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GROSS STRUCTURE OF HADRON AND DIBARYON RESONANCES SPECTRUM

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1 Introduction

It is well known that there exists a huge but finite number of hadronic resonances decaying via the strong interaction forces. As a rule, they have 2-body decay modes with sufficiently high branching ratios and their typical widths are of order $50 \div 100$ MeV. For baryonic resonances the corresponding 2-particle modes are $B + \mu$ (here B stands for a baryon and μ for a meson) and $\mu_1 + \mu_2$ for meson resonances (where indices indicate the meson type).

For all resonance families (with or without strangeness, charm, etc) the number of resonances is finite and this fact leads us to a question: what is the physical reason that puts a limit on the resonance spectrum?

To answer this question and to understand the gross structure of the known resonance spectra (we are talking about wide resonances having strong decay modes), the quasiclassical approach was used in refs.[1, 2]. This approach was based on the following key points: (i) every resonance having non-negligible $B + \mu$ decay mode can be considered as a resonating 2-particle system of a baryon and a meson; (ii) this system is bounded in the coordinate space, i.e. has a finite size irrespective of the particular dynamical model like bag models. This approach was surprisingly successful and resulted in a phenomenological formula which looks like the famous Balmer formula and describes the gross structure of the all known resonance spectra rather well. Moreover, it explains why the spectra are finite. It appears also that within the experimental uncertainty all baryon resonances have the same characteristic size $r_0 \sim 0.86$ fm which is close to the electromagnetic radius of the nucleon and to the confinement radius in bag models. Therefore, all baryon resonances including the strange and charmed ones can be considered as the so-called shape resonances. A special case is the $\Delta(1232)$-resonance, for which 2 resonance conditions hold simultaneously: with characteristic radii $r_0 \approx 0.86$ fm and $r_q \approx 0.2$ fm. That is why this resonance is so extraordinary in the pion-nucleon and pion-nuclear physics.

The leading term of the suggested mass formula was obtained for baryon resonances irrespective of the particular dynamical equation of motion or models. This formula is very close in structure to analogous expressions in bag models; this fact can be considered as a serious phenomenological argument in favour of bag models.

Interpretation of the quantities r_0 and r_q requires further investigations; at least they are very close to the characteristic radius of the quark-quark potential or the radius of the core of the NN potentials (0.2 fm) and to the size of the 6-quark system (0.8 fm) [3] respectively. We have used the asymptotic values of momenta in the resonance condition neglecting the interaction between mesons and baryons. Nevertheless the suggested treatment describes many aspects of the gross structure of baryon resonances which can be considered as a support in favour of the asymptotic freedom in quark-quark interaction and can help to understand the origin and role of the Regge poles in the elementary particle physics.

The aim of this article is to extend the quasiclassical treatment to the gross structure of the meson and dibaryon resonances decaying via strong interaction into two particles and to discuss the interpretation of the parameter r_0 in the leading term of the mass formula.

2 Quasiclassical treatment

Let us consider the baryon resonance as a system consisting of a meson and a baryon. The invariant mass of the baryon resonance at the resonance peak can be written according to [1, 2]:

$$M_n(B) = \sqrt{m_\mu^2 + (\frac{n+\gamma}{r_0})^2} + \sqrt{m_b^2 + (\frac{n+\gamma}{r_0})^2} + \Delta M_n, \qquad (1)$$

where B refers to the baryon resonance, the indices μ and b refer to the meson and baryon observed in the 2-particle decay of the baryon resonance $B \to b+\mu$ respectively. The "main" quantum number n is equal to 0, 1, 2... (1, 2, 3...) and γ is a number of the order $0 \leq \gamma \leq 1$ which depends on the boundary conditions for a given degree of freedom and on the type of a dynamical equation for the resonating system [4] (in [1, 2] it was assumed that γ can be equal to 0 or 1/2). The scaling parameter $r_0 = 0.86$ fm was associated in [1, 2] with the "nucleon size" without any further model interpretation. It is fixed in all calculations presented below.

Formula (1) describes the gross structure of the baryon resonance spectrum with a reasonable accuracy because the relation $\Delta M_n < \Gamma$ is valid in all investigated cases of the strong decay $B \to b + \mu$ including strangeness and charmed baryon resonance decays. The leading term of the mass formula describes only the "center of gravity" position of the corresponding multiplets and the gross structure of the hadron and di-baryon resonances. Their fine structure in each multiplets is determined by the residual interactions and corresponding quantum numbers which are not evaluated in the quasiclassical approach [1, 2]. Therefore the condition $\Delta M_n < \Gamma$ can be considered as an empirical fact.

Table 1

Spectrum of the invariant mass for meson resonances μ^* decaying into channels $\mu^* \to \pi + \pi$ due to the strong interaction.

$n+\gamma$	theory	exp	Γ	fraction(Γ_i/Γ)	$I^G(J^{PC})$	
1	536	$\eta(548)$	0.00119	$< 0.15\%$	$0^+(0^{-+})$	
2	958	$f_0(975)$	47	78%	$0^+(0^{++})$	
		$\eta'(958)$	0.198	$< 2\%$	$0^+(0^{-+})$	
3	1402	$f_0(1400)$	$150 \div 400$	94%	$0^+(0^{++})$	
0+1/2	361	388 ± 2[7]	11 ± 8[7]			
1+1/2	742	$\omega(783)$	8.4	2.2%	$0^-(1^{--})$	
		$\rho(770)$	151	$\approx 100\%$		$1^+(1^{--})$
2+1/2	1179	$f_2(1270)$	185	85%	$0^+(2^{++})$	
		$b_1(1235)$	155	$< 15\%$		$1^+(1^{+-})$
3+1/2	1628	$\rho(1700)$	235	seen		$1^+(1^{--})$
		$\rho_3(1690)$	215	24%		$1^+(3^{--})$
		$f_0(1710)$	146	seen	$0^+(0^{++})$	

We would like to analyze the spectrum of the meson resonances treating them as a meson plus meson resonances and using formula (1). Some of the results are given in Tables 1-3. All masses and widths are given in MeV. If the reference to the experimental data is not indicated, this means that they are taken from the "Review of Particle Properties" (Phys. Rev. D45, 11 (1992)).

Table 2

Spectrum of the invariant mass for meson resonances μ^* decaying into channels $\mu^* \to \pi + \rho$ due to the strong interaction.

n+γ	theory	exp	Γ	fraction(Γ_i/Γ)	$I^G(J^{PC})$	
1	1072	$h_1(1170)$	360	seen	$0^-(1^{+-})$	
		$\phi(1020)$	4.4	13%	$0^-(1^{--})$	
2	1376	$\omega(1390)$	229	dominant	$0^-(1^{--})$	
3	1735	$\omega(1600)$	100	seen	$0^-(1^{--})$	
		$\omega_3(1670)$	166	seen	$0^-(3^{--})$	
0+1/2	959	$\eta'(958)$	0.198	$< 4\%$	$0^+(0^{-+})$	
1+1/2	1215	$\pi(1300)$	$200 \div 600$	seen		$1^-(0^{-+})$
		$a_1(1260)$	≈ 400	dominant		$1^-(1^{++})$
		$a_2(1320)$	110	70%		$1^-(2^{++})$
2+1/2	1550	$\pi_2(1670)$	250	31%		$1^-(2^{-+})$
3+1/2	1928					

Table 3

Spectrum of the invariant mass for meson resonances μ^* decaying into channels $\mu^* \to \pi + K^*(892)$ due to the strong interaction.

n+γ	theory	exp	Γ	fraction(Γ_i/Γ)	$I^G(J^P)$
1	1189	$K_1(1270)$	90	16%	$1/2(1^+)$
2	1483	$K_1(1400)$	174	94%	$1/2(1^+)$
		$K_2(1430)$	99	25%	$1/2(2^+)$
3	1829	$K_2^*(1980)$	390	seen	$1/2(2^+)$
0+1/2	1080				
1+1/2	1327	$K^*(1410)$	227	$> 40\%$	$1/2(1^-)$
2+1/2	1651	$K^*(1630)$	323	30%	$1/2(1^-)$
		$K_2(1770)$	136	seen	$1/2(2^-)$
		$K_3^*(1780)$	164	27%	$1/2(3^-)$
3+1/2	2015				

The same results were obtained for all other meson resonances decaying into two meson channels via the strong interactions.

The calculations were also performed for dibaryon resonances. Despite the fact that there is disagreement between the results of different experimental groups, we have decided to use the experimental data coming from the Dubna collaboration [6, 7] (for details of discussions on the interpretation of existing experimental data see, for example, [6, 8, 9] and reviews [10, 11] of the situation in dibaryon problems) which are available for us. One can see very exciting correlations between the calculated results and experimental data.

Table 4

Spectrum of the invariant mass and widths for the diproton resonances. Here the experimental widths are the "visible" ones, i.e. not corrected for the mass resolution of the apparatus.

	$n+\gamma$	1/2	1	1+1/2	2	2+1/2	3	3+1/2
M	theory	1890	1932	1998	2088	2198	2326	2468
	exp	1886[6]	1937[6]	1999[6]	2087[6]	2172[6]		
Γ	theory	4	9	12	17	22		
	exp	4 ± 1	7 ± 2	9 ± 4	12 ± 7	7 ± 3		

Table 5

Spectrum of the invariant mass and widths for the neutron+proton resonances.

	$n+\gamma$	1/2	1	1+1/2	2	2+1/2	3	3+1/2
M	theory	1892	1933	2000	2089	2200	2327	2469
	exp			1998[7]	2084[7]			
Γ	theory	2	4	6	8	10		
	exp			14 ± 4	11 ± 5			

The existence of the new resonance S_{11} with the mass $m_{N^*(1125)} \approx 1115 - 1135$ MeV, width $\Gamma < 100$ MeV and the quantum numbers $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ was predicted in [2]. This prediction is consistent with the well-known fact that the transition with $\Delta T = 3/2$ in the decay of $\Lambda(1115)$-hyperon is hindered in comparison with the transition $\Delta(T = 1/2)$. Indeed, the branching ratio for $\Lambda \to \pi^- + p$ and $\Lambda \to \pi^0 + n$ is equal to 2, which is typical for the decay of particles having $T = 1/2$. Therefore it is natural to consider the decay of the Λ-hyperon in analogy with the hindered α-decay and vector meson dominance phenomena. The Λ-hyperon remains to be a strange particle until the constituent s-quark does not decay to the d- or u-quark due to the weak interaction. As a result of the weak interaction, the enhancement of the state with $T = 1/2$ can be interpreted as the display of the $N(1125)$-resonance created as a product of the decay of the Λ-hyperon. Further this N^*-resonance decays into channels $\pi^- p$ and $\pi^0 n$. So the dynamical origin of the famous ΔI=1/2 rule is related with the strong final state interaction between decayed particles resulting to the $N^*(1125)$ resonance.

The invariant mass spectrum for the proton+$N^*(1125)$ resonances is given in Table 6. Note that the cross section of the pionic double charge exchange on ^{54}Fe exhibits a pronounced resonance behaviour at low energies [12] which was interpreted as an indication of a resonance in the πNN subsystem with $J^P = 0^-$, T=0 and invariant mass 2065 MeV. The predicted low energy $N + N^*(1125)$ resonance has the same quantum numbers and can be considered as a candidate for the one observed in [12].

Table 6

Spectrum of the invariant mass for the proton+$N^*(1125)$ resonances.

$n+\gamma$	1/2	1	1+1/2	2	2+1/2	3	3+1/2
theory	2076	2114	2175	2259	2362	2481	2616
exp	2065[12]						

We look for possible resonances for the proton+$\Delta(1232)$ and $\pi + \Delta(1232)$ systems.

There is an experimental evidence [13] that the lowest proton+$\Delta(1232)$ resonance might have the invariant mass 2164 MeV. It is worthwhile to note that the authors of [14] come to the conclusion that "Secondary final-state interaction of π^+-meson and the Δ^{++}- isobar is assumed to be responsible for observed resonance production". This conclusion is consistent with our interpretation of resonances of that type and could be an analog of the Migdal-Watson effect.

Table 7

Spectrum of the invariant mass for the proton+$\Delta(1232)$ resonances.

$n+\gamma$	1/2	1	1+1/2	2	2+1/2	3	3+1/2
theory	2183	2219	2278	2358	2458	2574	2704
exp	2164[13]						

Table 8

Spectrum of the invariant mass for the $\pi^+ + \Delta(1232)$ resonances.

$n+\gamma$	1/2	1	1+1/2	2	2+1/2	3	3+1/2
theory	1417	1521	1650	1793	1948	2112	2284
exp	1438[15]	1522[15]			1894[15]		
	1491[14]	1586[14]	1680[14]				

Finally, usual quantum-mechanical estimations [16] of the widths of the $\Delta(1232)$-isobar, *the $N(1440)$ (Table 9), diproton (Table 4) and neutron+proton* (Table 5) resonances were performed in the similar calculation scheme as in the α-decay case.

Table 9

Widths of the $\Delta(1232)$-isobar and $N(1440)$ resonances.

	$n+\gamma$	1	1+1/2
M	theory	1234	1370
	exp	1232	1440
Γ	theory	$140^{(a)}$	$160^{(a)}$
	exp	$115 \div 125$	$250 \div 450$

(a)These widths are evaluated in the framework of the Kadmensky quantum- mechanical integral formulae [16] by using the quasiclassical approximation (see details and references in the review paper [16]).

We would like to make the following remark concerning the relation (1) which is similar to the Balmer formula.

In the derivation of formula (1) we have used only the relativistic kinematics and *main ideas of quantum theory:*

i)the Lui de Broglie relation for the wavelength of a microsystem having the momentum P:

$$\lambda = \frac{2\pi}{P}, \tag{2}$$

ii)the classical condition for the existence of stationary waves in the hollow resonator (resonances in quasistationary wave systems) with the effective size l_{eff}:

$$\frac{l_{eff}}{\lambda} \equiv Pr_0 = (n + \gamma), \tag{3}$$

where n=0,1,2,... (1,2,3...) and $0 \le \gamma \le 1$ is a number which depends on the boundary conditions for a given degree of freedom and on the type of a dynamical equation for the resonating system [4].

iii)the consistency of formulae (2) and (3) with the Heisenberg uncertainty relation

$$Pr_0 \ge \frac{1}{2}, \tag{4}$$

and the simplified version of the Bohr-Sommerfeld quantization condition

$$Pr_0 = n. \tag{5}$$

The fundamentality of assumptions used in obtaining formula (1) allows us to consider it as a *model-independent relation. Therefore, it is necessary to give an additional* interpretation on the basis of a certain model representation (for example, in the framework of quark models, the Regge poles, etc)

3 Pion-nucleon scattering and correspondence principle

Up to this point we did not use any detailed model of resonances to evaluate resonance spectra. But to estimate widths of resonances or to get an interpretation of the parameter r_0 we need a model. Let us consider the p-wave pion-nucleon scattering to discuss the latter question. The leading long-range attractive interaction in the channel P_{33} for the π^+p-scattering corresponds to the crossing Born diagram (see details in [5]) and the corresponding amplitude can be calculated in the first Born approximation. We can introduce an effective potential $U_{eff}^{\pi N}$ and easily determine the long-range part of the πN interaction using the correspondence principle

$$U_{eff}^{\pi N}(r) = f_{\pi NN}^2 \frac{m + m_\pi}{m m_\pi} (\frac{m}{m_\pi})^2 \frac{P_\pi^2}{\sqrt{s}} \frac{e^{-\alpha r}}{r}, \tag{6}$$

where

$$\alpha = \sqrt{2mE_\pi}; E_\pi = \sqrt{P_\pi^2 + m_\pi^2}; P_\pi = \frac{\lambda^{1/2}(s, m^2, m_\pi^2)}{2\sqrt{s}}$$

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx. \tag{7}$$

Here m (m_π) is the nucleon (pion) mass, P_π (E_π) is the pion momentum (energy) in the center mass system, s is the squared invariant mass of the resonance and $f_{\pi NN}$ is the coupling constant of the πNN interaction.

If we use the second Newton law

$$\frac{m_\pi v^2}{r} = -\frac{\partial U_{eff}^{\pi N}}{\partial r}, \tag{8}$$

the Bohr orbital condition of quantization

$$m_\pi v r = l, \tag{9}$$

and take into account the relativistic corrections ($m_\pi \to E_\pi$ in (8)), then we obtain the final equation

$$l^2 = f_{\pi NN}^2 \frac{m + m_\pi}{\sqrt{s}} \frac{m}{m_\pi} \frac{P_\pi^2}{E_\pi} r_0 (1 + \alpha r_0) e^{-\alpha r_0} \equiv F^2(s, r_0) \tag{10}$$

It is well-known that the Δ-resonance is the p-wave resonance, i.e. $l = 1$. We can fix $r_o = 0.86$ fm according to [1, 2] and obtain at the resonance peak ($\sqrt{s} = M_\Delta = 1232$ MeV)

$$F(M_\Delta^2, r_0 = 0.86) = 0.97 \approx 1 = l. \tag{11}$$

For the Roper resonance $N^*(1440)$ (i.e. P_{11}, l=1 and M_{N^*}=1440 MeV) we have again:

$$F(M_{N^*(1440)}^2, r_0 = 0.86) = 0.91 \approx 1 = l. \tag{12}$$

It should be stressed that the $\Delta(1232)$-isobar and the Roper resonances ($l = 1$) have almost the same value of the parameter $r_0 \approx (0.8 \div 0.9)$ fm.

Let us return to equation (10) and consider it for an arbitrary p-wave πN-resonance ($l = 1$). The solution of this equation gives us r_0 as a function of the invariant mass of the corresponding resonance (see Table 10 and Fig.1). One can see that for the $\Delta(1232)$ and N^*-resonances the "radial" (3) and the "orbital" (10) resonance conditions give us almost coinciding values of the "sizes" r_0 and the difference between r_0(radial) and r_0(orbital) increases with increasing resonance mass. It is interesting to note that equation (10) has the second solution at smaller values of $r < 0.2$ fm (for discussions about it see below).

Table 10

"Sizes" r_0 for the p-wave πN resonances ($l = 1$).

resonances	$\Delta(1232)$	$N^*(1440)$	$\Delta(1600)$	$N^*(1710)$	$\Delta(1920)$
r_0 (fm)	0.83	0.80	0.73	0.70	0.62

The quantization condition (10) contains four fundamental constants: $f_{\pi NN}$, m, m_π and the parameter r_0. One of them, for example, r_0 can be eliminated fixing its value as a solution of equation (10). So the mass formula (1) contains only three constants: m, m_π and $f_{\pi NN}$. Therefore these three fundamental constants completely determines the gross structure of hadron resonances.

We can now interpret the parameter r_0 in eqs. (1) and (10) as the radius of the 1-st Bohr orbital for the hadron resonances decaying into two-body channels due to strong interaction. Therefore the gross structure of the hadron resonance spectrum can be described as the resonances of the baryon and meson system (for the baryon resonances) or as the resonances of the meson and meson system (for the meson resonances) or as the resonance of the baryon and baryon system (for the dibaryon resonances) confined in the space within a region with the "size" r_0.

Finally, the interplay between the r_0 and $f_{\pi NN}$ is shown in Fig.2. One can see that $r_0 \propto ln(f_{\pi NN})$ as is expected from (10). This character of the analytical dependence $r_0 = r_0(f_{\pi NN})$ allows a new look on the simple use of perturbation theory for strong interactions.

4 Further discussions of the parameters r_0 and r_q

Let us return to hydrogen atoms. The Bohr quantization condition gives us the following expression for the energy eigenvalues

$$E_n = -\frac{me^4}{2n^2\hbar^2} \equiv -\frac{e^2}{2a_1 n^2}. \tag{13}$$

where a_1 is the radius for the first Bohr orbital. The radius for the n-st Borh orbital is equal to

$$a_n = n^2 a_1. \tag{14}$$

It means that a_n increases by increasing n and the first Bohr orbital has the smallest radius.

If we neglect the last term in (1) and subtract $m_1 + m_2$, then we obtain (under the conditions $m_1^2 > (\frac{n+\gamma}{r_0})^2$ and $m_2^2 > (\frac{n+\gamma}{r_0})^2$)

$$E_n \equiv M_n - m_1 - m_2 = \sqrt{m_1^2 + (\frac{n+\gamma}{r_0})^2} + \sqrt{m_2^2 + (\frac{n+\gamma}{r_0})^2} - m_1 - m_2 \approx \frac{1}{2m_{12}}(\frac{n+\gamma}{r_0})^2, \tag{15}$$

where $m_{12} = m_1 m_2/(m_1 + m_2)$. This equation can be obtained immediately from (3) using the nonrelativistic relation $E_n = P_n^2/2m_{12}$.

For s-wave bound states of nonsingular power-law potentials of the form $V(r) \propto r^\nu$ the reduced radial Schroedinger equation can be integrated [17] thus resulting in

$$E_n \propto (n - 1/4)^{2\nu/(2+\nu)}, \tag{16}$$

therefore the power-law potentials cannot give the energy eigenvalues like (15). On the other hand, one can see that the expression (15) coincides with the energy eigenvalues for an infinite rectangular well or resonance energies for the potential of the type $V_0\delta(r - r_0)$ (under the condition $V_0 \to \infty$). This observation indicates that the effective potential for resonances must have the $\delta(r - r_0)$-like functional behaviour as $r \to r_0$.

Therefore we can interpret the parameter r_0 as the confinement radius for the considered resonances.

In ref.[1, 2] we concluded that all baryon resonances can be considered as shape resonances. The special case is the $\Delta(1232)$-resonance, for which two resonance conditions hold simultaneously: with characteristic radii $r_0 \approx$0.86 fm and $r_q \approx$0.2 fm. The estimated value of r_q for the highest Δ-isobars lies in the region $0.1 < r_q < 0.3$ fm. From this and the Heisenberg uncertainty relation we can estimate that for a 2-body case the decay momentum P in the rest frame of the decaying resonance must satisfy the condition $P \leq 1000$ MeV/c. Indeed, one can easily check using the above-mentioned "Review of Particle Properties" that this condition is satisfied for all resonances. The highest value of P is equal to 1126 MeV/c for $N(2600) \to N\pi$ which corresponds to the distance 0.17 fm. It means that the dynamics which determines the phenomenon of hadronic resonances is going in the region $0.2 \leq 0.9$ fm, if we consider "usual" hadrons (without charm and beauty). We use the asymptotic values of momenta in the resonance condition (1) and the mass formula (10) neglecting the interaction between two

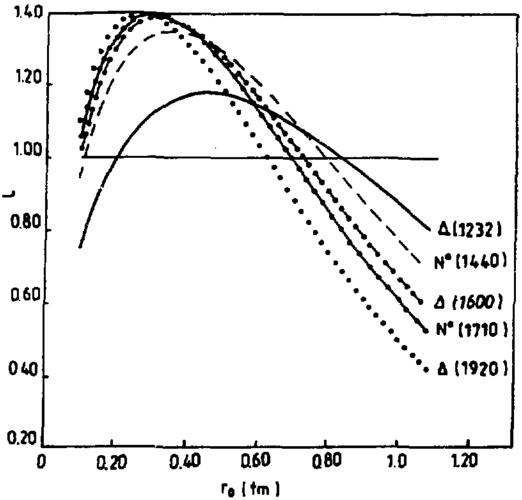

Fig.1 Dependence of the function $F^2(s, r_0)$ on r_0 at s fixed at masses of resonances with $l=1$. The point r_0 where these curves cross line $l=1$ gives r_0 as a solution of equation (10) (see the text).

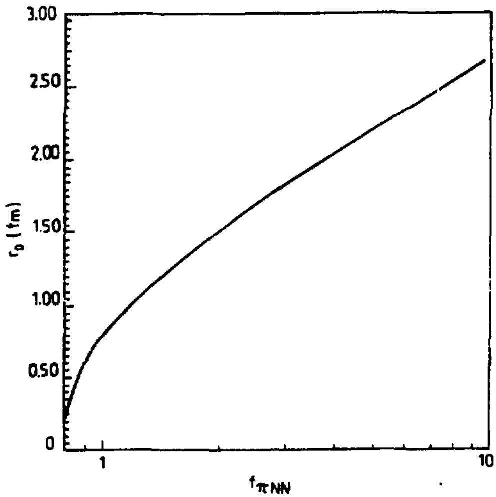

Fig.2 The connection between the parameter r_0 and $f_{\pi NN}$.

particles in the resonance. This is possible only if the interaction potential between the two particles is in the form close · the $\delta(r - r_0)$-like function. All these observations tell us that the resonance two particle decay phenomenon displays many features common to those of the α- decay successfully described by the nuclear cluster model [18].

5 Conclusion

The results obtained for the baryonic resonances [1, 2] with the use of the quasiclassical resonance condition can be easily generalized to all types of hadronic and dibaryonic resonances.

The parameter r_0 in the mass formula (1) and quantization equation (10) has been interpreted as the radius of the 1-st Bohr orbital or as the confinement radius which is nearly the same for all hadron and dibaryon resonances within the experimental accuracy.

Despite the fact that the quantization equation (10) was obtained from the Bohr quantization rule by using the correspondence principle in the evaluation of the πNN-effective interaction and that only one main diagram from all possible ones was taken into account, the accuracy of equations (1) and (10) is surprisingly high. It means that equation (1) could be useful for prediction and estimation of the invariant masses of unknown resonances. This observation requires further systematic investigations. We can only say that the correspondence principle between old classical and quantum theories played an outstanding role in the interpretation of the results of new theories and this "correspondence" allows one to go even into fine details. In this way one can get surprisingly good estimations of the resonance widths using well-known quantum-mechanical prescriptions, as we have demonstrated.

Finally, all arguments given in this paper and refs.[1, 2] bring us to the conclusion that the gross structure of the hadronic resonance spectra can be understood in a full analogy with the Bohr atomic model.

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Гареев Ф.А. и др. E2-92-474
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и дибарионных резонансов

Приведены простые аргументы, основанные на условии квантования Бора и принципа соответствия, для объяснения гросс структуры спектра адронных и дибарионных резонансов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Gross Structure of Hadron
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Simple arguments are given for the explanation of the gross structure of the specrtum of hadron and dibaryon resonances based on the Bohr quantization rule and the correspondence principle.

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

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