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E4-84-330

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DAMPING OF HIGHLY-EXCITED SINGLE-PARTICLE MODES IN ODD-A NUCLEI NEAR ^{90}Zr

Submitted to "ЯФ"

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1984

1. INTRODUCTION

Studies of high-lying excitations of odd-A nuclei in a variety of one-nucleon transfer reactions which were started more than ten years ago, have raised our understanding of nuclear structure to a great extent. New types of resonance-like structures at energies 4-20 MeV have been observed /1,2/. The experiments with polarized beams have made unambiguous spin assignment of these structures possible. The comparison of the experimental data with the theoretical predictions helps us to check the parameters of the nuclear average potential and to understand the mechanism of damping of the high-lying single-particle and single-hole modes.

A bulk of experimental data on the resonance-like structures in odd-A nuclei has been obtained on the target nucleus ^{90}Zr. Both neutron and proton pick-up and stripping experiments were performed on this target. From these data one can extract an information about neutron and proton single-particle states well above and below the Fermi surface. Moreover, as the damping of single-particle modes in an odd-A nucleus is due to their interaction with phonon excitations of a doubly-even core, one can investigate the isotopic dependence of the damping by studying the strength distributions of neutron and proton subshells with the same quantum numbers in odd-N and odd-Z nuclei having mutual core.

In this paper we study the fragmentation of high-lying single-particle and single-hole states in odd-A nuclei neighbouring the neutron closed-shell nucleus ^{90}Zr (^{91}Nb, ^{89}Y and ^{91}Zr). Note, the main part of the experimental papers has been devoted to the neutron deep-hole states in the ^{89}Zr nucleus /3,4/. However, the results of the corresponding theoretical calculations and detailed comparison between theory and experiment have been published in ref. /5/, and we shall not discuss these states here. There are only preliminary experimental data about the neutron and proton single-particle states excited in (^{3}He, d) and (α, ^{3}He)-reactions on ^{90}Zr /2/. Up to now the information about the strength distributions of different subshells are absent. It seems to us that the corresponding theoretical results will be useful for the experimentalists.

2. MODEL PARAMETERS

Our calculations are performed within quasi-particle-phonon model (QPM). The QPM has been used for such calculations already [5-9]. To calculate the fragmentation of the single-particle and single-hole states we take into account its interaction with one- and two-phonons excitations of the core. The structure of phonons is calculated in the RPA. The nuclear Hamiltonian consists of the phenomenological neutron and proton average potentials of the Saxon-Woods type, pairing BCS-forces and separable effective forces in the particle-hole channel. The parameters of the Saxon-Woods potentials are given in table 1. The fragments of the proton and neutron single-particle schemes are shown in figs. 1, 2, respectively. The form factor of effective separable forces $f(r)$ has a form $f(r) = dU/dr$, where U is central part of the Saxon-Woods potential. The parameters of the effective forces have been determined from the experimental data on the low-lying states and giant resonances of the core (^{90}Zr). Note, the pairing correlations in the proton system of ^{90}Zr are important and we take them into account in a traditional way [10]. As in earlier papers [5-9] we use the strength function method. The weight function of the Lorentz type has the width parameter $\Delta = 0.5$ MeV.

3. PROTON DEEP-HOLE STATES

First we discuss the results of calculations for the proton hole states which have already been studied experimentally [11,12]. The strength functions of the $1f_{7/2}$ and $2s_{1/2}$-subshells are displayed in fig.3. The centroid energies $\bar{E}_x$ and the second moments σ of the strength distributions are given in table 2.

Table 1

The parameters of the Saxon-Woods potential

A = 91	V_0 MeV	r_0 fm	α fm^{-1}	V_{so} MeV
Neutrons	44.7	1.29	1.613	9.23
Protons	56.9	1.24	1.587	9.62

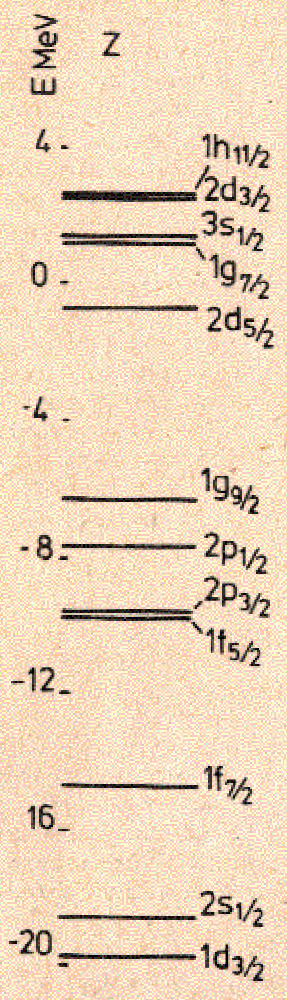

Fig.1. Part of the proton single-particle scheme (the parameters of the Saxon-Woods potential are given in table 1).

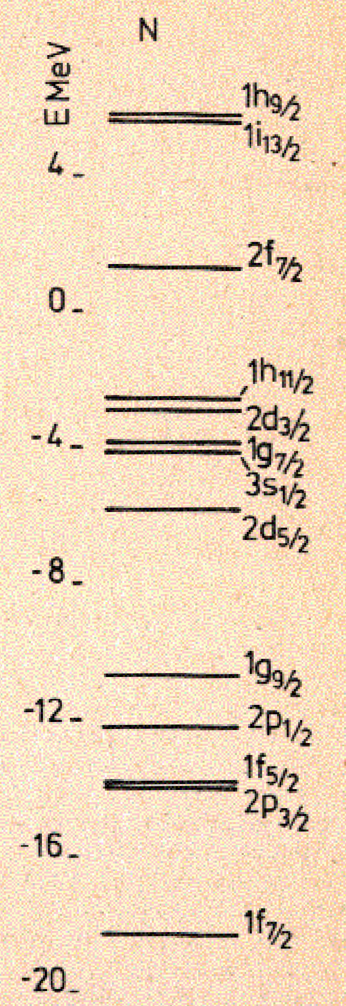

Fig.2. Part of the neutron single-particle scheme (the parameters of the Saxon-Woods potential are given in table 1).

There is no sense to show the $1f_{5/2}$-strength function, because the excitation energy of the $1f_{5/2}$-subshell is not high and the main part of its strength is concentrated in the lowest state $5/2^-$. The experimental and calculated characteristics of the $5/2^-_1$- state are the following: $E_x = 1.75$ MeV, $C^2S = 8.9$ [11] or 7.8 [13]; theory $E_x = 1.52$ MeV, $C^2S = 4.9$. It is difficult

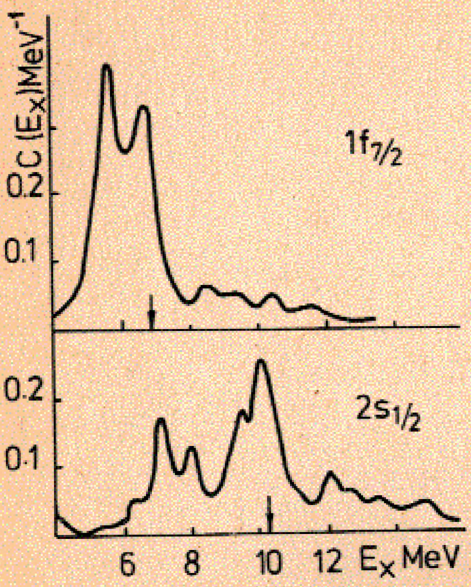

Fig.3. The strength functions of the proton deep-hole subshells $1f_{7/2}$ and $2s_{1/2}$ in ^{89}Y. Arrows point out the energies of the one-quasiparticle states $1f_{7/2}$ and $2s_{1/2}$.

to compare theory and experiment in that case because both experimental values of the $5/2_1^-$-state spectroscopic factor are larger than maximal possible value of it (6). The $1f_{5/2}$ - subshell is weakly fragmented, 94% of its strength is exhausted up to $E_x = 4.5$ MeV.

There are two pronounced peaks in the $(d, {}^3He)$ spectrum measured in a maximum of $\ell = 3$ angular distributions /11/. Their energies and strengths are given in table 3. The assignment to the 6.8 MeV-peak ($J^\pi = 7/2^-$) is unambiguous; for the 5.0 MeV - peak only transferred momentum $\ell = 3$ is determined. The theoretical strength function of the $1f_{7/2}$-subshell also has two strong peaks. One can see these peaks more clearly in fig.4 (upper part), where the $1f_{7/2}$-strength function is shown for $\Delta = 0.2$ MeV. The energies of the peaks agree with the experimental ones rather well. So, there is no $1f_{5/2}$-strength at the energies $E_x > 4.5$ MeV, we conclude that in both the peaks only the $1f_{7/2}$-strength is concentrated. But the theoretical spectroscopic factor of the first peak is twice as large as the experimental one. However, we should like to point out that C^2S_{exp} for the large interval $3.3 \le E_x \le 11.3$ MeV exceeds the maximal possible value, which equals 8. Moreover, it is impossible to determine the experimental width of the peaks from the data of ref./11/ exactly enough and the theoretical intervals ΔE_x, which we use in the calculation of C^2S_{th} (table 3), correspond to the experimental widths only roughly.

The theoretical and experimental values of the spin-orbit splitting of the proton 1f-shell are close to each other ($\Delta\epsilon^P_{so}(1f)_{th} = 5.3$ MeV, $\Delta\epsilon^P_{so}(1f)_{exp} = 5.1$ MeV). So the relative positions of the centroid energy of the single-particle strength distributions in the QPM depend on the single-particle scheme only, this fact means that our parameters of the Saxon-Woods potential are good enough. The parameters are taken from ref./14/ It is interesting that the parameters for the neutron potential from ref./14/ cannot explain the spin-orbit splitting

Table 2

The theoretical characteristics of the strength distributions of the deep-hole and high-lying single-particle states in ^{89}Y, ^{91}Nb and ^{91}Zr. The centroid energy $\bar{E}_x$, the second moments σ and the exhaustion of the whole spectroscopic strength (in %) for different energy intervals ΔE_x.

	$n\ell J$	ΔE_x, MeV	$\bar{E}_x$, MeV	σ, MeV	S
	$1f_{7/2}$	0 - 13.5	6.7	2.13	94%
Proton		4.6 -7.6	6.1	0.93	65%
deep-hole		3.5-18.5	10.3	3.15	92%
states	$2s_{1/2}$	5.5-11.5	8.9	1.63	63%
		5.5-8.5	7.3	0.90	25%
		8.5-11.5	9.9	1.11	38%
High-lying		0 - 14.0	8.55	2.17	95%
single-pro-	$1g_{7/2}$	4.0-8.1	6.3	0.89	59%
ton states		8.1-11.0	9.7	1.58	26%
	$1h_{11/2}$	0 - 14.0	9.4	2.51	89%
	$2f_{7/2}$	2.5-13.5	8.1	1.76	93%
High-lying		7.2-9.7	8.45	0.75	55%
single-neut-	$1i_{13/2}$	5.5-18.5	12.1	2.19	85%
ron states		9.4-13.9	11.5	1.22	54%
		7.5-16.5	12.6	1.60	83%
	$1h_{9/2}$	10.7-13.5	11.9	1.41	51%
		13.5-16.5	14.9	0.95	24%

Table 3

The experimental/11/ and theoretical characteristics of the proton $1f_{7/2}$-strength

Experiment			Theory		
ΔE_x, MeV	E_m *), MeV	C^2S	ΔE_x, MeV	E_m *) MeV	C^2S
-	5.0	0.8	0.5	5.6	1.8
-	6.8	2.1	1.0	6.8	2.1
3.3-11.3	-	9.2	3.3-11.0	-	6.8

*E_m- the energy of the peak;the theoretical intervals (the fourth column of the table)are symmetric with respect to E_m.

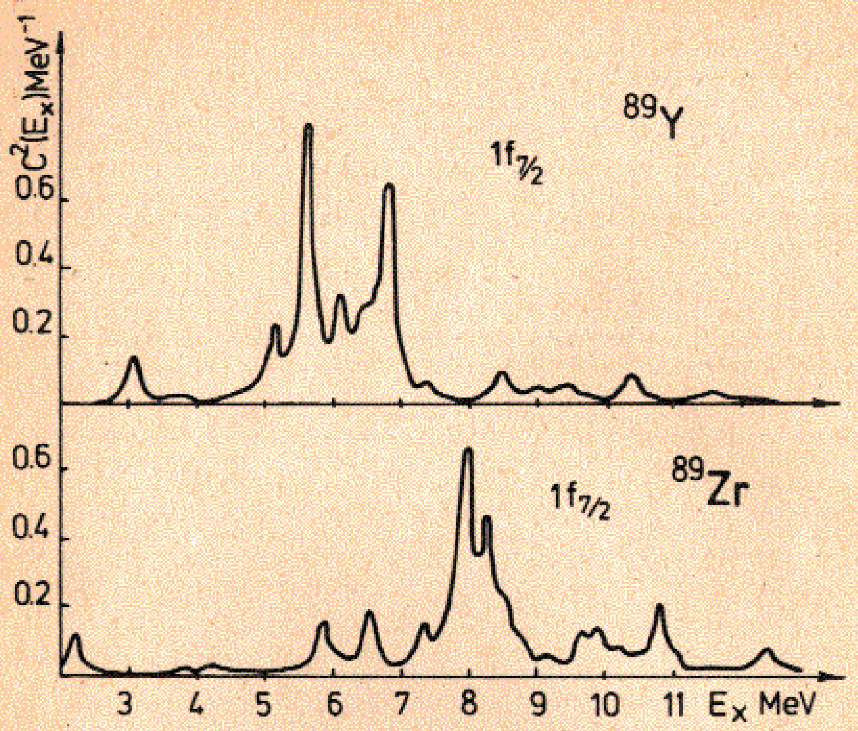

Fig.4. The strength functions of the proton hole subshell $1f_{7/2}$ in ^{89}Y and the neutron hole subshells in ^{89}Zr (see /5/, also). The averaging parameter Δ=0.2 MeV.

of the neutron 1f -shell. Its experimental value is 7 MeV, i.e., 2 MeV larger than the experimental $\Delta\epsilon^p_{so}$(1f). We do not know any theoretical neutron single-particle scheme which is calculated by the Hartree-Fock method or in some phenomenological average potential having so large $\Delta\epsilon^n_{so}$(1f). In the neutron scheme which we use in this paper (see fig.2 and table 1) $\Delta\epsilon^n_{so}$(1f) = = 4.5 MeV. We use the parameters from ref./15/ and our value of V^n_{so} is larger by 25% than that of ref./14/. So, we conclude that there is marked difference between experimental spin-orbit splittings of the proton and neutron 1f-shells and theory cannot explain this difference.

The proton $2s_{1/2}$-subshell is more deeply bound than the $1f_{7/2}$ subshell and is fragmented much stronger. The main part of its strength concentrates in two energy intervals which are clearly seen in fig.3. The corresponding centroid energies and second moments are given in table 3. The 2/3 of the whole $2s_{1/2}$-strength is exhausted in the energy range $5.5 \le E_x \le 11.5$ MeV. But according to the experimental data /12/ the main part of it is at much

higher excitation energy $13 \le E_x \le 17.5$ MeV. This is slightly surprising, so we have satisfactory agreement between theory and experiment for the $1f_{5/2}$ - and $1f_{7/2}$ -subshells. However, there are a few other examples of a disagreement between theoretical and experimental energies of the very deeply bound hole states: the neutron $1f_{7/2}$-subshell in ^{115}Sn/8/ and ^{89}Zr, ^{91}Mo/5/, the proton $1d_{5/2}$-subshell in ^{57}Co. The reasons for this disagreement may be quite different: firstly, it is very difficult to extract the subshell strength from the experimental spectra at such a high excitation energy; secondly, we have no "perfect" parameters for our phenomenological average potential and so on. But may be the reason is more fundamental, e.g., the dependence of the average potential on the excitation energy.

4. SINGLE-PROTON STATES

Up to now the strength distributions of only a few single-proton subshells in ^{145}Eu and ^{209}Bi nuclei have been measured /2,16/. The experimental data agree with our calculations satisfactorily /9/. Due to the known selectivity of the (α, t) - and (^{3}He,d)-processes for large momentum transfers the excitation of high-spin single proton states is enhanced. So, we calculate the strength distributions of the $1g_{7/2}$ - and $1h_{11/2}$ - subshells in ^{91}Nb only (fig.1). The corresponding strength functions are displayed in fig.5. The $1g_{7/2}$-strength is concentrated in two well-separated energy ranges having the widths equal to 2-3 MeV. The difference of their centroid energies is equal to 3.5 MeV. The $1h_{11/2}$-strength is distributed over a very wide energy range ΔE_x ~ 9 MeV. The strength distributions of the two subshells are overlapped, but the lower peak of the $1g_{7/2}$-strength distribu-

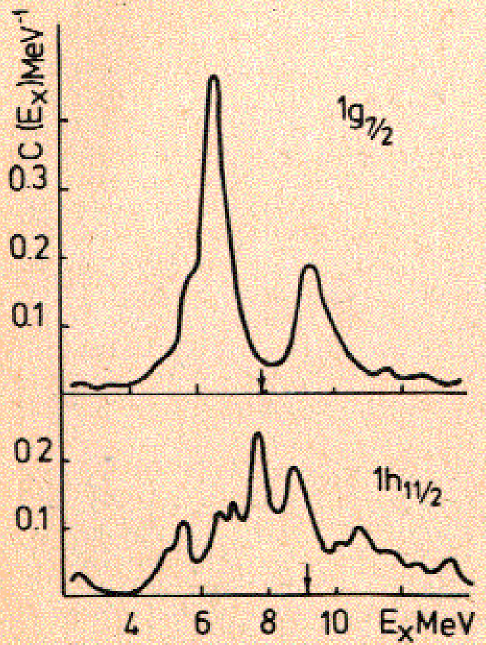

Fig.5. The strength function of the high-lying single-proton states $1g_{7/2}$ and $1h_{11/2}$ in ^{91}Nb. Arrows point out the energies of the one-quasiparticle states $1g_{7/2}$ and $1h_{11/2}$.

tions is so strong that one can hope to observe it in the experimental spectra.

5. SINGLE-NEUTRON STATES

As one can see in fig.2 there are three single-neutron subshells with a small escape-width in the excitation energy range $6 \leq E_x \leq 15$ MeV of ^{91}Zr nucleus. The strength functions of these three states - $1h_{9/2}$, $1i_{13/2}$ and $2f_{7/2}$ - are shown in fig.6 and the corresponding values of $\bar{E}_x, \sigma$ and C^2S are given in table 2. The orbital angular momentum of the $2f_{7/2}$-subshell is smaller than those of the two other subshells. Nevertheless, it seems to be possible to extract $2f_{7/2}$-contribution from the experimental cross-section, so the $2f_{7/2}$-state is placed relatively far from the other subshells and is fragmented not so strongly, therefore its strength distribution is overlapped with other distributions weakly. Note, the strength functions of the $1i_{13/2}$- and $1h_{9/2}$-subshells are quite different though these subshells are placed close to each other in the single particle scheme (fig.2). The reason is two-fold. Firstly, the maximal interaction matrix elements of the $1i_{13/2}$-state are larger by 30% than those of the $1h_{9/2}$-state. Secondly, the density of the complex states with $J^\pi = 13/2^+$ is markedly higher than the density of the $9/2^-$-states at the excitation energy studied.

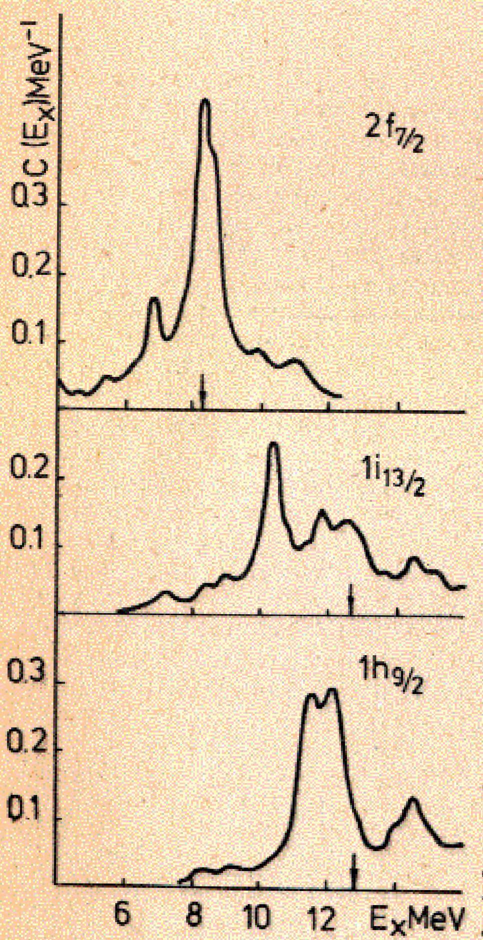

Fig.6. The strength functions of the high-lying single-neutron states $2f_{7/2}$, $1i_{13/2}$ and $1h_{9/2}$ in ^{91}Zr. Arrows point out the energies of the one-quasiparticle states $2f_{7/2}$, $1i_{13/2}$ and $1h_{9/2}$.

6. THE FRAGMENTATION OF THE PROTON AND NEUTRON $1f_{7/2}$-SUBSHELLS

As we have mentioned in the Introduction the comparison of the strength distributions of the proton and neutron subshells with the same quantum numbers $n\ell J$ in odd-A nuclei having mutual doubly-even core is useful in studying of the isotopic effects in the damping.

It is possible to make some qualitative predictions within the QPM for these effects in odd-A nuclei with the semimagic core (as, e.g., ^{90}Zr or Sn-isotopes). By writing the matrix element of the quasiparticle-phonon interaction as $\Gamma(j_1 j_2, \lambda i)$, we have the following expression for it /7,10/:

$$\Gamma(j_1 j_2, \lambda i) = \frac{\langle j_1 \| f(r) Y_\lambda \| j_2 \rangle}{\sqrt{\mathcal{Y}_r^{\lambda i}}} (u_{j_1} u_{j_2} - v_{j_1} v_{j_2}), \quad (1)$$

where u_j, v_j are the Bogolubov coefficients, $\mathcal{Y}_r^{\lambda i}$ is the normalizing factor in the one-phonon wave function. There are two of them for the phonon with momentum λ and number i - one for the proton two-quasiparticle components of the phonon wave function and the other for the neutron ones. Therefore, the coefficient $\mathcal{Y}_r^{\lambda i}$ has an isotopic index $r = p, n$ and single-particle quantum numbers j_1 and j_2 have the same isotopic index as $\mathcal{Y}_r^{\lambda i}$. As a rule $\mathcal{Y}_n^{\lambda i} \neq \mathcal{Y}_p^{\lambda i}$ and the coupling strength of proton quasiparticles with the phonon λi differs from the coupling strength of the neutron quasiparticles with the same phonon. Only in the case when one of the two constants of the λ-pole force - isoscalar or isovector - is equal to zero these normalizing coefficients are equal to each other. But for the lowest one-phonon states in semimagic doubly-even nuclei the values of $\mathcal{Y}_n^{\lambda i}$ and $\mathcal{Y}_p^{\lambda i}$ differ strongly. The smaller value has the coefficient which corresponds to the magic system of nucleons (or system without pairing correlations). For example, in our case, the values of $\mathcal{Y}_n^{\lambda i}$ and $\mathcal{Y}_p^{\lambda i}$ of the first vibrational 2^+-state in ^{90}Zr ($\lambda, i = 2,1$) are the following: $\mathcal{Y}_n^{21} = 20{,}6$ MeV^{-2}, $\mathcal{Y}_p^{21} = 40{,}2$ MeV^{-2}, i.e., $\mathcal{Y}_p^{21} > \mathcal{Y}_n^{21}$. Therefore, the values of $\Gamma(1f_{7/2}\ j_2, \lambda i)$ in the nucleus ^{89}Y are smaller than those in the nucleus ^{89}Zr. The other factor which decreases the matrix elements $\Gamma(1f_{7/2}\ j_2, \lambda i)$ in ^{89}Y is the superfluid factor $|u_{j_1} u_{j_2} - v_{j_1} v_{j_2}|$. This factor is equal to unity in the system without pairing and is smaller than unity when pairing exists. Due to these effects the fragmentation of the $1f_{7/2}$-subshell in ^{89}Zr should be stronger than in ^{89}Y.

The strength functions of the proton and neutron $1f_{7/2}$-subshells are shown in fig.4. The second moment σ_n of the neutron strength distribution is larger than σ_p of the proton one

(σ_n = 2.44 MeV, σ_p = 2.13 MeV). The energy range in which the 2/3 of the $1f_{7/2}$-strength is exhausted is also larger for the neutron subshell than for the proton one. In the first case ΔE_x = 4.7 MeV (5.2 $\le E_x \le$ 9.9 MeV, σ_n = 1.04 MeV) and in the second case ΔE_x = 3 MeV (4.6 $\le E_x \le$ 7.6 MeV, σ_p = 0.93 MeV).

Unfortunately, experimental strength distribution detailed enough to check our predictions are not available. We can make only rough comparison of the two strength functions. So, our calculations agree with the experimental data on the proton $1f_{7/2}$ -strength, we can suggest that the experimental and theoretical strength functions are closed to each other in the first approximation. On the other hand, from the comparison of the theoretical and experimental distributions of the neutron $1f_{7/2}$ -strength[4,5] one can see that experimental fragmentation of the neutron $1f_{7/2}$-state is much stronger than the theoretical ones. For example, the experimental second moment is equal to 3.8 MeV and the high-energy tail of the distribution extends up to $E_x \approx$20 MeV. Therefore, it seems to us that the experimental data support the theoretical predictions.

The isotopic effect should exist in other odd-A nuclei with semimagic doubly-even core, e.g., in the odd isotopes of Sn and Sb. But in these nuclei the proton states should be fragmented stronger than the neutron ones.

The authors are indebted to Prof. V.G.Soloviev and Dr.S.Gales for the consultations.

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Received by Publishing Department
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Вдовин А.И., Стоянов Ч. E4-84-330

Затухание сильновозбужденных одночастичных мод в нечетных ядрах, соседних с ^{90}Zr

В рамках квазичастично-фононной модели ядра рассчитаны распределения силы глубоколежащих протонных дырочных состояний и высоколежащих протонных и нейтронных одночастичных состояний, возбуждаемых в реакциях передачи одного нуклона на ядре-мишени ^{90}Zr. Результаты для протонных дырок удовлетворительно согласуются с экспериментом. Обсуждаются изотопические эффекты в затухании высоколежащих одночастичных ядерных возбуждений.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1984

Vdovin A.I., Stoyanov Ch. E4-84-330

Damping of Highly-Excited Single-Particle Modes in Odd-A Nuclei Near ^{90}Zr

The strength distribution of high-lying proton and neutron single-particle states and the proton deep-hole states which are excited in one-nucleon transfer reactions on ^{90}Zr-target are studied within the quasiparticle-phonon model. Theoretical results for the proton-hole states agree with the experimental data satisfactorily. The difference in the damping of proton and neutron hole states is discussed.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1984