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SCALING EFFECTS AND GROSS STRUCTURE OF BARYON RESONANCES SPECTRUM

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1. Introduction

Despite abundant theoretical and experimental publications (see for example [1, 2] and references therein) devoted to the study of the excitations of nucleon and subnucleon degrees of freedom, the Δ-isobar excitations are of great interest mainly due to an enigmatic selectivity of the Δ-isobar excitations. Indeed from the presence of the P_{33}-resonance in πN-scattering it follows logically that this resonance will be excited in nucleon-nucleon collisions while in the nucleon-nucleus collisions the same phenomenon should be much less pronounced. It is natural to expect that first of all a lot of soft low-lying states in nuclei will be excited by a nucleon-nucleus collision. However, one experimentally observed the pronounced Δ-isobar peak (see, for example, the (p,n) [3] and $(^3He, t)$ [4, 5] reaction data on nuclei) on the nonresonance background due to "soft" processes. Therefore the pronounced Δ-isobar peak in reactions of the type $(N, N')_\Delta$ can be considered an analog of giant resonances. If we recall the existence of the shape resonance, then it is natural to search the characteristic quantities having dimensions of length which can help us to understand the problem of selectivity of the Δ-isobar excitations and the systematics of the baryon resonances.

2. Resonances and stationary waves

As a rule, the resonances in wave systems arise if the ratio of the effective radius l_{eff} of a resonating system ("well") to the length λ of the corresponding wave is equal to:

$$l_{eff} = (n + \gamma)\lambda, \tag{1}$$

where n=0,1,2,... and γ is a number of the order $0 \leq \gamma \leq 1$ depending on the boundary conditions for a given degree of freedom and on the type of a dynamical equation for the resonating system [6].

We would like to analyze the spectrum of the Δ-isobar (see the Baryon Summary Table in [7]). From this table we can conclude, neglecting the effects of the L-dependence and spin-orbital interaction, that the spectrum contains four multiplets separated from each other by ~ 400 MeV. Such an oscillator-like character of the gross-structure of the Δ-spectrum admits us to assume that the Δ- resonant states of the πN system can be approximately described by the oscillator potential with the parameter

$< r_0 >= \sqrt{\hbar/m\omega} \sim 0.86$ fm which is close to the electromagnetic radius of the nucleon.

Table 1

Scaling properties of the Δ-isobars. Here $P_\pi(lab)$ is the projectile-pion momentum in the laboratory system corresponding to the maximum of the Δ-resonance cross section in πN-scattering, $P_\pi(cm)$ is the same momentum in the center of mass, $\tilde{P}_\pi(cm)$ is the pion momentum from the Δ-decay in the Δ-isobar rest frame, $< r_0 >= \sqrt{\hbar/m\omega} = 0.86$ fm, γ=0 and n=1,2,3,4.

Resonances	$P_\pi(lab)$ (scatt.) (GeV/c)	$P_\pi(cm)$ (scatt.) (GeV/c)	$\tilde{P}_\pi(cm)$ (decay) (GeV/c)	$1/\tilde{P}_\pi(cm)$ (fm)	$\frac{< r_0 >}{n+\gamma}$ (fm)
Δ(1232)	0.30	0.227	0.227	0.86	0.86
Δ(1620)	0.91	0.526	0.526	0.38	0.43
Δ(1950)	1.54	0.741	0.741	0.27	0.29
Δ(2420)	2.64	1.023	1.023	0.19	0.21

For the pions emitted in the Δ-isobar decay the values of momenta in the Δ-isobar rest frame do not contradict this estimation and coincide with the analogous values of momenta for the pion beam (see Table 1) exciting the Δ-resonances. Besides, the momenta of the emitted pions are within a good accuracy equal to the momentum $\tilde{P}^0_\pi(cm) \sim 0.23$ GeV/c ($\tilde{P}^0_\pi(cm)$ means the pion momentum from Δ(1232) decay) multiplied by the integer. The momentum $\tilde{P}^0_\pi(cm)$ defines the nucleon size, $1/\tilde{P}^0_\pi(cm) \sim 0.86$ fm.

The same calculations were performed for N^* resonances (see Table 2). One can see from Table 2 that the systematics of the N^* resonances based on the use of the "quantum" number n, brings to the indication on the existence of the weak pronounced resonance P_{11} with the mass $m_{N^*} \approx$ 1115-1135 MeV and width $\Gamma < 100$ MeV. The existing experimental data [8, 9] on the total cross section of the $\pi^- p$ scattering do not contradict the above- mentioned suspicion and this resonance can be hidden in the threshold effects.

Table 2

Scaling properties of the N^*-resonances. Here $P_\pi(lab)$ is the projectile-pion momentum in the laboratory system corresponding to the maximum of the N^*-resonance cross section in the πN-scattering, $P_\pi(cm)$ the same momentum in the center of mass, $\tilde{P}_\pi(cm)$ is the pion momentum from

the N^*-decay in the N^*-resonance rest frame, $< r_0 >= \sqrt{\hbar/m\omega} = 0.86$ fm, γ=1/2 and n=0, 1, 2, 3, 4.

Resonances	$P_\pi(lab)$ (scatt.) (GeV/c)	$P_\pi(cm)$ (scatt.) (GeV/c)	$\tilde{P}_\pi(cm)$ (decay) (GeV/c)	$1/\tilde{P}_\pi(cm)$ (fm)	$\frac{< r_0 >}{n+\gamma}$ (fm)
N(1125)?	0.137	0.144	0.144	1.73	1.72
N(1440)	0.610	0.397	0.398	0.50	0.57
N(1710)	1.070	0.587	0.587	0.34	0.34
N(2200)	2.140	0.905	0.894	0.22	0.25
N(2600)	3.120	1.126	1.126	0.18	0.19

The widths of the Δ and N^* resonances have been estimated in the considered approximations and the corresponding results are given in Table 3.

Table 3

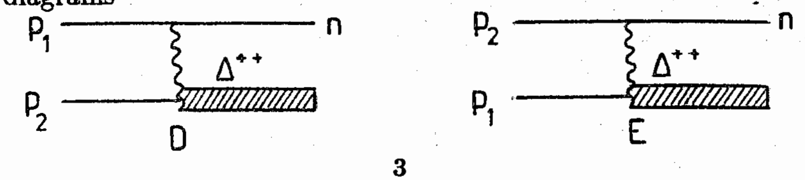
The widths Γ (MeV) of the Δ and N^* resonances.

Δ	Γ_{exp}	Γ	N^*	Γ_{exp}	Γ
Δ(1232)	110-120(115)	140	N(1125)?	~20	<100
Δ(1620)	120-160(140)	180	N(1440)	120-350(200)	160
Δ(1950)	200-340(240)	200	N(1710)	90-130(110)	190
Δ(2420)	300-500(300)	220	N(2200)	300-500(400)	200
			N(2600)	>300(400)	220

Therefore the above-mentioned arguments testify the Δ- and N^* resonances are the shape resonances in πN-scattering. The same conclusion is true for all types of baryon resonances including the strange and charmed ones.

3. Δ-resonances in nucleon-nucleon scattering

The characteristic features of the nucleon-nucleon scattering with the Δ -isobar excitation are the following: 1) the Δ-isobars are excited by virtual pions rather than by real pions and 2) the colliding nucleons are identical particles and therefore two coherent processes contribute to reaction $NN \to N\Delta$. For example the charge-exchange reaction $p+p \to n+\Delta^{++}$ is described by the superposition of the direct (D) and exchange (E) diagrams



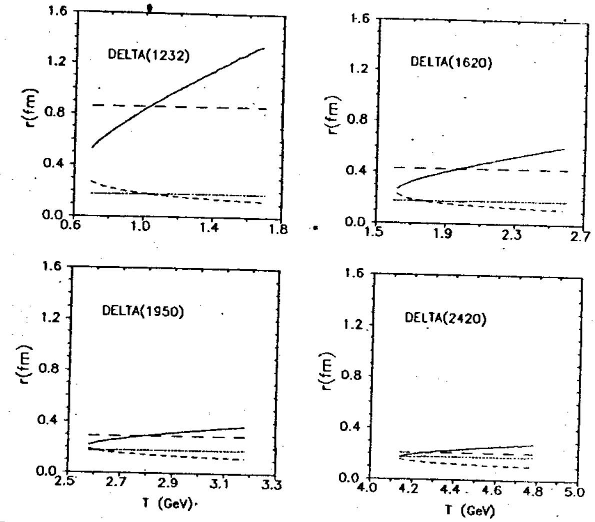


Fig.1 The energy dependence of the direct radius r_d (solid curves) and exchange one r_{ex} (dotted curves). The long-dashed lines correspond to the "nucleon" size $< r_0 >$=0.86 fm while the short-dashed r_q=0.18 fm.

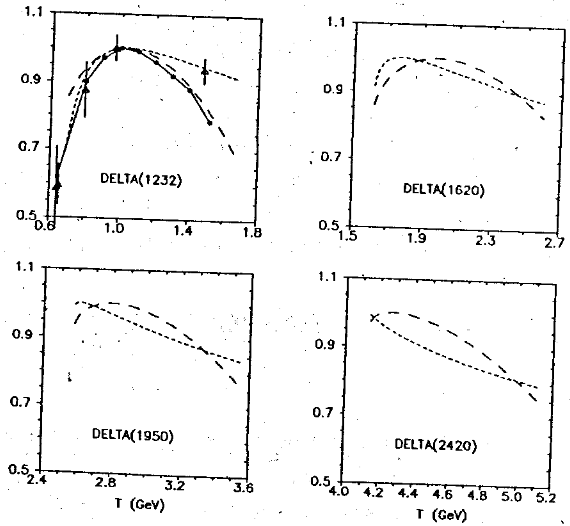


Fig.2 The energy dependence of the functions δx_d (long-dashed curves) and δx_{ex} (short-dashed curves). The triangles (bullets) correspond to the total cross sections of the reaction $p+p \rightarrow n+p+\pi^+$ ($p+p \rightarrow n+\Delta^{++}$) normalized to the unity in the maximum [7].

Therefore, unlike the free πN-scattering, in the reaction $(p,n)_\Delta$ and analogous processes the two characteristic scales have to correspond to two invariant transfer momenta

$$t_d = (P_1 - P_n)^2 = (P_2 - P_\Delta)^2 \equiv t, \qquad (2)$$

$$t_{ex} = (P_2 - P_n)^2 = (P_1 - P_\Delta)^2 \equiv u, \qquad (3)$$

where t and u are the standard Mandelstam variables. We can introduce some distances corresponding to these variables

$$r_d = 1/\sqrt{-t_d}, \qquad (4)$$

$$r_{ex} = 1/\sqrt{-t_{ex}}. \qquad (5)$$

As one can see from Fig.1, for all the main Δ-isobars ($\Delta(1232)$, $\Delta(1620)$, $\Delta(1950)$ and $\Delta(2420)$) the values r_d and r_{ex} for the charge-exchange reaction $p+p \rightarrow n+\Delta^{++}$ at $\theta = 0°$ are close only in the vicinity of the Δ-isobar creation threshold (at the threshold u=t, $s = s_{min}$, where $s = (P_1+P_2)^2$ is the third Mandelstam variable-squared invariant mass of the system). With increasing the projectile-proton energy the value of r_d increases rather quickly while the value of r_{ex} decreases slowly. The starting points of r_d for different isobars change abruptly (roughly speaking according to $\sim 1/n$, where n=1, 2, 3, 4 for the $\Delta(1232)$, $\Delta(1620)$, $\Delta(1950)$ and $\Delta(2420)$ respectively). The same is valid for the values of r_{ex} with the exception that the amplitudes of these jumps are essentially smaller and r_{ex} lies in the region $0.1 \leq r_{ex} \leq 0.3$ fm that is sufficiently close to the value of the characteristic "hard" size of the nucleon: $r_q \sim 0.2$ fm. The quantity r_q can be interpreted either as the radius of the hard core, or of the Jastrov correlations, or as the radius of the constituent quark, or somewhat like this. We will further call r_q as the size of nucleonic constituents without a concrete interpretation.

It is useful to introduce the characteristic functions:

$$\delta x_d \equiv 1 - (\frac{(n+\gamma)r_d - < r_0 >}{< r_0 >})^2, \qquad (6)$$

$$\delta x_{ex} \equiv 1 - (\frac{r_{ex} - r_q}{r_q})^2. \qquad (7)$$

The energy dependence of δx_d and δx_{ex} exhibits a rather prominent resonant character (see Fig.2); the positions of maxima of δx_d and δx_{ex} coincide for the $\Delta(1232)$-isobar case (we used $< r_d >= 0.86$ fm and

r_q=0.18 fm). The curves $\delta x_d(T)$ and $\delta x_{ex}(T)$ are correlated with each other and also with the function

$$\tilde{\sigma_\Delta}(T) \equiv \sigma_{p+p\to n+\Delta^{++}}(T)/\sigma^{max}_{p+p\to n+\Delta^{++}}(T), \tag{8}$$

describing the energy dependence of the total P_{33}-resonant creation cross section [7].

The positions of maxima of the δx_d and δx_{ex} become different with increasing the Δ-isobar mass; the maximum of δx_{ex} rapidly approaches the Δ-isobar creation threshold and comes to the kinematically forbidden region of the Δ(2420).

The above-mentioned behaviour of quantities δx_d and δx_{ex} can be interpreted in the following way. In the energy region $T \approx 1$ GeV the "direct" virtual pion comes in the resonance with the nucleon as a whole while the "exchange" virtual pion comes simultaneously in the resonance with constituent of the nucleon. The constructive interference between the "direct" and "exchange" amplitudes leads to the resonance amplification of the Δ-isobar creation cross section and also to the remarkable increase of the total and inelastic cross section for p+p collision [7, 13]. With the increasing beam energy the "direct" and "exchange" resonances move apart from each other; therefore the Δ(1232)-isobar is excited weakly at $T_p > 3$ GeV. The formation of heavier Δ-resonances in proton-proton collisions is always suppressed due to the break-down of the resonance conditions for the "direct" and "exchange" amplitudes. The suggested twofold scaling model of the Δ-isobar creation allows us also to explain qualitatively the disappearance of the heavier Δ-resonances. Indeed, in accordance with the Table 1 the condition

$$\frac{< r_0 >}{n+\gamma} \geq r_q, \tag{9}$$

does not fulfil at n=5 this means that the wave length of the pion becomes smaller than the size of constituent and the wall of the "nucleonic potential well" is screened by r_q.

The selective excitation of the Δ(1232)-isobar in the energy region $T_p \sim 1$ GeV can be considered as a display of the twofold shape resonance. From the point of view of the scattering theory such resonance can be interpreted as an anomalous amplification of the process due to the fulfillment of condition for the simultaneous resonance interaction in the final (initial) states of the two pairs of particles [10] (in our case the interaction of the virtual pions with the nucleon and constituent).

4. Quasiclassical arguments

Let us rewrite the resonance condition (1)

$$P\frac{l_{eff}}{2\pi} \equiv Pr_0 = n + \gamma, \tag{10}$$

where $P = 2\pi/\lambda$. It is interesting to note that a similar condition of the resonance holds for wave systems of any physical nature irrespective of a concrete dynamical equation. From another side we can write the Heisenberg uncertainty relation

$$Pr_0 \geq \frac{1}{2}. \tag{11}$$

One can see that equations (10) and (11) are very similar, solutions of (10) are always solutions of equation (11). For example, the Bohr-Sommerfeld quantatization condition for the hydrogen atoms is given as

$$L = (n+\gamma)\lambda, \tag{12}$$

where n=1,2,3,...and γ=0 (or n=0,1,2,...and γ=1), $L = 2\pi R$, R is the radius of the Bohr orbital, $\lambda = h/mv$ and equation (12) can be rewritten as (here we used the atomic notation)

$$PR = n\hbar, \tag{13}$$

which coincides with equation (10) and obeys equation (11).

For an atomic, system the Heisenberg uncertainty relation is $PR \geq \hbar$ (not $\geq \hbar/2$) due to the fact that wave packets for atomic systems are essentially different from the Gaussian form. The Gaussian form of wave packets corresponds to the $PR \geq \hbar/2$ and numerous calculations in the Glauber approximation in the elementary particle physics tell us that the wave packets for elementary particles have a Gaussian form. Therefore in this case we obtain γ=1/2 and n=0, 1, 2,...

Let us consider the baryon resonance as a system consisting of a meson and a baryon. The invariant mass of the baryon resonance is given by

$$\sqrt{s} = \sqrt{P_\mu^2 + m_\mu^2} + \sqrt{P_B^2 + m_B^2} \equiv \sqrt{P_\mu^2 + m_\mu^2} + \sqrt{P_\mu^2 + m_B^2}, \tag{14}$$

where the indices μ and B refer to the meson and baryon respectively. The invariant mass of the baryon resonance at the resonance peak according to our above-discussed calculations can be written as follows:

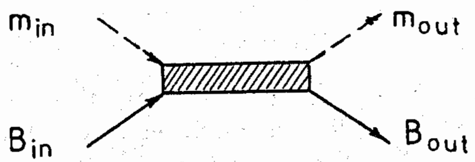
$$M_n(B) = \sqrt{m_\mu^2 + (\frac{n+\gamma}{r_0})^2} + \sqrt{m_B^2 + (\frac{n+\gamma}{r_0})^2} + \Delta M_n, \tag{15}$$

where $\Delta M_n < \Gamma$ is the correction for the dependence of the baryon resonance invariant mass on different quantum numbers and by definition it is equal to

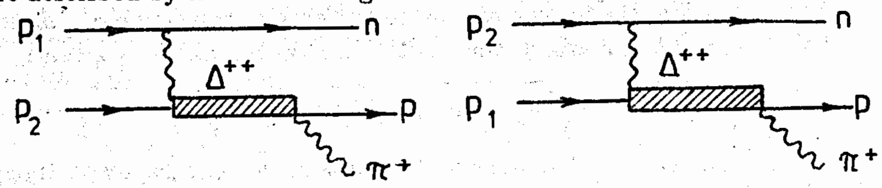
$$\Delta M_n(I,l,J,P,S,C,..) = \sqrt{s} - \sqrt{m_\mu^2 + (\frac{n+\gamma}{r_0})^2} + \sqrt{m_B^2 + (\frac{n+\gamma}{r_0})^2}. \quad (16)$$

Formula (15) for the baryon resonance mass is an analog of the Weiczekker formula for the nuclear mass in the sense that the leading term in (15) describes the gross properties of resonances and the corrections due to the concrete structure of the considering multiplet. It is interesting to note that a quite analogous mass formula with the same mathematical structure was obtained in the bag models [11, 12]. The leading term of the mass formula was obtained from the general resonance condition which can be applied to any system ($\lambda \le r_0$) irrespective of the dynamical equation of motion and concrete models in which the corrections ΔM can be calculated.

All reactions with creation of baryon resonances and their subsequent decay due to the strong interaction are described by diagrams of the type where m_{in} (m_{out}) and B_{in} (B_{out}) are ingoing (outgoing) mesons and



baryons respectively, the fat solid line is the propagator of the corresponding baryon resonance. This structure is the same for the real and virtual incoming mesons and is independent of the method of registration of final states. For example, the reactions $p+p \to n+\Delta^{++} \to n+p+\pi^+$ are described by the sum of diagrams and the inclusive cross section with



the registration of neutrons is equal to (see the notation in [13])

$$\frac{d^2\sigma}{d\Omega_n dE_n} = \frac{2m^3 P_n}{\lambda^{1/2}(s,m^2,m^2)(2\pi)^3}\Gamma_\Delta(s_\Delta) \mid G_\Delta(s_\Delta) \mid^2$$

$$S_f <\mid M(p+p \to n+\Delta^{++}) \mid^2>, \quad (17)$$

$$\mid G_\Delta(s_\Delta) \mid^2 \approx \frac{4M_\Delta^2}{(M_\Delta^2 - s_\Delta)^2 + M_\Delta^2\Gamma_\Delta^2}, \quad (18)$$

$$\Gamma_\Delta = \frac{1}{6\pi}(\frac{f_{\pi N\Delta}}{m_\pi})^2 P_\pi^3 \frac{m}{\sqrt{s_\Delta}}, P_\pi = \sqrt{E_\pi^2 - m_\pi^2}, E_\pi = \frac{s_\Delta - m^2 + m_\pi^2}{2\sqrt{s_\Delta}}, \quad (19)$$

where $M(p+p \to n+\Delta^{++})$ is the creation amplitude for the Δ-isobar.

Formula (17) is obtained in the $\pi + \rho + g'$ model [2, 14] neglecting contributions of the decay amplitudes [13, 15]. In the vicinity of the Δ-resonance this approximation is well argued for reactions $p+p \to n+X$ and $n+p \to p+X$. This approximation becomes worse when going away from the Δ-peak especially for processes $n+p \to p+X$ [13] while formula (17) is still reasonably good for integral effects and qualitative estimations.

Expression (17) contains the "nucleonic" ($< r_0 >$=0.86 fm) and "constituent" ($r_q \approx$0.2 fm) sizes in a factorized form. Indeed, the resonance term $\Gamma_\Delta(s_\Delta) \mid G_\Delta(s_\Delta) \mid^2$ reaches a maximum at $s_\Delta = M_\Delta^2$, which is possible according to (14), (15) and table 1 at n=1, γ=0, r_0=0.86 fm and

$$M_\Delta = \sqrt{m_\pi^2 + (\frac{1}{0.86})^2} + \sqrt{m^2 + (\frac{1}{0.86})^2} + \Delta M_\Delta, \quad (20)$$

while $\Delta M_\Delta \ll \Gamma_\Delta(M_\Delta)$. Therefore the "nucleonic" size $< r_0 > \approx$0.8 fm is hidden in the propagator of the Δ-isobar.

The amplitude $M(p+p \to n+\Delta^{++})$ contains the form factors $F_{\pi NN}$ and $F_{\pi N\Delta}$, in which the scale $r \sim 0.2$ fm is hidden. Therefore the mathematical structure of the theory is such that the essential amplification of the cross section $d^2\sigma/d\Omega dE$ or σ_{tot} is only possible when the resonance on the size $r_0 \sim 0.8$ fm exists simultaneously with the resonance on the size $r_q \sim 0.2$ fm.

Formula (17) is the first term of the Mittag-Leffler expansion of the NN amplitudes over resonances and can be generalized to the case of an arbitrary resonance by the change $M_\Delta \to M_n$.

Finally we would like to remark that the resonance parameterizations of electromagnetic formfactors of the nucleon was used in the 50's [16] (which are an analogous as to the form and as to the physical content to the vertex functions $F_{\pi NN}$, $F_{\rho NN}$, ...). In the same time twofold resonance models were investigated in the electron-nucleon scattering [17]. However the resonance form factors for the "kern" and "resonance" were introduced in the additive form. As result it was impossible to satisfy to the first principle of the quantum field theory and existing experimental data (see details in [18]).

5. Conclusion

The results obtained for the Δ-isobar resonances [19] can be generalized for all types of baryon resonances including the strange and charmed ones.

The possibility of using the quasiclassical resonance condition is analyzed in the baryon resonance physics. It is shown that this approximation allows us to describe the gross structure of the baryon spectrum. In these studies the baryon resonances were treated as baryons plus mesons. We conclude that all baryon resonances have within the experimental uncertainty the same characteristic size $r_0 \sim 0.8$ 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 shape resonances while only the $\Delta(1232)$-resonance displays as the twofold shape resonance, which causes its unique distinction and selectivity in the pion-nucleon and pion-nuclear physics.

The leading term in the mass formula is obtained for baryon resonances irrespective of the form of the concrete dynamical equation of motion or models. This formula is very close in structure to analogous expressions in bag models, which can be considered as a serious phenomenological argument in favour of bag models.

In the considered quasiclassical approach the widths of the Δ and N^*-resonances are described with a reasonable accuracy. The qualitative explanation of the selectivity for the Δ-isobar excitation in reactions of type $(p,n)_\Delta$ and $A(p,n)_\Delta B$ is given. We conclude that a simple diffraction mechanism is responsible for the disappearance of heavier baryon resonances (the limitation of baryon resonances from above).

The interpretation of the quantities $< r_0 >$ and r_q requires further investigations; at least they are very close to the radius of the quark-quark potential (0.2 fm) and to the size of the 6-quark system (0.8 fm) [20] respectively. We use 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's poles in the elementary particle physics.

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Масштабные эффекты
и гросс структура спектра
барионных резонансов

Приведены простые аргументы, связанные с размерными эффектами, для объяснения гросс структуры спектра барионных резонансов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1992

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Scaling Effects and Gross Structure
of Baryon Resonances Spectrum

Simple arguments are given for the explanation of the gross structure of the spectrum of baryon resonances based on the scaling analysis.

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

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