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PAST, PRESENT AND FUTURE IN MESON SPECTROSCOPY*

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At the turn of the millennium, a decade of interesting new results will end with major questions being answered. We have a much cleaner picture about the spectrum of light mesons. There are candidates for glueballs and hybrids/multiquarks with a very detailed knowledge about their observable quantities. But there are still many open questions, which will not be answered with the existing data being acquired by the successful experiments of the last decade.

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Meson spectroscopy is still an exciting and active field in medium energy physics. The driving force behind the continued interest in meson spectroscopy is the desire to obtain a better understanding of the following aspects:

- The spectrum of "standard" hadrons (mesons and baryons) contains information on their constituents and the force which keeps them together (non-perturbative QCD). But it is not yet clear how this information can be revealed from the data.
- A spectrum of "non-standard" (exotic) hadrons is proposed different from the conventional qqq baryons and $q\bar{q}$ mesons. They are classified as glueballs, hybrids or multiquark states, depending on their constituents which are only gluons (gg) or a valence gluon strongly coupled to a meson ($q\bar{q}g$) or an array of joined (anti)quarks.
- Theoretical attempts are made to describe and/or to predict missing states in the hadronic spectrum via low-energy perturbative models.

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Apart from many "standard hadrons" which have been discovered in the past, I will concentrate on what has been achieved and where are the weak points in questions about glueballs and hybrids and how to attack them in the future.

1. Experiments

Important experiments in the past decade for the current knowledge about meson spectroscopy are the Crystal Barrel and Obelix experiment at LEAR, being central detectors for nucleon–antinucleon reactions and E852 at BNL and VES in Serpkhow being forward spectrometers for charge exchange reactions. The typical layout for the latter ones is a forward tracking system and an electromagnetic calorimetry device and some detectors around the target to measure the slow nucleons exiting the target area. Since most nucleon–antinucleon annihilations are investigated using the electromagnetic cascade of the protonium system, most events are accumulated with zero momentum, so to speak at rest. Therefore the detectors are central detector consisting of tracking chambers and electromagnetic calorimetry, all inside a magnetic field providing determination of the momenta of charged particles. The main advantages of Crystal Barrel against Obelix are the high statistics and the excellent electromagnetic calorimeter.

2. Glueballs and the scalar mystery

Glueballs are known to be bound state of valence gluons. An experimental review of the status of the search for these is, however, biased by the theoretical eye-glasses you are wearing. A completely unbiased view of the spectrum of light mesons is impossible since masses and widths of these particles are not standard model predictions. Many predictions are based on mostly phenomenological models motivated by the static properties of gluons and quarks, but their reliability is rather limited. The closest approach to the standard model is the calculation on the lattice which still suffers from lack of CPU power for an appropriate precision for the extrapolations for vanishing lattice spacings, although they show promising results [14]. Thus the only reliable features are the existence and the static properties of the constituents of light mesons, the gluons and the quarks.

Since end of the seventies we know that gluons are not only a theoretical assumption, but a physical particle which was observed in three jet events at various detectors at DESY in electron positron annihilation. Two of the jets originated from quark–antiquark production, where the third was proven to be a remnant from gluon bremsstrahlung. About ten years later at CERN in four jet events at LEP the gluon was also proven to have a colour degree of freedom. Thus gluons are able to interact with themselves and can build up states without quark degrees of freedom. These so called glueballs have been predicted since a very long time. A detailed discussion about the history can be found elsewhere [9].

After more than 25 years of search for glueballs it becomes more an more certain that the glueball cannot be observed as a pure state — having no quarks in it. We have emerging evidence that the glueball, as other isoscalar particles, mixes with ordinary mesons because of the finite width of them. Therefore mixed states arise with very complicated properties, somewhere between conventional and exotic mesons. Since glueballs are not expected to be stable, one has to produce them in a hadronic interaction and to study its production and decay properties. In order to enhance the rate one needs processes with a large fraction of quark–antiquark-annihilation diagrams in order to provide enough hard gluons to interact with each other. Such processes are known as gluon rich. These are radiative J/ψ-decays, double pomeron production, nucleon–antinucleon interaction and strangeness production in non-strange charge exchange reactions. In addition to knowing

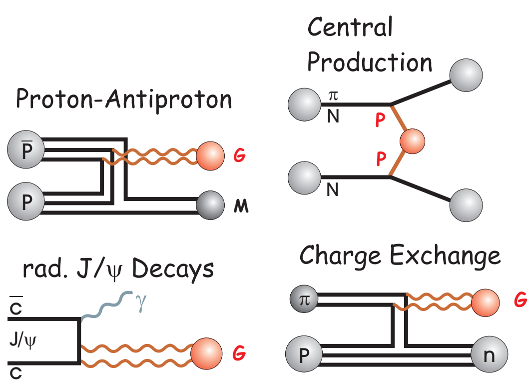

Fig. 1. Proposed production processes for glueballs

in which reactions one should investigate, one needs an idea about the static properties of glueballs, like mass, lifetime and branching ratios. A lot of tooling is around but the picture is very incoherent and therefore I will touch only a few topics. One very important property of a pure glueball is that it is an SU(3)-singlet. The main question is, can we trust SU(3) in this energy domain at all. Various analysis have proven that SU(3) gives useful relationships for the branching fractions of tensor, vector and axial vector mesons without $s\bar{s}$-suppression if one includes reasonable angular momentum barrier functions and integrates properly over the allowed phasespace (including opening thresholds) [8]. If one translates the SU(3) picture of meson decays into the glueball picture one gets a graph like Fig. 2(a). This decay is so called flavour blind, that means all quark flavours are produced democratically at the gluon vertices. This idea of flavour blindness has been proven to work for the χ_{c0} and χ_{c2} states. But things could be more complicated. It is nearly impossible to calculate the impact of higher orders, therefore the contributions of graphs like Fig. 2(b) may spoil the flavour democracy and increase $\eta\eta$ final states quite remarkably. The best knowledge so far

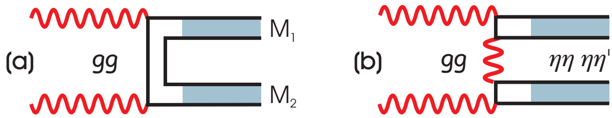

Fig. 2. The naive decay of a glueball (a) should be flavour blind but the unknown amount of reactions like (b) and the mixing with conventional mesons with other SU(3)-coupling constants may change the picture quite dramatically.

in respect of the mass of glueballs comes from the lattice. Recent improvements verify the results presented at former conferences. The scalar glueball should be the lightest one between 1.5 and 1.7 GeV$/c^2$. The tensor glueball is somewhat heavier with a well measured ratio of $m_{2^{++}}/m_{0^{++}} \approx 1.5$ [14].

The experimental situation in the scalar regime has been dramatically improved in the passed decade. The results of the nucleon–antinucleon experiments verify the existence of at least three isoscalar mesons: $f_0(975)$, $f_0(1370)$ and the $f_0(1500)$ (former name $G(1590)$ from GAMS). These could be identified by using high sophisticated K-Matrix analyses including various channels like 3π, $2\pi\eta$, $2\eta\pi$ and 5π taking unitarity into account. These results have been verified in central production [6] and rad. J/ψ decays as far as limited statistics allows for it.

A careful look to the $\pi\pi$ scattering wave with $L = 0$ exhibits some interesting structures. There is obviously a very broad bump, which is called $f_0(1300)$ whereas the resonant nature is not proven yet. In addition there are several dips in this structure, where the deepness is related to its $\pi\pi$-coupling. If the coupling is larger, the dip is more pronounced. *E.g.* the $f_0(1370)$ which decays dominantly into 4π appears to be a very small dip. If in the last structure the $f_j(1700)$ appears at all is under discussion. There is conflicting experimental evidence for this particle to be a scalar or a tensor state. While central production prefers tensor properties the rad. J/ψ analysis yields a scalar resonance. A lot of effort is now put in this very serious question which would increase the number of light scalar isoscalar resonances to the number of five. The number of scalar isoscalars is therefore between 3 and 5. Since the quark-model predicts only two, there is room for an exotic particle. Having so many states — which one is the glueball? or is there any at all? Unfortunately there is no unique answer to this question.

The new experimental data provides us a lot of information, but it's still not sufficient to draw a consistent picture. There are three main scenarios which are on the market. The first one assumes, that the $f_j(1700)$ has spin 0 and together with $f_0(1500)$ and $f_0(1370)$ they are mixed states out of two isoscalar $q\bar{q}$ and a glueball. In order to work an $a_0(1450)$ and $K_0^*(1430)$ are needed to complete this decuplet. This arrangement explains qualitatively the branching ratios. The $a_0(980)$ and the $f_0(975)$ are leftovers and being $K\bar{K}$ molecules. A crucial test for this model would be the measurement of the $\gamma\gamma$-couplings which are sensitive to the $q\bar{q}$ admixture [6].

Another kind of arrangement appears if one allows for instanton induced interactions, which apply to (pseudo)scalar mesons. Calculations have shown, that an $f_0(975)$ is easily explained as a $q\bar{q}$ meson even with its low mass. However for the $a_0(980)$ there is still no place within the nonet. The second isoscalar could then be either the $f_0(1370)$ or the $f_0(1500)$ and the remaining ones, including the $f_j(1700)$ could be glueball candidates or two of them could be mixed.

The third kind of scenarios arises when both, the $a_0(980)$ and $f_0(980)$ are both $q\bar{q}$ states. Such models are the results of an relativistic unquenching of the bare mesonic states which leads to a major shift in the observed mass of these resonances. The exact placement of the more massive resonances depend on the specific approach, but all allow for a glueball in the 1.5 GeV/c^2.

One sees, the most important question at the moment is: what are the $a_0(980)$ and $f_0(975)$? are they of the same kind? is at least one of them a meson? These questions must be answered in order to get a more comprehensive picture of the scalar sector. This could be done in ϕ-factories by studying the rad. ϕ decays into scalar mesons.

Most models don't precisely predict the branching ratios for the other well measured channels. Nevertheless it is important to measure all the subdominant channels in order to have some input. Unfortunately, the main source of information is in the process of exhausting since methodological problems arise with the high statistics. Main areas of concern are the bad knowledge of initial state decomposition and proper lineshapes, which become important if one looks for small effects with many resonances like in the $K\bar{K}$ final states.

From all this one can draw the conclusion that the discovery of the $f_0(1500)$ about several years ago was an important step forward in the process of identifying the scalar glueball. Finding this particle in conjunction with the $f_0(1370)$ a situation arose where more states appear than necessary in the $q\bar{q}$ scheme. Unfortunately none of the various scalar isoscalars could be clearly identified so far as pure $q\bar{q}$ or exotic states. But we are able to ask questions about specific particles where the answer, in contrast to former times, really will tell us something solid about the spectrum of light mesons. The main questions in the scalar sector for the foreseeable future are: Are the $a_0(980)$ and the $f_0(975)$ isospin partners of the same kind, *e.g.* same internal structure? Is the $f_0(975)$ a $q\bar{q}$ state? What is the spin of the $f_j(1710)$? How strongly couples $\gamma\gamma$ to all of the scalar mesons? What is the $K\bar{K}$ coupling of the scalar mesons? and what is the production rate in J/ψ radiative decays?

3. Traces of exotic matter

Exotic quantum numbers are predicted for all types of exotic mesons, but in the case of glueballs the expected mass is far too heavy to be accessed by common meson spectroscopy experiments. Light mesons with exotic quantum numbers are expected in the hybrid- or in the multiquark-sector. Unfortunately most multiquark-states are expected to be not or very loosely bound [3]. A common picture for light hybrids is to look at it in terms of a $q\bar{q}$ pair as a colour octet state and gluon ($q\bar{q}$-picture). Apart from the decay of hybrids their production is a critical item. Reactions which may be utilized to produce hybrids have to produce the valence gluon. It is believed that reactions with quark annihilations may produce hard gluons to be incorporated in a final state hadron. Potential reactions are the nucleon–antinucleon reaction and the charge exchange mechanism. The advantage of πp reactions is the unambiguous final state where a straight-forward energy independent partial wave analysis can be applied, but the final states are usually dominated by the production of conventional mesons whose production dominated by the production of conventional mesons whose production rate is reversal orders of magnitude higher. In the nucleon–antinucleon annihilation the belief is that the production rate of exotics is much higher. However the analysis is much more complicated and not free of ambiguities since at least one additional particle in the final state may distort the clear picture. We will see that these complementary methods will give the same results supporting the existence of such particles in nature.

The first discovery of a resonance with the exotic quantum number J^{PC}=1^{-+} was made by GAMS in the charge exchange reaction $\pi^- p \to nX^0$, $X^0 \to \pi^0\eta$ at an incident momentum of 100 GeV/c. It has been shown that a FB asymmetry exists which could be explained by an exotic wave, the $M(1405)$ or better known as $\hat{\rho}(1405)$. However, the main contribution to this reaction is the production of the $a_2(1320)$, a well known tensor meson. This result was in question for a long time, especially because of ambiguities in the analysis method. Since only some of the eight non-trivial solutions for the momentum analysis show the exotic wave it was under strong attack. Some years later the experiment E179 at KEK also presented their results on the similar reaction $\pi^- p \to \pi^- \eta p$ where all solution show an exotic wave. However their result shows three degenerated mesons (in mass and width) in S-wave, P-wave and D-wave with the properties of the $a_2(1320)$. This also yielded some criticism about the reliability of the knowledge of the acceptance of their detector. This discussion together with the quest for glueballs gave rise to several new experiments in the charge exchange and the nucleon–antinucleon sector. Two experiments, E852 at BNL and Crystal Barrel at LEAR have added important information to the spectroscopy of $\pi\eta$ systems. Nearly at the same time they published last year evidence for an exotic wave in a complementary way so that the existence of the $\hat{\rho}(1400)$ could be established. The measurement at Crystal Barrel was made using a liquid deuterium target and looking at the reaction $\bar{p}d \to \pi^- \pi^0 \eta p$. The channel $\pi^- \pi^0 \eta$ has isospin $I = 1$ and circumvents problems with dominant scalar resonances which are forbidden in this process. The dominant resonances are $\rho(770)$ and $a_2(1320)$. But to describe the Dalitz plot (Fig. 3(a)) an exotic wave in $\pi\eta$ is needed [10]. The evidence comes mostly from the very strong triple interference of all three resonances. The yield of the exotic wave is 10 % which is in the order of the rate for the $a_2(1320)$ which is remarkably high for such an object. In contrast to that channel Crystal Barrel tried several years ago to find an exotic object in the channel $\bar{p}p \to \pi^0 \pi^0 \eta p$. In this channel the scalars are extremely dominant and the discovery of the $\hat{\rho}(1400)$ was impossible [10]. Nevertheless it has been shown that the existence also in this data set has been verified by using various data sets with different initial state decomposition [10]. The experiment E852 at BNL follows the long history of charge exchange reactions and has investigated the reactions $\pi^- p \to \pi^0 \eta n$ and $\pi^- p \to \pi^- \eta p$. With much larger statistics than GAMS and an excellent detector for neutral and charged particles they were able to give a definite answer to the $\pi\eta$ channel in that domain. Assuming unnatural parity exchange (no ρ-exchange!) they found an exotic wave apart from a dominant tensor, the $a_2(1320)$ (see Fig. 3(a)). They proved the phase motion against this well known tensor to be resonant [11]. Unfortunately they were not able to find so far the $\pi\eta$' mode as well which is needed to identify this resonance as a hybrid, since a hybrid should have an SU(3)-like decay pattern which is different to that of conventional mesons [10]. The absence of a $\pi\eta$' signal in the 1400 MeV/c^2 region does not mean that there is no exotic activity. VES and E852 have shown that in the $\pi\eta$' channel around 1650 MeV/c^2 an exotic wave exists, also with J^{PC}=1^{-+} [11, 12]. The same experiments find the same exotic wave in the production of three pions. The 1^{-+} $\rho\pi$ wave shows a clear phase motion against the tensor resonance $a_2(1680)$ which has been discovered by Crystal Barrel. There are only a few pieces of information in the designated hybrid channels, like $f_1\pi$. E818 at BNL has measured (but with low statistics) the partial wave

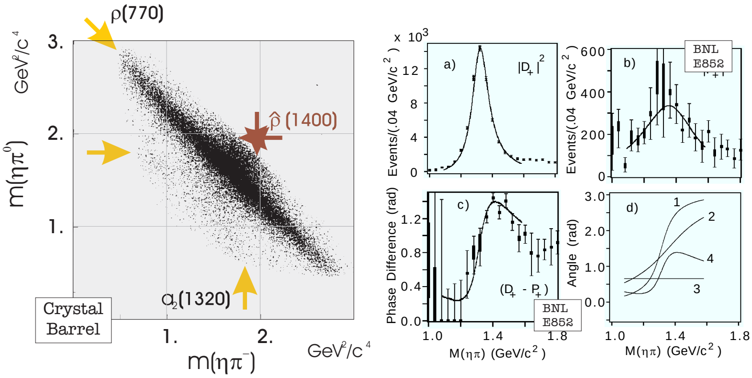

Fig. 3. Left — Dalitz plot of the reaction $\bar{p}d \to \pi^-\pi^0\eta p$ measured by Crystal Barrel. The strong diagonal band indicates the $\rho(770)$. The enhancement in the middle of the band can only be described with a triple interference of ρ, a$_2$(1320) and an exotic vector $\hat{\rho}(1400)$. Right — plots for the reaction $\pi^-p \to \pi^-\eta p$ measured by E852 at BNL. a) shows the tensor wave and a dominant a$_2$(1320)-signal, b) shows a bump in the P-wave. c) and (d) show the phases of the P-wave (4) relative to the D-wave. d) shows the phases separately ($1 = D$, $2 = P$, 3=prod., $4 = D - P$).

decomposition of the $KK\bar{}\pi\pi$ channel and found an exotic $f_1\pi$ wave being compatible with a $m = 2$ GeV$/c^2$ hybrid [11]. VES finds something similar in the same channel but with very low statistics they were not able to settle this resonance [12]. The recent experiment E852 at BNL has verified the resonance in the channel where the f_1 decays to $\pi\pi\eta$ and gets evidence for this resonance around $m = 1.9$–2 GeV$/c^2$ as well.

At present there is a large number of candidates for mesons with exotic quantum numbers. It was long awaited to find one, now there are three. Are there really three hybrids. The decay pattern of the first one looks more likely like a multiquark-state, while the signal at 1600 MeV$/c^2$ looks more like a hybrid with its strong coupling to $\pi\rho$. But if the so called $\pi_1(1400)$ is multiquark-state, where are its non-exotic companions. One interpretation is that they appear as the NLO-part of a Fock-expansion of mesons. If the first term (the meson) is J^{PC}-forbidden, the multiquark is unobservable. Otherwise it is suppressed due to the domination of mesonic features.

4. The future

The experimental achievements in the past years is remarkable, but nevertheless only a small piece of information has been found and a lot of questions are still open. It is important to clarify the light 1^{-+} sector and to add information from other sectors where hybrids are expected *e.g.* $J^{PC}{=}0^{+-}$

or 2^{+-} as well as in the domain of conventional quantum numbers. It has to be verified if the level ordering from the lattice is correct. This implies the search for a light pseudoscalar. All this could be performed in Primakoff-like reactions where one creates a rho via VDM out of a photon and combines this with an incident or a target meson. Such experiments could be either made in a hadronic environment (like Compass) or in a high current electron machine (*e.g.* CEBAF [4]). Another rich field is the spectroscopy of $D_{(\mathrm{S})}$-mesons, where the couplings of light scalars to $s\bar{s}$ (see Fig. 4) can be measured very accurately at B-Factories, like BaBar, Belle and/or CLEO III. Some results for these decays with limited statistics from former experiments have been already presented [7].

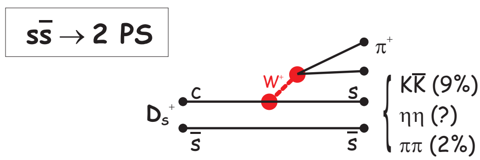

Fig. 4. Decay graph for the production of s$\bar{s}$-states in D_{S}-decays

A much more ambitious project is the concept of a high energy storage ring (HESR) with the option of antiproton-annihilation at GSI (see Fig. 5). This ring would be served by a 100–200 Tm PS-like proton accelerator, producing the antiprotons on an external target. The antiprotons will be stored in a separate ring with e^--cooling and in internal detector using a gas-jet- or a thin-wire target. Thus allowing high statistics meson spectroscopy experiments in the light- as well as in the very promising charm-meson-sector. An antiproton storage ring is the ideal place to do high statistics explorative studies for a large variety of topics in medium energy physics.

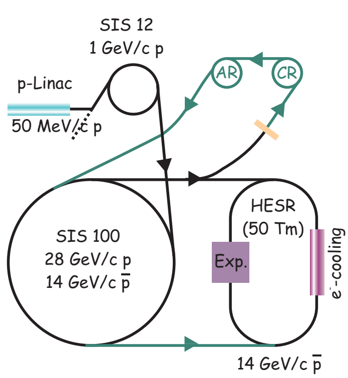

Fig. 5. The proposed accelerator complex for the HESR project

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