Radial Excitation of the Elementary Particle Resonances

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Abstract

Elementary particle resonances have been systematically analyzed from the first principles: the conservation laws of energy-momentum and Ehrenfest adiabatic invariant. As a result resonance decay product momenta and masses of resonances were established to be quantized. Radial excited states of resonances were revealed. The observations give us a possibility to formulate the strategy of experimental searches for new resonances and to systematize already known ones.

1 Introduction

The merits of contemporary quark models in describing properties of elementary particles are impressive. However, they contain many free parameters, assumptions, and important parts of contemporary experimental data which are not explained in the framework of these models. One of the difficulties of quark notions is in the fact that quarks have not been observed in an experiment. An explanation is that, following Tyapkin's hypothesis [1], quarks are quasiparticles in full analogy with those in nuclear physics, solid-state physics, etc.

Further discussion we will be based on the hypothesis that conservation laws of energy-momentum and the Ehrenfest's adiabatic invariant and also the resonator principle for standing waves of any physical nature are common for all hierarchic systems. Considering some examples in classical and quantum physics we will carry out a systematic analysis of known elementary particle resonances.

The analogy between the relativistic form of a free particle Hamilton function and dispersion relations for standing waves in a hollow metallic resonator (waveguide) has been discussed long ago (for a recent review see, for example, paper [2]). It seems that the underlined analogy has a deep physical cause.

Let us carry out a visual comparative analysis of quantization of a classical field for the string displacement $q(t,x)$ and scalar field which are described by the same equations [3]. The classical field of displacement is described by the equation

$$\frac{\partial^2 q(t,x)}{\partial t^2} - \frac{\partial^2 q(t,x)}{\partial x^2} = 0, \qquad (1)$$

where the linear density of the string and the velocity of spreading of oscillations are equal to unity. The following relations are present when both ends of the string are fixed: $q(t,0) = q(t,a) = 0$. Then, classical eigenstates of equation (1) are

$$q(t,x) \sim exp[\pm i\omega_n t] sin(k_n x), \quad k_n a = n\pi. \qquad (2)$$

The Klein-Gordon equation is a relativistic analog of (1)

$$\frac{\partial^2 \phi(t,\vec{r})}{\partial t^2} - \triangle\phi(t,\vec{r}) + [m^2 + V(\vec{r})]\phi(t,\vec{r}) = 0, \qquad (3)$$

It describes a neutral scalar field where m is the particle mass and $V(\vec{r})$ denote the potential of an external field interacting with the field ϕ. When $V = 0$ and the field ϕ is defined in the interval $[0,a]$ with zero boundary conditions $\phi(t,0) = \phi(t,a) = 0$, the eigenfunctions and eigenfrequencies in the one-dimensional case acquire the form

$$\phi_n(t,x) \sim exp[\pm i\omega_n t] sin(k_n x), \quad k_n a = n\pi, \quad \omega_n = \sqrt{m^2 + k_n^2} = \sqrt{m^2 + \frac{n^2\pi^2}{a^2}}. \qquad (4)$$

So, the quantized fields of displacements and eigenfrequencies of a classical string and eigenfunctions and eigenfrequencies of a relativistic scalar field have the same analytical form. They coincide when $m = 0$. This is a consequence of the identity of appropriate equations and boundary conditions. Moreover, the formulas for eigenfrequencies of a classical string and a quantum relativistic scalar field coincide with those for eigenfrequencies of classical resonators. That is the correspondence principle between classical physics and quantum mechanics and this correspondence does not depend on Planck's constant $\hbar$.

Furthermore, the ratio of the average kinetic energy of a system to its frequency $\overline{E}_{kin}/\nu$, according to Boltzmann's theorem [4], is the Ehrenfest adiabatic invariant, and this affirmation does not depend on the type of interaction of constituents belonging to the whole system. Actually, Lord Rayleigh pointed out the fact in 1902 that in some sine-like oscillating systems (standing waves in an adiabatically decreasing cavity, a transversely oscillating string inside a narrow shrinking ring) occur adiabatic changes so that the correlation between energy and frequency remains fixed [5].

Our discussions might seem old-fashioned. But the coincidence of predictions following from the Ehrenfest adiabatic invariant quantization condition with true results of quantum theory obtained from analytical calculations is extraordinary. When some parameters of a system change adiabatically, the Ehrenfest adiabatic invariant is an integral of motion in the classical and quantum mechanics. Therefore, quantization of this invariant leads to the known results of quantum theory. Apparently, the Ehrenfest adiabatic invariant is an universal invariant for periodic motions including resonances of elementary particles. We have checked this inference using a systematic analysis of experimental data for asymptotic momenta P of decay products of elementary particle resonances. We have used the Bohr-Sommerfeld quantization rule (as a special case of the Ehrenfest adiabatic invariant quantization rule)

$$P_n = n\hbar/r_n = nP_0 \ \ or \ \ P_n = P_0/n. \tag{5}$$

The results of our calculations are presented below in Table 1.

2 Common structure of the mass distribution of elementary particle resonances

To establish some common properties of mass distribution of elementary particle resonances, we demonstrate the usefulness of a commensurable principle of decay asymptotic momenta. In other words, we check the quantization condition (5). Some of the resonances have a dominant decay channel, and apparently the momentum of this channel must manifest itself in decays properties through other channels. We know that almost pure one-particle states are observed in nuclei. Consequently, they manifest themselves in more complex collective states of nuclei [6]. By analogy we consider that the dominant resonance decay channels are similar to one-particle states of nuclei. Let us analyze available experimental data to check the quantization of decay asymptotic momenta and masses of resonances using formulae suitable for resonators.

It is known that the pion $\pi^{\pm}$ decays through the muon and the neutrino with probability about unity and momentum $P = 29.7918$ $(P \approx 30) MeV/c$. We are unable to explain this property of the pion; we only suggest that it is fundamental for comprehension of the structure of some resonances. We can , however, use the resonator principle formulated above to calculate the masses of heavier mesons. Let us suggest that their asymptotic decay momenta are multiples of 29.7918 MeV/c, i.e. $P_n = n{*}29.7918;\ \ n = 1, 2, 3, ...$

The masses of resonances are calculated by the formula $M_{th} = \sqrt{m_a^2 + P_n^2} + \sqrt{m_b^2 + P_n^2}$ where m_a and m_b are the masses of decay products of the resonance to be considered. The resonance masses calculated with momenta commensurable with momenta from the other dominant channels are illustrated in Table 1. Experimental data are taken from [7].

3 Common conclusions

Table 1 contain rich information, and it is possible to make many fundamental conclusions based on it:

1) We think that the results contained in the table convincingly demonstrate the empirical fact of commensurability of resonance decay product momenta within the accuracy of existing experimental data. In other words, decay momenta obey the Bohr-Sommerfeld quantization rule. It is clear that commensurability of momenta does not depend on the type of interaction between resonance decay products, quantum numbers of resonances and type of particles. Moreover, commensurability of momenta

is justified for stable micro-and-macrosystems [15, 16]. It seems to be a universal property of Nature, and many periodic structures are just conditioned by this property. A main question arises here: is this commensurability precise or approximate? We do not know the answer but think that it is as precise as the one in solids and crystals. If so, the common structure of elementary particles must be analogous to that of solids and crystals. An excellent possibility for prediction of new resonances and verification of masses of existing ones arises in any case.

2) We are able to interpret many of resonances as radial excitations of a resonator. For example, $\rho(770)$, $\rho(1450)$ and $\rho(2150)$-mesons decay through two pions with momenta 358, 719 and 1065 MeV/c, i.e. their momenta are multiples of each other. This observation allows to predict masses and quantum numbers of radial-excited resonances.

3) The systematic of resonance decay chains and decay products [7] in turn suggests a simple idea about the structure of elementary particles: all heavy particles decay into lighter ones in a tree-like manner, and the final decay products are electrons, photons, neutrinos and protons. Resonance decay has a self-similar cascade character and, moreover, the relevant decay channel momenta are commensurable.

4) All the resonance decays studied follow the rules given above. We did not find an anomalous resonance decay. Let, for example, discuss the f_1 and f_2-resonances (see [7], p.558). The quark $q\overline{q}$-model predicts two isoscalar 1^3P_1-states. But three states $f_1(1285)$, $f_1(1420)$ and $f_1(1510)$ are known from experiment with quantum numbers 1^{++}. So one of them does not fit into the framework of the quark model. Therefore, different scenarios have been proposed for this shortcoming. Table 1 illustrate that decay momenta obey a commensurable rule. The same is the case for tensor mesons f_2 2^{++}. The quark model predicts two tensor mesons, but many more are found. Really, the number of f_1 and f_2-resonances must be much larger compared to what has been experimentally found so far. The radially excited resonances have to exist, and their masses can be calculated using the multiple momentum rule [17].

Thus, we come to the conclusion that resonances have an extremely rich structure. They are complex wave systems. All the motions of subsystems (constituents) are commensurable according to the laws of wave mechanics. Thus, there is observed self-coordination of constituents of matter between each other and also with the whole system irrespective of the type of interaction between the constituents. Moreover, the constituents of matter (clusters) are similar to each other and to the whole system. Actually, the resonances decay in sequence in a tree-like manner forward for lighter ones so that the branches of the tree are similar to each other and to the whole tree.

Our systematic analysis of resonance decay products shows that the corresponding motions of the constituents do not exist independently. The motions of constituents in one resonance are consistent with motions of constituents in the others. Each resonance itself plays a three-fold role: has a complex structure, is included into other resonances, and takes part in the exchange between components of a subsystem keeping up the unity of structure. Thus, a harmonic unity of motions of all particles is established. No particle is able to be more fundamental than others. Therefore, we come to the fundamental approach of the elementary particle physics problem that has been suggested by Chew and Frautschi [18]. Philosophically, these two approaches are the same but they differ physically in some respects: the origin of the Chew-Frautschi theory is the S-matrix theory for strong interactions; our conclusions do not depend on the type of interaction and are based on the principles of commensurability and similarity following from the conservation laws of energy-momentum and the Ehrenfest adiabatic invariant. This self-coordination of motions in subsystems of one resonance with those of the others and self-coordination of the motions of resonances themselves and the participation of subsystems and resonances in exchange lead to the hierarchy of motions and to the self-organization of matter at the quantum level.

4 Conclusion

It seems that the rich experimental material on elementary particle resonances cannot be understood without introducing new conceptions about the internal structure of the particles which fly out when the resonances decay. We have given sufficiently clear arguments in favor of the fact that nature of resonances obeys common principles: these resonances are a direct manifestation of the complex internal structure of the particles. The prevailing opinion is that these resonances appear when low energy particles collide and interact at large distances. Therefore they do not give information about the internal structure of colliding particles. Hence, a conventional conclusion is that the information about internal structure of "elementary" particles may be derived from high energy collisions and becomes more precise with increasing energy of particles. We think that resonances are conditioned by a complex internal structure of the particles themselves, so that experimental data at all energies are useful. The material contained in this work demonstrates, as it seems to us, the equivalence of this affirmation to the physics of processes. Our approach, based on the first principles, is free from any parameters, and it reproduces the centroids of experimental data. The accuracy of our calculations depends on the accuracy of the initial experimental data used. Often our calculations give a higher accuracy on resonance masses than existing experimental data, if the initial data have a high accuracy. There are many predictions of resonance masses in this article, and these predictions are verified. From our systematic analysis we are led to the conclusion that resonance decay momenta are quantized.

Thus, we come to a conclusion about existence of radially excited states, and we believe in it. Many of the well established resonances have their radially excited partners with decay momenta which are multiples of these of low lying or high lying resonances. This observation may serve as an instrument for prediction of radial excited resonances with quantum numbers defined beforehand. Consequently, a simple phenomenological principle of systematization of the elementary particle resonance mass spectrum is revealed. The radial excited states are known in many branches of physics (in atoms, nuclei, molecules, solids, etc.). The presence of these states in elementary particles physics is natural. Finally, we have established that experimental values of masses of PP and $\overline{P}P$ resonances [20] coincide within the accuracy of experimental data. Actually, the conservation laws of energy-momentum and Ehrenfest adiabatic invariant for (particle-particle) and (particle-antiparticle) systems must be fulfilled in the same manner. This remarkable observation was highlighted in our earlier works [15, 16]. The fundamental conclusion is the following: many meson resonances must have their dibaryon partners. If so, good perspectives for combined systematic analysis of meson and dibaryon resonances are opened.

To understand how an unstable particle (resonance) can communicate with some open channels we found, it is necessary to develop an analogy between the behavior of unstable particles and resonant cavities such as organ pipes, electromagnetic resonators. Chew, Gell-Mann and Rosenfeld were the first who paid attention to this analogy in 1964 [21]. They discussed in detail the possibility of representing elementary particle resonances as resonant cavities in full analogy with our approach. But the 1964 paper [21] remained unnoticed.

Thus, a parameter-free approach suggested by us and based on the first principles, allows us to formulate a strategy of experimental searches for new resonances with quantum numbers defined beforehand.

We began our search with the following motivation: varied phenomena in nature are governed by simple laws common for micro- and macrosystems [15]. They are conservation laws of energy-momentum and the Ehrenfest adiabatic invariant. If so, the geometric quantization has to be universal because it is the ordinary unification of these laws. Hence, this unification of universal laws in the geometric quantization rule makes it possible to formulate the resonator principle and the commensurability principle of motions in microsystems. The existing experimental facilities for low, intermediate and high energies will be sufficient to verify our affirmation. The influence of an external field is usually used to establish the eigenfrequencies of the resonator. The resonance phenomena arise when the frequency of the external field coincides with eigenfrequencies of the resonator to be researched. Therefore, we suggest natural method for determination of the eigenfrequencies (energies) of "elementary particles" based on collisions of different and the same particles. Resonances will arise when the eigenfrequencies of the internal relative motions will coincide with eigenfrequencies of the colliding particles.

The validity of our phenomenological approach is corroborated by the results of systematic analysis of decay products of an enormous number of resonances. The most reliable evidence is the good description of the mass distribution of resonances and predictions of new ones.

In conclusion, we note that many of the ideas presented in this paper were born under the influence of papers by A.M. Baldin [22]. We are very indebted to J.S. Vaagen, A. Tyapkin, K. Gridnev, A.Shirkov, F.Pen'kov, F.Dubovik, V. Fedyanin, P.Korovin and Yu. Popov for useful discussions and friendly critique.

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Table 1. Invariant masses of resonances decaying through binary channels with momenta $P_n = n * 29.7918$ MeV/c.

resonances	decay channels	P_{exp}	n	P_{exp}/n	M_{exp}	M_{th}
$\pi^{\pm}$	$\mu^{\pm}\nu_{\mu}$	29.79	1	29.79	139.56995	139.56995
$X(285)$	$\pi^{\pm}\pi^{\mp}$	—	1	29.79	not seen	285.43
$X(300)$	$\pi^{\pm}\pi^{\mp}$	—	2	29.79	not seen	303.51
X(330)	$\pi^{\pm}\pi^{\mp}$	89.87	3	29.96	332 ± 3[8]	331.47
X(370)	$\pi^{\pm}\pi^{\mp}$	—	4	29.79	not seen	367.05
X(400)	$\pi^{-}\pi^{-}$	141.15	5	28.23	397 ± 7	408.26
X(450)	$\pi^{\pm}\pi^{\mp}$	179.66	6	29.94	455 [9]	453.57
X(450)	$\pi^{-}\pi^{-}$	174.56	6	29.09	447 ± 7 [8]	453.57
X(500)	$\pi^{-}\pi^{-}$	213.41	7	30.49	510 ± 7[8]	501.88
X(550)	$\pi^{\pm}\pi^{\mp}$	236.95	8	29.62	550[9]	552.39
X(600)	$\pi^{\pm}\pi^{\mp}$	265.56	9	29.51	~ 600[9]	604.55
X(650)	$\pi^{\pm}\pi^{\mp}$	294.61	10	29.46	652 ± 2[8]	657.98
X(650)	$\pi^{-}\pi^{-}$	293.51	10	29.35	650 ± 8[8]	657.98
X(700)	$\pi^{\pm}\pi^{\mp}$	—	11	29.79	not seen	712.39
$\rho(770)$	$\pi^{\pm}\pi^{\mp}$	358	12	29.83	768.5 ± 0.6	767.56
X(820)	$\pi^{-}\pi^{-}$	386.58	13	29.74	822 ± 9[8]	823.35
X(880)	$\pi^{\pm}\pi^{\mp}$	—	14	29.79	not seen	879.64
X(936)	$\pi^{\pm}\pi^{\mp}$	—	15	29.79	not seen	936.33
$f_0(980)$	$\pi^{\pm}\pi^{\mp}$	469.70	16	29.36	980 ± 10	993.36
X(1050)	$\pi^{\pm}\pi^{\mp}$	—	17	29.79	not seen	1050.68
X(1100)	$\pi^{\pm}\pi^{\mp}$	—	18	29.79	not seen	1108.24
X(1165)	$\pi^{\pm}\pi^{\mp}$	—	19	29.79	not seen	1165.99
X(1220)	$\pi^{\pm}\pi^{\mp}$	—	20	29.79	not seen	1223.93
$f_2(1270)$	$\pi^{\pm}\pi^{\mp}$	622.03	21	29.62	1275 ± 5	1282.01
$\rho(1450)$	$\pi^{\pm}\pi^{\mp}$	719	24	29.96	1424 ± 25	1457.00
$f_2'(1525)$	$\pi^{\pm}\pi^{\mp}$	749.62	25	29.98	1525 ± 5	1515.52
$f_0(1500)$	$\pi^{\pm}\pi^{\mp}$	738.43	25	29.54	1503 ± 11	1515.52
$f_2(1565)$	$\pi^{\pm}\pi^{\mp}$	769.95	26	29.61	1565 ± 20	1574.12
$f_2(1640)$	$\pi^{\pm}\pi^{\mp}$	807.02	27	29.89	1638 ± 6	1632.79
$\rho_3(1690)$	$\pi^{\pm}\pi^{\mp}$	831.37	28	29.69	1686 ± 4	1691.53
$\rho(1700)$	$\pi^{\pm}\pi^{\mp}$	853.67	29	29.44	1730 ± 30	1750.33
$X(1740)$	$\pi^{\pm}\pi^{\mp}$	860.76	29	29.68	1744 ± 15	1750.33
$f_2(1810)$	$\pi^{\pm}\pi^{\mp}$	896.70	30	29.89	1815 ± 12	1809.17
$f_2(1950)$	$\pi^{\pm}\pi^{\mp}$	988.19	33	29.95	~ 1996	1985.97
$\rho(2150)$	$\pi^{\pm}\pi^{\mp}$	984.15	33	29.82	~ 1988	1985.97
$f_4(2050)$	$\pi^{\pm}\pi^{\mp}$	1012.42	34	29.78	2044 ± 11	2044.98
$\rho(2150)$	$\pi^{\pm}\pi^{\mp}$	1040.68	35	29.73	~ 2100	2104.02
$f_0(2200)$	$\pi^{\pm}\pi^{\mp}$	1051.78	35	30.05	~ 2122	2104.02
$\rho(2150)$	$\pi^{\pm}\pi^{\mp}$	1075.99	36	29.89	~ 2170	2163.10
$f_2(2150)$	$\pi^{\pm}\pi^{\mp}$	1104.21	37	29.84	~ 2226	2222.19
$f_0(2200)$	$\pi^{\pm}\pi^{\mp}$	1152.08	39	29.54	~ 2321	2340.47
$f_6(2510)$	$\pi^{\pm}\pi^{\mp}$	1247.21	42	29.70	2510 ± 30	2518.03

Table 1. (continuation).

resonances	decay channels	P_{exp}	n	P_{exp}/n	M_{exp}	M_{th}
B(1876)	pp	29.94	1	29.94	1877.5 ± 0.5[10]	1877.49
B(1880)	pp	—	2	—	not seen	1880.32
B(1885)	pp	94.31	3	31.44	1886 ± 1[10]	1885.04
B(1890)	pp	120.67	4	30.17	1892[10]	1891.62
B(1900)	pp	142.29	5	28.49	1898 ± 1[10]	1900.05
X(1900)	$p\overline{p}$	138.91	5	27.78	1897 ± 1	1900.05
B(1910)	pp	180.62	6	30.10	1911[10]	1910.30
B(1920)	pp	207.76	7	29.68	1922[10]	1922.34
X(1920)	$p\overline{p}$	203.09	7	29.01	~ 1920	1922.34
B(1936)	pp	240.08	8	30.01	1936 ± 0.3[11]	1936.14
X(1936)	$p\overline{p}$	240.08	8	30.01	$1937.3^{+1.3}_{-0.7}$	1936.14
B(1950)	pp	274.14	9	30.46	1951 ± 0.3[11]	1951.66
B(1970)	pp	298.14	10	29.81	1969 ± 2[12]	1968.87
X(1970)	$p\overline{p}$	296.48	10	29.65	1968	1968.87
B(1990)	pp	328.15	11	29.83	1989 ± 1[13]	1987.71
B(2008)	pp	357.30	12	29.76	2008 ± 3	2008.15
X(2008)	$p\overline{p}$	361.49	12	30.12	2011 ± 7	2008.15
X(2030)	$p\overline{p}$	381.86	13	29.37	2026 ± 5	2030.12
B(2050)	pp	415.12	14	29.65	2052[12]	2053.60
B(2080)	pp	447.44	15	29.83	2079 ± 4[13]	2078.51
X(2080)	$p\overline{p}$	448.60	15	29.91	2080 ± 10	2078.51
B(2105)	pp	477.97	16	29.87	2106 ± 4[10]	2104.82
B(2130)	pp	502.80	17	29.58	2129 ± 5[10]	2132.47
B(2160)	pp	534.83	18	29.71	2160 ± 3[14]	2161.41
$\rho(2150)$	$p\overline{p}$	529.77	18	29.43	2155 ± 15	2161.41
B(2190)	pp	566.45	19	29.81	2192 ± 3[14]	2191.58
$\rho(2150)$	$p\overline{p}$	567.41	19	29.86	2193 ± 2	2191.58
$f_J(2220)$	$p\overline{p}$	597.75	20	29.89	2225 ± 6	2222.95
B(2220)	pp	593.08	20	29.65	2220	2222.95
$\rho_5(2350)$	$p\overline{p}$	714.75	24	29.87	2359 ± 2	2359.31
X(2850)	$p\overline{p}$	1072.51	36	29.79	2850 ± 5	2850.00
X(3370)	$p\overline{p}$	1399.60	47	29.78	3370 ± 10	3371.03