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ON FRAGMENTATION OF TWO-QUASIPARTICLE STATES IN SOME SPHERICAL NUCLEI

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1. INTRODUCTION

In recent years the strength distributions of simple nuclear states for wide energy regions have successfully been studied experimentally and theoretically. The one- and two-nucleon transfer reactions serve as an effective tool for an experimental study of the two-quasiparticle state strength distributions. The resonance-like structures are observed in the two-neutron transfer reaction cross sections /1-6/.

The two-quasiparticle state strength distributions for different spherical nuclei have been calculated within the quasiparticle-phonon model /7/ (QPM) in ref. /8-10/. It was shown that the resonance-like structures observed in (p, t) reactions are specified by the fragmentation of two-quasiparticle states. The existence of two substructures in ^{114}Sn observed /5/ via the $(\alpha, {}^6\mathrm{He})$ reaction on ^{116}Sn and in other Sn isotopes has been explained in our paper /10/.

The present paper is aimed at calculating the fragmentation of two-quasiparticle states which can be excited in the two-neutron transfer reactions in some Zn, Zr and Mo isotopes. We analyse recent experimental data /4,6/.

2. BASIC FORMULAE AND NUMERICAL DETAILS

The method of calculation of the two-quasiparticle state fragmentation within QPM is presented in ref. /8/; here we give only a brief description of the method.

The QPM Hamiltonian includes the average field as Saxon-Woods potential, the pairing interaction and the separable multipole and spin-multipole forces. The excited state wave function of a doubly even spherical nucleus is

$$\Psi_\nu(JM) = \{\sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{JM}\}\Psi_0, \tag{1}$$

where Ψ_0 is the ground-state wave function and $Q^+_{\lambda\mu i}$ is the phonon creation operator

$$Q_{\lambda\mu i} = \frac{1}{2}\sum_{jj_o}\{\psi^{\lambda i}_{jj_o}[a^+_{jm} a^+_{j_o m_o}]_{\lambda\mu} - (-)^{\lambda-\mu}\phi^{\lambda i}_{jj_o}[a_{j_o m_o} a_{jm}]_{\lambda -\mu}\}. \tag{2}$$

Here α^{+}_{jm} (α_{jm}) is the quasiparticle creation (annihilation) operator. The RPA equations for the phonon amplitudes and the seqular equation defining the eigenenergies η_{ν} of the states (1) and the quantities R and P are given in ref.[7]. The two-quasiparticle component $\{jj_0\}_J$ with spin J of the states ν, described by the wave function (1), is

$$\Phi_{jj_o}(J,\eta) = \frac{1}{2} \left| \sum_i R_i(J\nu)\psi^{Ji}_{jj_o}\right|^2 . \tag{3}$$

At intermediate and high excitation energies the level density is high, and therefore to calculate the average values one can use the strength function

$$\Phi_{jj_o}(J,\eta) = \frac{1}{2\pi} \sum_{\nu} \Phi_{jj_o}(J,\eta_{\nu}) \frac{\Delta}{(\eta-\eta_{\nu})^2 + \Delta^2/4} . \tag{4}$$

One can find the expression for $\Phi_{jj_0}(J,\eta)$ in terms of the QPM Hamiltonian parameters in ref.[7,8]. The energy interval Δ determines the method of presenting the results of calculations. With Φ_{jj_o} one can calculate the spectroscopic factors $S'_{jj_o}(\eta)$ of nucleon transfer on the subshell j (j_o is the target spin)[8] and the spectroscopic amplitudes for pick-up of two-neutrons from deeply-bound hole states[11]. In the last case

$$S_{jj_o}(J,\eta) = v_j v_{j_o} \Phi_{jj_o}(J,\eta), \tag{5}$$

where v_j is the Bogolubov transformation coefficient. The integral characteristics of the two-quasiparticle strength distribution in the energy interval ΔE are the centroid energy

$$E_{jj_o} = \sum_{\nu\in\Delta E} \eta_{\nu}\Phi_{jj_o}(J,\eta_{\nu}) \Big/ \sum_{\nu\in\Delta E} \Phi_{jj_o}(J,\eta_{\nu}) \tag{6}$$

and the summed strength

$$N_{jj_o} = \sum_{\nu\in\Delta E} \Phi_{jj_o}(J,\eta_{\nu}). \tag{7}$$

The spreading widths of strength distributions are often extracted experimentally:

$$\Gamma_{jj_o} = 2{,}35\sigma, \quad \sigma^2 = \frac{1}{N_{jj_o}} \int_{\Delta E} (E_{jj_o}-\eta)^2 \Phi_{jj_o}(J,\eta)\, d\eta . \tag{8}$$

In our calculations we use the same set of parameters for the Saxon-Woods potential and pairing interaction as in ref.[12]. All our calculations of the fragmention of two-quasiparticle states have been performed with the code GIRES[13].

3. RESULTS OF CALCULATION

To extract any information on the two-quasiparticle states from the two-nucleon transfer reactions data is a rather hard task due to a simultaneous excitation of many configurations with different spin values. The states being excited from pick-up of a neutron from a deep orbit and a neutron from the Fermi level or nearest hole level are called the valence-hole (v-d) states[2-4]. The states being arised from pick-up of two neutrons from deep orbits are called two-hole (d-d) states.

The cross sections of the (p,t) reactions with 52 MeV protons on nuclei in a broad range of masses have been measured in ref.[4]. Bumps of two-hole states at excitation energies (7-9) MeV were observed. The classification of excited states in accordance with v-d and d-d types within the pairing model[14] have been performed in ref.[4].

We analysed these and other experimental data for some spherical nuclei.

The experimental energy dependence[4] of the cross section of the ^{68}Zn(p,t)^{66}Zn reaction is shown in fig. 1a). There are three bumps at energies 6.9, 9.5 and 12 MeV in the experimental cross section. The widths of these bumps are of about 2-3 MeV. Fig. 1b) shows the calculated strength function $\Phi_{jj_o}(\eta)$ which is summed with statistical weights $g(J) = (2J+1)/(2j+1)(2j_0+1)$ over all possible spins of final states for the v-d configurations $\{1f_{5/2}, 1f_{7/2}\}$, $\{2p_{3/2}, 1f_{7/2}\}$, $\{2p_{3/2}, 2s_{1/2}\}$, $\{2p_{3/2}, 1d_{3/2}\}$, $\{1f_{5/2}, 2s_{1/2}\}$, $\{1f_{5/2}, 2d_{3/2}\}$ and the d-d configuration $\{1f_{7/2}, 1f_{7/2}\}$ in ^{66}Zn. We calculated the strength distribution of all two-quasiparticle states which could be excited in two-neutron transfer reactions in ^{66}Zn within the excitation energy interval (6-15) MeV. The integral characteristics of these states for different energy intervals ΔE are given in table 1. As can be seen from fig. 1 there are three prominent bumps in the calculated strength distribution of the v-d and d-d configurations in ^{66}Zn. The calculated energies to two high-lying bumps are shifted up to 1 MeV in comparison with experimental values. The experimentally observed bump at the energy 6.9 MeV corresponds to the excitation of the v-d configurations $\{1f_{5/2}, 1f_{7/2}\}$, $\{2p_{3/2}, 1f_{7/2}\}$. The calculated value $\Gamma_{jj_o} = 1.9$ MeV of the width for the configuration $\{2p_{3/2}, 1f_{7/2}\}$ is in good agreement with the experimental one $\Gamma_{jj_o} = 2.1$ MeV.

The small bump in the experimental cross section at the energy 8 MeV corresponds to the excitation of the d-d configuration $\{1f_{7/2}, 1f_{7/2}\}$. As can be seen from fig. 1b) and table 1 19% of the strength of the afore-mentioned configuration is located around 8 MeV. The bump at the energy 9.5 MeV has a complex structure and is formed by the v-d and d-d configurations.

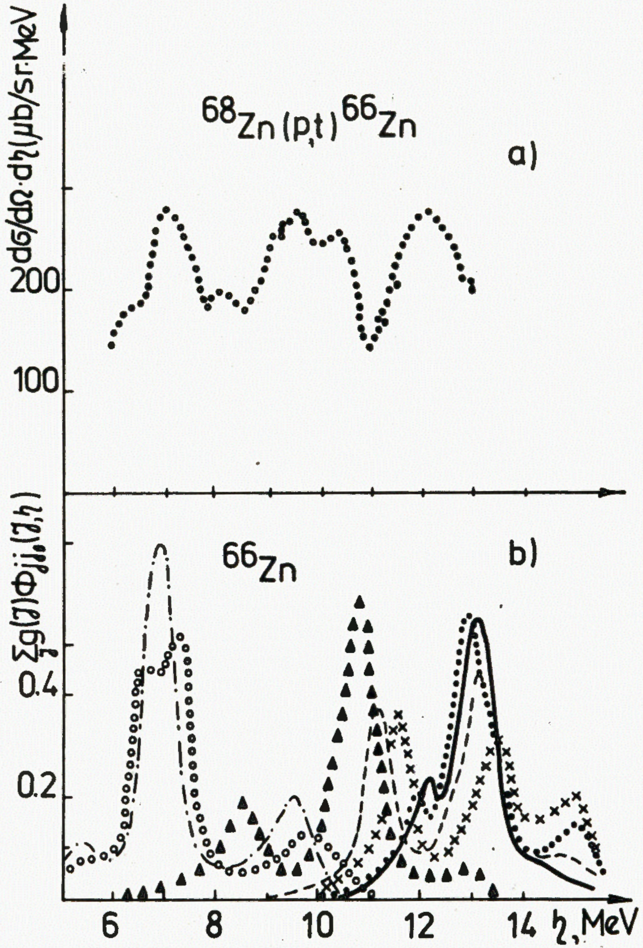

Fig. 1. a) Energy dependence of the ^{68}Zn(p, t)^{66}Zn cross section; b) Strength functions for the v – d and d – d configurations in ^{66}Zn

circle curve – $\{1f_{7/2}, 2p_{3/2}\}$ configuration
chain curve – $\{1f_{7/2}, 1f_{5/2}\}$ configuration
triangle curve – $\{1f_{7/2}, 1f_{7/2}\}$ configuration
broken curve – $\{1f_{5/2}, 2s_{1/2}\}$ configuration
cross curve – $\{2p_{3/2}, 2s_{1/2}\}$ configuration
dotted curve – $\{1f_{5/2}, 1d_{3/2}\}$ configuration
full curve – $\{2p_{3/2}, 1d_{3/2}\}$ configuration.

Table 1

Integral characteristics of the v – d and d – d configurations in ^{66}Zn

$\{jJ_0\}$	ΔE, MeV	E_{jj_0}, MeV	Γ_{jj_0}, MeV	N_{jj_0} (%)
$\{1f_{7/2}, 1f_{5/2}\}$	4.0 - 5.7	5.1	0.91	10.6
	5.8 - 8.2	6.9	1.1	60.3
	8.2 - 10.5	9.2	1.1	19.2
$\{1f_{7/2}, 2p_{3/2}\}$	4.0 - 8.5	6.9	1.9	64.8
	8.5 - 11.0	9.7	1.3	18.2
$\{1f_{7/2}, 1f_{7/2}\}$	6.0 - 9.5	8.5	1.4	19.3
	9.5 - 12.5	10.8	1.3	48.8
$\{2p_{3/2}, 2s_{1/2}\}$	10.0 - 12.5	11.5	1.2	32.3
	12.5 - 14.4	13.5	1.0	31.9
$\{1f_{5/2}, 2s_{1/2}\}$	9.0 - 12.1	11.1	1.3	34.3
	12.1 - 14.4	13.1	1.2	43.1
$\{1f_{5/2}, 1d_{3/2}\}$	10.0 - 12.1	11.8	-	18.1
	12.1 - 14.2	12.9	1.2	56.0
$\{2p_{3/2}, 1d_{3/2}\}$	10.0 - 12.5	11.9	-	21.3
	12.5 - 14.6	13.1	1.2	48.7

In accordance with our calculations about 50% of the strength of the state $\{1f_{7/2}, 1f_{7/2}\}$ and about 30% of the strength of the states $\{2p_{3/2}, 2s_{1/2}\}$, $\{1f_{5/2}, 2s_{1/2}\}$ are localized within the energy interval (9-12) MeV. The contribution of other states is not more than 20% in this energy region. So, a broad bump observed in the (p, t) cross section at energies (8,5-11) MeV is caused by the excitation of many two-quasiparticle states. It should have a fine substructure. It is interesting to investigate a fine substructure of this bump via the (α, ^{6}He) reaction which is selective towards a large angular momentum transfer at high incident energy. The overlaped configurations $\{2p_{3/2}, 2s_{1/2}\}$, $\{1f_{5/2}, 2s_{1/2}\}$, $\{1f_{5/2}, 1d_{3/2}\}$, $\{2p_{3/2}, 1d_{3/2}\}$ form the third observed bump. About 32% to 56%

of their strengths are exhausted in the energy interval (12-14.5) MeV. So, we can conclude that the bumps observed recently /4/ in the $^{68}Zn(p,t)^{66}Zn$ cross sections are caused by the excitation of different two-quasiparticle states. Modifying slightly the parameters of the Saxon-Woods potential one can remove a disagreement between the theoretical and experimental values of bump energies.

In the (p, t) reactions /4/ peaks in the cross sections are observed for the Mo and Zr isotopes. The centres of gravity of the bumps are located at excitation energies of about 8 to 9 MeV. For example, the centre of gravity of the observed bump is located at the energy 8,3 MeV. The calculated strength functions for the v-d configurations $\{2d_{5/2}, 1f_{5/2}\}$, $\{2d_{5/2}, 2p_{1/2,3/2}\}$, $\{2d_{5/2}, 1g_{9/2}\}$ and the d-d configuration $\{1g_{9/2}, 1g_{9/2}\}$ are shown in fig. 2. The centres of gravity of the bumps observed in the (p, t) reactions are denoted by arrows. The integral characteristics of two-quasiparticle states are given in table 2. As can be seen from fig. 2 and table 2 the centre of gravity of the bump in ^{94}Mo is close to the calculated centroid energies for the v-d configuration $\{2d_{5/2}, 1f_{7/2}\}$ and the d-d configuration $\{1g_{9/2}, 1g_{9/2}\}$. These configurations are overlapped. They both should be excited via the (p, t) reaction. Apart from the afore-mentioned configurations the v-d states $\{2d_{5/2}, 2p_{1/2}\}$, $\{2d_{5/2}, 2p_{3/2}\}$ are located within the energy interval (6-10) MeV. Four configurations form a broad bump having a fine structure. There is some indication to an existence of such a fine structure in the triton spectrum from the $^{96}Mo(p,t)^{94}Mo$ reaction /4/. A bump in the $^{95}Mo(p,d)^{94}Mo$ cross section has been observed /15/ at the energy 4.9 MeV. Only v-d states could be excited in this reaction. It is seen from fig. 2 and table 2 that 67.5% of the strength of the v-d state $\{2d_{5/2}, 1g_{9/2}\}$ is concentrated at the energy 5 MeV in good agreement with experimental data. Similar two-quasiparticle strength distributions take place in ^{96}Mo (see fig.2) and ^{98}Mo. In all Mo isotopes an excitation of the d-d configurations is accompanied by an excitation of the v-d configurations. Using the (p, d) reactions on odd Mo isotopes one can test excitation of the v-d configurations in even Mo isotopes. The existence of bumps in the (p, d) and (p, t) cross sections at the same energies would give a strong support for excitation of the v-d configurations. The $^{94}Zr(p,t)^{92}Zr$ cross section has a bump at the energy E_{jj_0} = 8.6 MeV. One can see from fig. 1a that the same v-d and d-d states are excited in ^{92}Zr as in ^{94}Mo. The strength distributions of these states in both nuclei are similar.

There is a more complete experimental information for ^{88}Zr. The experimental cross section /4/ of the $^{90}Zr(p,t)^{88}Zr$ reaction

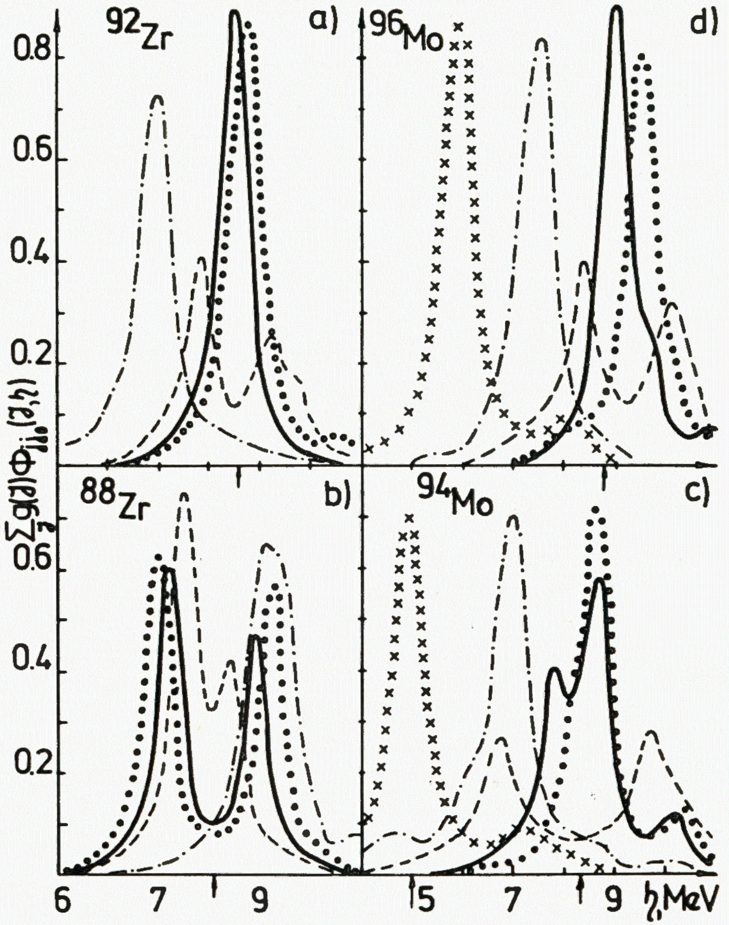

Fig. 2. Strength functions for the v-d and d-d configurations a) in ^{92}Zr, c) in ^{94}Mo, d) in ^{96}Mo
dotted curve - $\{1g_{9/2}, 1g_{9/2}\}$ configuration
full curve - $\{2d_{5/2}, 1f_{5/2}\}$ configuration
broken curve - $\{2d_{5/2}, 2p_{3/2}\}$ configuration
chain curve - $\{2d_{5/2}, 2p_{1/2}\}$ configuration
cross curve - $\{2d_{5/2}, 1g_{9/2}\}$ cobfiguration
b) in ^{88}Zr
dotted curve - $\{2p_{3/2}, 2p_{3/2}\}$ configuration
full curve - $\{2p_{3/2}, 1f_{5/2}\}$ configuration
broken curve - $\{1f_{5/2}, 1f_{5/2}\}$ configuration
chain curve - $\{1f_{7/2}, 1g_{9/2}\}$ configuration

Table 2

Integral characteristics of the v-d and d-d configurations in ^{88}Zr and ^{94}Mo

Nucleus	$\{jj_0\}$	ΔE, MeV	E_{jj_0}, MeV	Γ_{jj_0}, MeV	N_{jj_0} (%)
^{88}Zr	$\{2p_{3/2}, 2p_{3/2}\}$	6.0-8.2	7.0	1.2	51.3
		8.3-11.0	9.3	1.1	42.3
	$\{2p_{3/2}, 1f_{5/2}\}$	6.0-8.2	7.1	1.2	46.8
		8.3-11.0	8.9	1.1	34.8
	$\{1f_{5/2}, 1f_{5/2}\}$	6.0-8.0	7.5	-	54.9
		8.0-10.0	8.4	-	29.7
	$\{1g_{9/2}, 1f_{7/2}\}$	6.0-10.5	9.2	1.7	85.2
^{94}Mo	$\{2d_{5/2}, 1g_{9/2}\}$	4.0-6.4	5.0	1.1	67.5
		6.5-9.0	7.3	1.2	9.8
	$\{2d_{5/2}, 2p_{3/2}\}$	4.1-8.0	6.7	1.7	35.4
		8.1-11.5	9.7	1.8	42.6
	$\{2d_{5/2}, 2p_{1/2}\}$	5.0-9.0	7.0	1.8	71.4
	$\{2d_{5/2}, 1f_{5/2}\}$	6.0-8.2	7.8	-	34.5
		8.3-9.5	8.6	-	40.3
		9.6-11.2	10.1	-	11.1
	$\{1g_{9/2}, 1g_{9/2}\}$	6.0-9.8	8.6	1.5	71.5
		9.8-11.5	10.4	0.9	5.8

with 52 MeV protons has rather a broad bump with the centre of gravity E_{jj_0} = 8.1 MeV. Experimental data for the same reaction with 168 MeV protons /6/ show an existence of two peaks at the energies E_{jj_0} = 7.0 MeV and E_{jj_0}= 8.5 MeV. A bump at the energy E_{jj_0}= 7.5 MeV has been observed in the ^{90}Zr(α, ^{6}He) ^{88}Zr cross sections with 218 MeV α-particles /6/. Calculated strength distributions for the v-d and d-d configurations which could be excited in these reactions in ^{88}Zr at the energies (6-10)MeV are shown in fig. 2. As can be seen from table 2 and fig. 2 51.3% of the state $\{2p_{3/2}, 2p_{3/2}\}$ strength and 46.8% of the state $\{2p_{3/2}, 1f_{5/2}\}$ strength are located at the energies E_{jj_0} = =7.0 MeV and E_{jj_0} = 7.1 MeV, 54.9% and 30% of the state $\{1f_{5/2}, 1f_{5/2}\}$ strength are localized at the energies 7.5 MeV and 8.4 MeV, respectively. It seems quite possible that the aforementioned states are excited via the (p, t) and (α, ^{6}He) reactions in ref./6/. Of about 30 to 40% of the strength of the configurations $\{2p_{3/2}, 2p_{3/2}\}$ and $\{2p_{3/2}, 1f_{5/2}\}$ are exhausted within the energy interval (8.0-10.5) MeV. 85% of the strength of the v-d state $\{1g_{9/2}, 1f_{7/2}\}$ is concentrated at the enenrgy E_{jj_0} = 9.2 MeV. All states discussed above form a broad bump which was observed in the (p, t) reaction with 52 MeV protons /4/. Increase in the proton beam energy for the (p, t) reaction and the use of the (α, ^{6}He) reaction let us to search a fine structure of this bump /6/. It is interesting to investigate excitation of the v-d configuration $\{1g_{9/2}, 1f_{7/2}\}$ in ^{88}Zr via the one-neutron transfer reactions.

4. CONCLUSION

The calculations and comparison with the experimental data show that within QPM one can correctly describe the two-quasiparticle strength distributions in a broad range of excitation energies. Our calculations enabled one to shed more light on the structures of bumps observed in the two-neutron transfer cross sections and predict their energy locations. Up to now there is a large uncertainty for the configuration strength observed experimentally. To solve this problem one has to compare the experimental cross sections with the theoretical ones.

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Воронов В.В. E4-84-377
О фрагментации двухквазичастичных состояний в некоторых сферических ядрах

В рамках квазичастично-фононной модели исследовано распределение силы двухквазичастичных состояний в ряде сферических ядер, которые могут возбуждаться в реакциях двухнуклонных передач. Проведен анализ экспериментальных данных, полученных в реакциях (p, t) и $(\alpha, {}^6\mathrm{He})$. Показано, что наблюдаемые на эксперименте пики в сечениях соответствуют возбуждению валентно-дырочных и двухдырочных состояний.

Работа выполнена в Лаборатории теоретический физики ОИЯИ.

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Voronov V.V. E4-84-377
On Fragmentation of Two-Quasiparticle States in Some Spherical Nuclei

Strength distributions of two-quasiparticle states which could be excited in two-neutron transfer reactions on some spherical nuclei is calculated within the quasiparticle-phonon model. The experimental data for (p, t) and $(\alpha, {}^6\mathrm{He})$ reactions are analysed. It is shown that bumps observed via these reactions are specified by excited valence-hole and hole-hole states.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1984