uncertainty in spins and parities. The energy dependence of the imaginary part of the DOP was approximated by formula (4) from [3] with $n = 4$ and $E_0 \neq E_F$. Its parameters (β_I and E_0) were varied to describe the E_{nlj}^{exp} data in the best way possible. The depth parameter V_{so} of the spin-orbit potential was varied as well. The parameters α_I and β_s were determined according to [3] by means of systematics regularities [8].

To find the slope parameter γ of the exponential energy dependence of the DOP's Hartree–Fock component, the energy value of the deepest $1s_{1/2}$ level was estimated to be −60 MeV for $^{64, 66, 68, 70}$Zn nuclei. The E_{F} energy was defined as the energy at which the N_{nlj} occupation probability approximating the experimental data reaches a value of 0.5. The $V_{HF}(E_F)$ parameter was found in describing the E_{nlj}^{exp} values closest to E_F. The parameter values of the neutron DOP of the

Table 1. Parameters of the neutron DOP of ^{64,66,68,70}Zn nuclei

DOP parameters	^{64}Zn	^{66}Zn	^{68}Zn	^{70}Zn
α_I	86.0	84.5	83.0	82.0
β_S	55	54	60	60
r_s	1.203	1.204	1.205	1.206
E_F	−10.5	−8.75	−8.5	−8.0
$V_{HF}(E_F)$	47.88	47.00	46.60	44.93
γ	0.435	0.420	0.423	0.435
r_{HF}	1.279	1.278	1.278	1.277
r_d	1.320	1.278	1.278	1.277
V_{so}	7.0	7.0	6.0	7.0
r_{so}	1.024	1.025	1.027	1.028

Note: The α_I values are given in MeV fm^3; E_F, $V_{HF}(E_F)$, and β_S, in MeV; V_{so}, in MeV fm^2; r_{HF}, r_d, r_s, and r_{so}, in fm; γ is a dimensionless parameter; β_I = 0.7 MeV, E_0 = −3 MeV, $a_{HF} = a_d$ = 0.534 fm, a_s = 0.668 fm, and a_{so} = 0.59 fm.

Table 2. Single-particle energies (MeV) of the neutron subshells of ^{64,66,68,70}Zn nuclei

Subshell	^{64}Zn		^{66}Zn		^{68}Zn		^{70}Zn	
	$E_{nlj}^{\exp}$	E_{nlj}^{DOP}	$E_{nlj}^{\exp}$	E_{nlj}^{DOP}	$E_{nlj}^{\exp}$	E_{nlj}^{DOP}	$E_{nlj}^{\exp}$	E_{nlj}^{DOP}
$1g_{9/2}$	6.91(69)	6.77	7.00(70)	7.09	6.34(64)	6.68	6.41(64)	6.23
$2p_{1/2}$	8.75(123)	8.89	8.40(85)	8.53	8.289(107)	8.89	7.10(71)	8.04
$1f_{5/2}$	9.95(103)	9.24	9.36(94)	8.86	10.19(112)	9.64	9.78(120)	8.43
$2p_{3/2}$	11.11(117)	10.39	10.76(107)	10.09		10.26	9.62(96)	9.82
χ^2		0.22		0.18		0.28		0.75

^{64,66,68,70}Zn nuclei are given in Table 1. The energy E_{nlj}^{DOP} calculated in solving the Schroedinger equation with the DOP and corresponding $\chi^2 < 1$ values are given in Table 2, where they are compared to the experimental data from [2].

Note the considerable difference of the gaps Δ between the $2p_{1/2}$ and $1g_{9/2}$ subshells in the Ni and Zn isotopes (figure). The experimental values and those calculated with the DOP gap Δ values are given in Table 3. The average gap values $\langle\Delta^{\exp}\rangle = 2.47$ (60) and 1.46 (80) MeV for Ni and Zn isotopes, respectively. These values are described well with the DOP: $\langle\Delta^{DOP}\rangle = 2.94$ and 1.89 MeV for Ni and Zn isotopes, respectively. The experimental gap $\langle\Delta^{\exp}\rangle$ was reduced by a factor of 1.7 upon the transition from Ni to Zn; the calculated gap, by a factor of 1.5.

A particularly strong reduction in the gap $\Delta^{\exp}$ is observed for ^{70}Zn. It should therefore be noted that the initial data on the spectroscopic factors of the pick-up reaction (which was further subjected to renormalization in [2]) were obtained for this nucleus in the 1960s (see the reference in [2]) in analyzing the reaction cross-section of (^{3}He, α) by the distorted wave approximation. The results of such analysis depend strongly on the choice of the optical potential parameters of ^{3}He and α [9], which were not sufficiently well known at that time; the total error $\Delta^{\exp}$ in ^{70}Zn can therefore exceed the one determined in [2]. The figure thus shows both a dashed line drawn through all of the experimental $E_{2p_{1/2}}^{\exp}$ values for the Zn isotope and a dashed-and-dotted line drawn through the $E_{2p_{1/2}}^{\exp}$ values for the ^{64,66,68}Zn isotopes.

Table 3. Energy gap Δ (MeV) between the neutron $2p_{1/2}$ and $1g_{9/2}$ states in Ni and Zn isotopes

Nucleus	$\Delta^{\exp}$	Δ^{DOP}	Nucleus	$\Delta^{\exp}$	Δ^{DOP}
^{58}Ni	2.74 (100)	3.46	^{64}Zn	1.84 (90)	2.12
^{60}Ni	2.57 (60)	3.06	^{66}Zn	1.40 (90)	1.44
^{62}Ni	2.20 (70)	2.88	^{68}Zn	1.94 (100)	2.21
^{64}Ni	2.06 (20)	2.75	^{70}Zn	0.68 (50)	1.81
^{68}Ni	2.80 (60)	2.57			

CONCLUSIONS

Even if we allow for a possible large error in the gap value $\Delta^{\exp}$ for ^{70}Zn, the neutron shell parameters of ^{64,66,68,70}Zn nuclei obtained in [2] testify to the disappearance within them of the magicity of the number $N = 40$. Our analysis of the obtained data within a mean field model with the DOP allowed us to fit the calculated single-particle energies with the experimental energies within the limits of the error of the latter.

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