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# INVESTIGATION OF THE GROSS STRUCTURE OF SPECTRA AND MASS DISTRIBUTIONS OF HADRONIC RESONANCES

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# 1 Introduction

In earlier papers [1]–[3] we outlined an approach to describe resonance spectra of hadronic resonances having strong 2-particle decay modes. This approach was surprisingly successful in reproducing the known resonances. The invariant masses of unknown hadronic resonances were also predicted. Moreover, it allowed us to get rather good estimates of widths for those resonance families (including dibaryons), where the interaction potential between their decay products is more or less well known.

The aim of this article is to extend the systematical investigation of the gross structure of hadronic resonance spectra and their mass distributions in framework of the suggested approach.

# 2 General arguments

Our point of view is based on some very general key points: 1) every hadronic resonance can be treated as a radiating system confined in the coordinate space within a region with the characteristic size $r_0$=0.86 fm; 2) when this system has a non-negligible 2-particle decay mode, it can be considered as a corresponding binary particle system at the final stage of its life; 3) for a system of that sort the classical resonance (eigen-frequency) condition is valid for the existence of eigenwaves in an open radiating resonator (antenna) with the effective size $r_0$:

$$Pr_0 = (n + \gamma), \tag{1}$$

Here $P$ is the asymptotic momentum (i.e. the momentum measured in experiment) of decay products taken in the rest frame of the resonance, $n$ is an integer positive number and $0 \leq \gamma \leq 1$ is a number that depends on the boundary conditions for a given degree of freedom and on the type of dynamical equation for the resonating system. The case ($\gamma$=1/2 and l=n=0, 1, 2,...) can be interpreted as the radial quantization (see details in ref.[4])

$$Pr_0 = l + 1/2, \tag{2}$$

while the case ($\gamma$=0 and n=l=1, 2, 3,...) can be considered as the well-known Bohr-Sommerfeld orbital quantization

$$Pr_0 = l. \tag{3}$$

Note that the wavelength $\lambda_1 = 2\pi/P$ corresponding to the first resonance ($n = 1$ for $\gamma = 0$ and $n = 0$ for $\gamma = 1/2$) must be of an order of $r_0$; that one can see from dimensional considerations (for details see ref. [2]). This is a difference with the Bohr-Sommerfeld quantization conditions for a bound state, where the wavelength $\lambda_1$ must be smaller than the characteristic size of the considered system, as it is well known.

In order to calculate invariant resonance masses for given pairs of decay product (meson+meson, baryon+meson, baryon+baryon), a mass formula that incorporates the above-mentioned key points was used in papers [1]-[3] with the same value of the parameter $r_0 = 0.86 fm$ fixed in all calculations presented below and in refs.[1]-[4] as well:

$$m_n(R) = \sqrt{m_1^2 + P^2} + \sqrt{m_2^2 + P^2} = \sqrt{m_1^2 + (\frac{n+\gamma}{r_0})^2} + \sqrt{m_2^2 + (\frac{n+\gamma}{r_0})^2}, \quad (4)$$

where $R$ labels the resonance, the indices 1 and 2 refer to the constituents 1 and 2 observed in the 2-particle decay of the resonance $R \to 1+2$, respectively. This mass formula describes only the "center of gravity" position of the corresponding multiplets, in other words, the gross structure of the hadron and dibaryon resonances. The fine structure of each multiplet is determined by residual interactions and corresponding quantum numbers that are not contained in the approach [1]-[3].

Some examples of our predictions (covering low and high invariant masses including also bottomonium region) and comparison with recent data were given in refs. [1]-[4]. Very exciting correlations between the calculated results and experimental data were obtained. The parameter $r_0 = 0.86 fm$ was associated with the first Bohr orbital or with the confinement radius in refs. [1]-[4] . It is worthwhile to note that the method of the identical particles interferometry (see review paper [5]) was successfully used in order to measure sizes of particle emission regions. As an example we show in Fig.1 the data (taken from compilation [6]) on sizes of the pion emitting region $R_0$ in $e^+e^-$ collisions versus center-of-mass energy. One can see that $r_0$ is very close to $R_0$. Therefore the parameter $r_0$ can be interpreted as the radius of the particle radiation region.

The quantization condition (1) of the asymptotic momenta for a resonating system was obtained in the papers cited above in a heuristic way. We have recently derived Eq.(1) from general quantum mechanical arguments starting from the well-known R - matrix theory of the resonance reactions[4]. It was shown that the resonating system has waves with the wavelength of the order $r_0$ or $Pr_0 \approx l + 1/2$ well localized near its surface. This phenomenon is in a full analogy (in the correspondence principle sense) with the "whispering gallery" phenomenon in acoustics first observed by Rayleigh [7] in 1910, with open radiating resonators in classical electrodynamics [8] and with the rainbow and glory effects [9]. The same phenomenon was observed in the consideration of the "stadium billiard" problem in classical mechanics [10, 11, 12]. It is interesting to mention that in nuclear physics the significant non-uniformity of the distribution of single-particle energies (gross shells, properties of magic nuclei, non-sphericity of nuclei, gross structure of resonances in the optical model, etc.) is a result of the semiclassical quantization of motion along many-dimensional closed orbits (see refs. [13, 14] for details and bibliography).

The question of what are underlying reasons for such a surface localization is beyond the scope of this paper; still it is worthwhile to note that it is effects of refraction of inner waves that are responsible for emergence of the localized surface-like waves in the examples mentioned above. Therefore we would like to exploit the wave nature of particles at low energies when their de Broglie wavelengths are of the same order as the radius of strong interactions.

In short, our general physical conception of resonances is as follows: *it is the periodic motion and refraction of waves in the restricted region of space that are* *responsible for the creation of resonances in any resonating system. Within the R-matrix approach we put at the boundary of this region the condition of radiation of physical particles that can be observed at large (asymptotic) distances and require proper matching of corresponding "external" wave functions with the "inner" part of the wave function of the considered system. This "inner" part can be constructed using any reasonable existing model and at distance $r_0$ it must be projected into physically observed states for matching with the "external" part.*

The general structure of the resonance spectra is not understood yet; there are no reliable predictions that could be used in searches for new or exotic resonances. On the other hand, resonance phenomena are typical for nuclear physics; studies of their gross properties resulted in the most fundamental notions of the nuclear physics; they were carried out using rather general and simple approaches with great success. These approaches are used to predict new nuclear resonances, their strengths, widths and quantum numbers. Therefore it seems instructive to look for possible analogies between hadronic and nuclear resonances and to apply some ideas and methods developed in nuclear theory for the problem of hadronic resonances.

# 3 Density of mesonic states

A simplified version of the strength function method can be used for calculations of the numbers and densities of experimentally well established [16] meson states (except strange mesons due to their scarce statistics) as function of their invariant masses (for details see monograph [15]). With this goal we have taken the density of mesonic resonant states as a sum of normalized Breit-Wigner distributions:

$$\frac{dN}{dm} = \frac{1}{2\pi}\sum_i A_i \frac{\Gamma_i}{(m - m_i)^2 + \Gamma_i^2/4}, \tag{5}$$

where $m_i$ and $\Gamma_i$ are the masses and widths of the experimentally observed mesonic resonant states [16], $A_i = (2J_i + 1)(2I_i + 1)$ is the number of states per resonance. The total mesonic density (full curve) is plotted in Fig.2 as function of $m$. One can see that this density displays the regular periodic oscillation structure with a period $\Delta m \approx 200$ MeV (predicted in ref.[3]) in regions of the light unflavored mesons (S=C=B=0), charmed and bottom mesons.

# 4 Light unflavored mesons (S=C=B=0)

The results of our calculations are strongly correlated with the experimental data (Fig.3; stars: calculated "center of gravity" of positions of the $n$-pion resonances) except the region of the dipion mass $m(\pi\pi)_S$=360 MeV and the region of the 6-pion or $\eta\eta$ mass $m(\eta\eta)_S$=1118 MeV. We think that these regions require more attentive experimental investigation (for a detailed discussion see ref.[3]). The invariant masses of resonances decaying into $n$-pions were calculated in the following way. First, we calculate the dipion mass in the ground state resonance ($m(\pi\pi)_S$=360 MeV using the quantization condition ($Pr_0 = l + 1/2$=1/2) according to Eq. (2); then we again exploit this formula using $m(\pi\pi)_S$=360 MeV and the mass of third pion

$m((\pi\pi)_S\pi)_S$, and so on. This is a method for calculating and predicting the invariant resonant masses of clusters, which may consist of $n$-particles of a different physical nature as we demonstrated in the above-mentioned publications. Prediction for the resonance production of clusters nearly above threshold is important due to the scarce information about it.

To summarize this section we say the following: the mass spectrum for the ground state resonances has almost equidistant character and the distance between the resonances ("center of gravity" of resonances) is equal to ≈200 MeV if these resonances are created by simply adding pions step by step. Adding K-mesons gives the distance of about 500 MeV ($m_{theor}(K^+K^-)_S$= 1014 MeV, $m_{theor}((K^+K^-)_S K)_S$ = 1533 MeV, $m_{theor}((K^+K^-)_S(K^+K^-)_S)_S$ = 2052 MeV); adding D-mesons: about 1900 MeV; adding B-mesons: about 5300 MeV, and so on. Then the rotational-like states should be based on the "ground state" resonances [3].

# 5 The charmonium system

The modern status of the charmonium system was presented by T.Barnes in the review talk [17]. The charmonium system can be considered using complementary approaches.

1. The properties of this system is usually described as radially excited $c\bar{c}$ states (see ref.[17] for details).

2. Within the concept described in Sect.2, the mass distribution of this system can be evaluated using the formula (4) for n-pion resonances. The state $((8\pi)_S(8\pi)_S)_P$ with the mass 3100 MeV looks like a candidate for the $J/\psi(3097)$ state; the states $(J/\psi(3097)\pi)_S$, $(J/\psi(3097)(2\pi)_S)_S$ and $(J/\psi(3097)(6\pi)_S)_S$ with the masses 3280, 3478 and 4240 MeV respectively are not observed so far; the state $(J/\psi(3097)(4\pi)_S)_S$ with mass 3866 MeV seems to be observed: there are some indications on existence of the state with the mass 3836 MeV [18]. The states $(J/\psi(3097)(3\pi)_S)_S$, $(J/\psi(3097)(5\pi)_S)_S$ and $(J/\psi(3097)(7\pi)_S)_S$ with the masses 3668, 4053 and 4438 MeV can be decay products of the states $\psi(3685)$, $\psi(4040)$, $\psi(4415)$ respectively. The results of our calculations are displayed in Fig.4.

3. The charmonium states (at least some of them) might be a dimeson in P-state $(D\overline{D})_P$, $(D\overline{D}^*)_P$, $(D^*\overline{D}^*)_P$ molecular states following to suggestion by Voloshin and Okun [19], similarly to the $K\overline{K}$-molecule description of the $f_0(975)$ and $a_0(980)$ proposed subsequently by Weinstein and Isgur [20]. Indeed, the experimental data and our calculations according to the formula (4) show that the states $\psi(3770)$ and $\psi(4040)$ are candidates for such dimeson molecular states (our model describes very well as the masses of these resonances as decaying momentum too, see Table 1; the state $(D\overline{D}^*)_P$ with the mass 3906 (our estimation) is not observed in experiment).

Table 1
Calculated masses of the some charmonium states

$\eta_c(2980), I^G(J^{PC}) = 0^+(0^{-+})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $(\omega(1390)\omega(1600))_S$ | – | | 115 | 2999 | 1/2 |
| $((\phi\phi)_S\eta'(958))_S$ | – | – | 115 | 3021 | 1/2 |

$J/\psi(3097), I^G(J^{PC}) = 0^-(1^{--})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $((8\pi)_S(8\pi)_S)_P$ | – | | 229 | 3100 | 1 |
| $(\Xi(1530)\overline{\Xi}(1530))_P$ | – | – | 229 | 3098 | 1 |

$\psi(3686), I^G(J^{PC}) = ?^?(1^{--})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $(J/\psi(3097)\eta(547))_S$ | 2.7% | 196 | 115 | 3658 | 1/2 |
| $(J/\psi(3097)(\pi^0\pi^0)_S)_D$ | 18.4% | 481 | – | 3704 | 2 |
| $(J/\psi(3097)(\pi^+\pi^-)_S)_D$ | 32.4% | 477 | – | 3714 | 2 |

$\psi(3770), I^G(J^{PC}) = ?^?(1^{--})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $(D\overline{D})_P$ | dominant | 242 | 229 | 3766 | 1 |
| $(\eta_c(2980)\omega(783))_S$ | not seen | — | 115 | 3773 | 1/2 |

$\psi(4040), I^G(J^{PC}) = ?^?(1^{--})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $D^0\overline{D}^0$ | seen | 774 | 803 | 4059 | 3+1/2 |
| $D^*(2010)^0\overline{D}^0$ | seen | 577 | 574 | 4040 | 2+1/2 |
| $(D^*(2010)^0\overline{D}^*(2010)^0)_P$ | seen | 228 | 229 | 4040 | 1 |
| $(\eta'(958)J/\psi(3097))_S$ | not seen | — | 115 | 4064 | 1/2 |
| $(\eta_c(2980)\phi(1020))_S$ | not seen | — | 115 | 4010 | 1/2 |
| $(J/\psi(3097)(5\pi)_S)_S$ | not seen | — | — | 4053 | 1/2 |

$\psi(4160), I^G(J^{PC}) = ?^?(1^{--})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $(\psi(3770)(\pi^-\pi^+)_S)_S$ | not seen | — | 115 | 4150 | 1/2 |

$\psi(4415), I^G(J^{PC}) = ?^?(1^{--})$

| Decay modes | Fraction $\Gamma_i/\Gamma$ | P(exp) | P(theor) | m(theor) | $n+\gamma$ |
|---|---|---|---|---|---|
| $(23\pi)_S$ | not seen | — | — | 4416 | 1/2 |
| $(J/\psi(3097)\eta(1295))_S$ | not seen | — | 115 | 4402 | 1/2 |
| $(J/\psi(3097)(7\pi)_S)_S$ | not seen | — | — | 4438 | 1/2 |

One can find in the Table 1 a number of unobserved decay channels for the well established resonances. The characteristic feature of all these unobserved channels is that the corresponding decay momentum *is small:* $\sim 100\ MeV/c$.

Finally, **the charmonium system might have molecular states in three-meson ($1^{--}$) decay channels**. We suggest the following candidates:

- for $\eta_c(2980)$ - decay: the system $[[\eta'(958)\eta'(958)]_P\eta'(958)]_P$ with the mass 2970 MeV,
- for $J/\psi(3097)$: the system $[[\phi(1020)\phi(1020)]_S\phi(1020)]_S$ with the mass m=3082 MeV,
- for $\psi(3686)$: the system $[[\phi(1020)\phi(1020)]_S\omega(1600)]_S$ with the mass m=3660 MeV,
- for $\psi(4160)$: the system $[[\omega(1390)\omega(1390)]_S\omega(1390)]_S$ with the mass m=4180 MeV,
- for $\psi(4415)$: the system $[[\omega(1390)\omega(1390)]_S\omega(1600)]_S$ with the mass m=4395 MeV.

# 6 The bottomonium system

The modern status of the bottomonium system was presented by D.Besson and T.Skwarnicki in the review paper [21]; see also recent results from CLEO Collaboration [22]. The bottomonium is usually described as radially excited $b\bar{b}$ system. Our results obtained within the concept described in Sections 2 and 5 are shown in Fig.5. They are surprisingly well correlated with the experimental data except the regions of masses 9640, 9840 and 10227 MeV. Like in the case of charmonium, the dimeson $(B\overline{B})_P$ molecular state with the mass 10568 MeV can be put in correspondence with the $\Upsilon(10580)$. The dimeson states $(B\overline{B}^*)_P$ and $(B^*\overline{B}^*)_P$ with masses 10614 and 10660 MeV respectively are not observed.

Finally, as in the charmonium case, **the bottomonium system might also have molecular states in three charmonium meson ($1^{--}$) decay channels**. We suggest the following candidates:

- for $\Upsilon(9460)$ - decay: the system $[[J/\psi(3097)J/\psi(3097)]_S\psi(3280)]_S$ with the mass 9481 MeV,
- for $\Upsilon(10023)$ - decay: the system $[[J/\psi(3097)J/\psi(3097)]_S\psi(3770)]_S$ with the mass 9971 MeV,

- for $\Upsilon(10355)$ - decay: the system $[[J/\psi(3097)J/\psi(3097)]_S\psi(4160)]_S$ with the mass 10361 MeV.

- for $\Upsilon(10580)$ - decay: the systems $[[J/\psi(3097)J/\psi(3097)]_S\psi(4415)]_S$ and $[[J/\psi(3097)\psi(3685)]_S\psi(3770)]_S$ with the masses 10615 and 10559 MeV respectively,

- for $\Upsilon(10860)$ - decay: the system $[[J/\psi(3097)\psi(3685)]_S\psi(4040)]_S$ with the mass 10829 MeV,

- for $\Upsilon(11020)$ - decay: the system $[[J/\psi(3097)\psi(3685)]_S\psi(4240)]_S$ with the mass 11028 MeV.

The following systems are not observed so far:

1. $[[\eta_c(2980)\eta_c(2980)]_P\eta_c(2980)]_P$ with the mass 8971 MeV,

2. $[[J/\psi(3097)J/\psi(3097)]_SJ/\psi(3097)]_S$ with the mass 9298 MeV,

3. $[[J/\psi(3097)J/\psi(3097)]_S\psi(3478)]_S$ with the mass 9679 MeV,

4. $[[J/\psi(3097)J/\psi(3097)]_S\psi(3685)]_S$ with the mass 9886 MeV (there are some indications on existence of this state [23]),

5. $[[J/\psi(3097)J/\psi(3097)]_S\psi(4040)]_S$ with the mass 10241 MeV,

6. $[[J/\psi(3097)\psi(3685)]_S\psi(4415)]_S$ with the mass 11203 MeV (there are some indications on existence of this state [24]).

Thus the suggested mass formula should give almost the same mass of a resonance for every of its 2-particle, 3-particle,... n-particle decay modes and *exactly the same mass within* a *full coupled - channel treatment* without changing the parameter $r_0$ if the approach is self-consistent. Multiparticle decays can be considered as a chain of binary decays: the 2-particle decay of a "primary" resonance into two clusters; than these clusters again decay into 2-particles and so on. This is consistent with the observation that multiparticle decay production processes proceed mainly through resonance production and their subsequent decay. Therefore the multiparticle decays can be treated as a tree-like phenomena where the intermediate resonances play an essential role. It indicates a way how to use the suggested approach in studies of such decays of resonances.

We demonstrated that the three-meson $(1^{--})$ molecular states in decay channels should play an essential role in understanding of mass distributions of systems with charm and bottom. It is remarkable that **the $\psi$ particles are about 3 times heavier than the $\phi$ and $\omega$ particles. The $\Upsilon$ particles are about 9 times heavier than the $\phi$ and $\omega$ particles and about 3 times heavier than the $\psi$ particles.**

The main characteristic feature of such molecular-type states is the following: the relative momentum in any binary subsystem is very low: $\sim$ 100 MeV/c. Therefore the observed phenomena is the low energy resonance and requires an additional investigation.

It justifies further assumption that **three-meson ($1^{--}$) molecular states might be in the regions 27- 33 GeV, 81-100 GeV (W and Z boson region) 240-300 GeV** and so on.

Finally, it seems extremely interesting to note that the molecular states in three-particle decay channels exist also for different meson and baryon resonances. We indicate here a few of them as examples for consideration only:

- for $\eta(547)$ - decay: the system $[[\pi\pi]_S\pi]_S$ with the mass 556 MeV,
- for $\eta'(958)$ - decay: the system $[[\pi\pi]_S\eta]_S$ with the mass 938 MeV,
- for N(1440) $P_{11}$ - decay: the system $[[N\pi]_P\pi]_S$ with the mass 1420 MeV,
- for N(1520) $D_{13}$ - decay: the system $[[N\pi]_P\pi]_P$ with the mass 1522 MeV,
- for $(PP\pi)(2065)$ [25, 26] decay: the system $[[pp]_S\pi]_S$ with the mass 2076 MeV.

# 7 Baryons

The density of baryonic states was calculated as was described in Sect.3. All well established baryonic resonances were included. The theoretical evaluation was carried out within the following conception: the mass formula (4) is used for the decay channel states $[N[n\pi]_S]_S$ and $[[[N\pi]_P \equiv \Delta][n\pi]_S]_S$. The results of calculations are shown in Fig.6. We conclude that the mass spectrum for the baryonic resonances has almost equidistant behaviour and distances between "center of gravity" of resonances is equal to $\approx$ 100 MeV.

# 8 Conclusion

Following our general physical conception of resonances we carried out the systematical investigation of the gross structure of spectra and mass distributions of all known hadronic resonances starting from light mesons and ending with bottomonium resonances. The Balmer-like mass formula obtained from first principles in refs. [1]-[4] was used in this study; its accuracy is surprisingly high and unusual for this branch of physics.

The regular periodic structures in the invariant mass distribution of resonances is established. They have the period $\Delta m \approx$200 MeV in regions of the light unflavored, $\psi$ and $\Upsilon$ mesons and $\Delta m \approx$100 MeV for baryon resonances. Such regular behaviour of the invariant mass of resonances is due to the emergence of many-dimensional closed orbits where some states have the regions of high amplitude as in the standard nuclear physics [13, 14].

Results of systematical investigations carried out in this paper and papers [1]-[4] of the invariant mass distribution of resonances confirm that our general conception is adequate to the physics of the processes under consideration. The approach based on this conception has one **fixed** constant $r_0 = 0.86 fm$ which can be interpreted as a radius of the particle radiation region. The question is now, is this parameter really an universal one. We have all the time used the asymptotic values of the momenta in

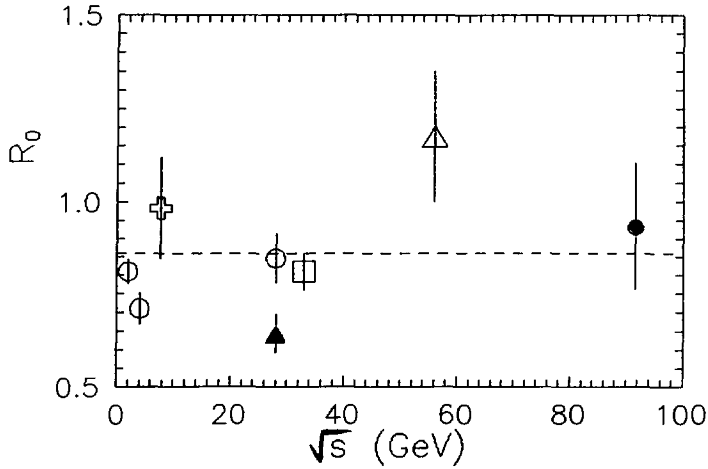


Fig.1 The experimental data on size of the pion emitting region $R_0$ in $e^+e^-$ collisions versus center-of-mass energy (taken from compilation [6]).

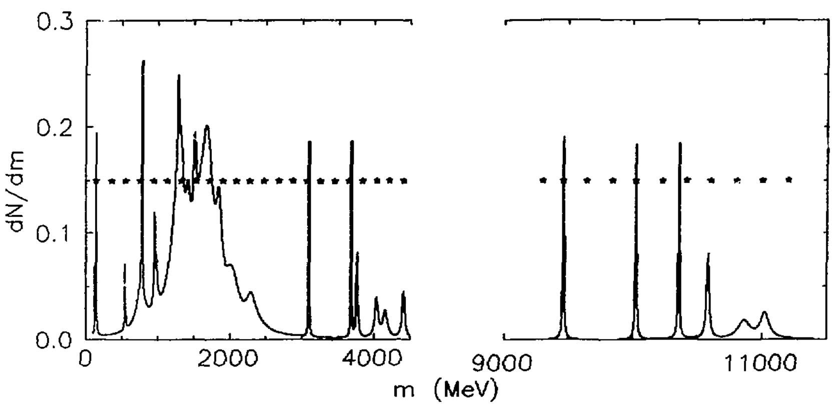


Fig.2 Total density distribution (full line) of well established experimentally [13] meson states as function of mass, and "center of gravity" (stars) position of the n-pion resonances calculated according the formula (4).

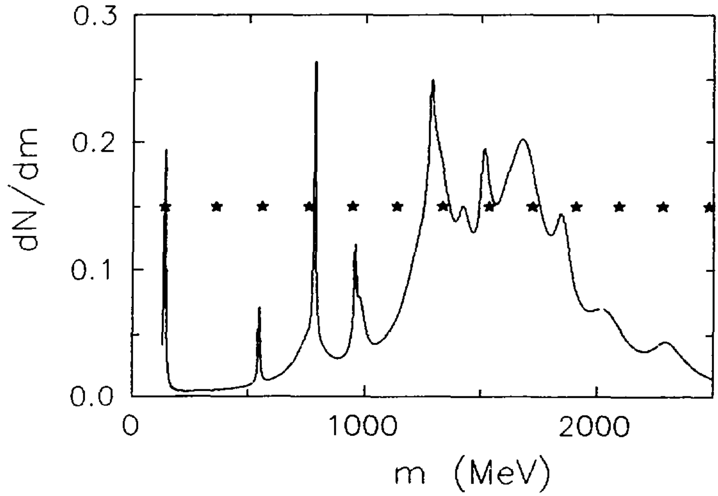


**Fig.3** The same as on Fig.2 but for the light unflavored meson states.

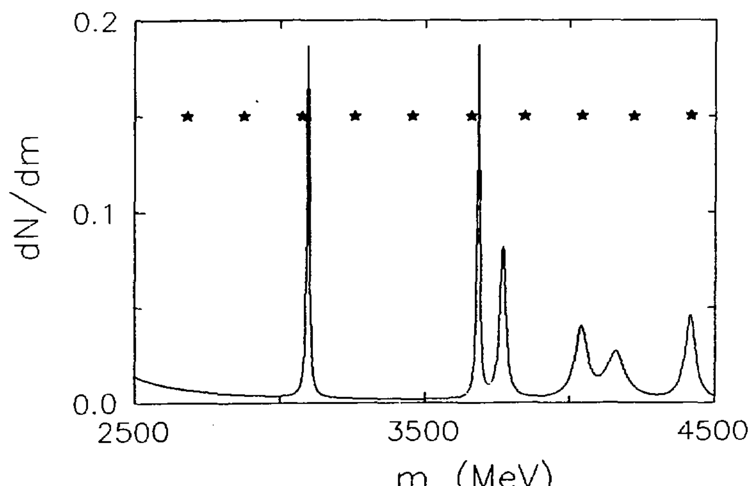


**Fig.4** The same as on Fig.2 but for the charmonium states.

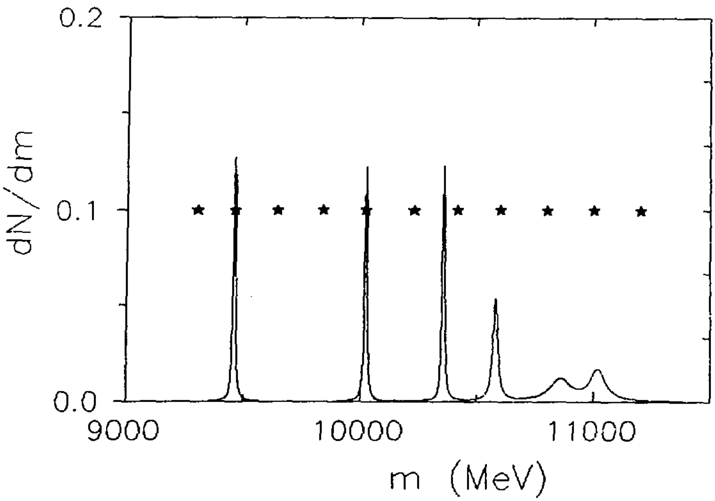


fig.5 The same as on Fig.2 but for the bottomonium states

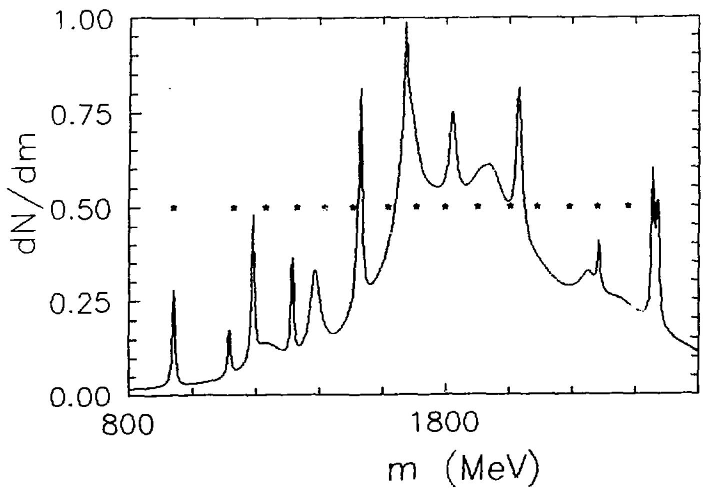


fig.6 The same as on Fig.2 but for the baryonic states

the resonance condition neglecting possible interactions between the decay products. We suspect that it is justified because of considering resonances as well-localized surface-like waves of their decay products (which carry properties characteristic for the interplay between effective size and the wavelength of the system); therefore our consideration must be independent on a particular form of the interaction as far as such localization takes place.

We demonstrated that the three-meson ($1^{--}$) molecular states in decay channels should play an essential role in understanding of mass distributions of the $\psi$ and $\Upsilon$ mesons. The main characteristic feature of such molecular-type states is that the relative momentum in any their binary subsystems is very low: $\sim$ 100 MeV/c. Therefore this phenomenon is the typical low energy resonance.

We predict the existence of new rich regions of ($1^{--}$) resonances: 27- 33 GeV, 81-100 GeV (W and Z boson region), 240-300 GeV and so on.

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