In-flight annihilation $\bar{p}p \rightarrow \phi \phi$ and $\bar{p}p \rightarrow \bar{K}K$
with JETSET at LEAR

Nikolaus Hamann

CERN, PPE Division
CH - 1211 Geneva 23, Switzerland

(representing the JETSET Collaboration)

Abstract

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CERN, PPE Division
CH – 1211 Geneva 23, Switzerland

representing the JETSET Collaboration:

R. Armenteros$^1$, D. Bassi$^2$, P. Birien$^2$, R.K. Bock$^3$, A. Buzzo$^3$, E. Chesi$^1$,
P.T. Debevec$^4$, R. Dobinson$^1$, R.A. Eisenstein$^4$, T. Fearnley$^1$, M. Ferro Luzzi$^1$,
J. Franz$^2$, M.A. Graham$^4$, N. Hamann$^1$, R. Harfield$^1$, P. Harris$^4$, D. Hertzog$^4$,
S. Hughes$^4$, T. Johansson$^7$, R. Jones$^1$, K. Kilian$^5$, K. Kirsebom$^3$, A. Klett$^2$,
H. Korsmo$^8$, M. Lovetere$^3$, A. Lundby$^2$, M. Macri$^3$, M. Marinelli$^3$, P. Martinengo$^3$,
L. Mattera$^3$, B. Mouëjdic$^1$, W. Oelert$^2$, S. Ohlsson$^7$, B. Osculati$^3$, J.–M. Perreau$^1$,
M.G. Piac$^3$, M. Price$^1$, P. Reimer$^4$, E. Rössle$^2$, A. Santroni$^3$, A. Scalsi$^3$,

$^1$ CERN, Geneva, Switzerland
$^2$ University of Freiburg, Freiburg, Fed. Rep. Germany
$^3$ University of Genova and INFN, Genova, Italy
$^4$ University of Illinois, Urbana – Champaign (IL), USA
$^6$ University of Oslo, Oslo, Norway
$^7$ University of Uppsala, Uppsala, Sweden

Abstract

The JETSET experiment (PS202) at CERN–LEAR uses an internal gas-jet target surrounded by a compact general-purpose detector. The initial physics programme involves the spectroscopy of hadronic states, including glueballs, hybrids and multi-quark states, in the mass range up to 2.4 GeV. Emphasis is put on the reactions $\bar{p}p \to \phi\phi$, $\omega\phi$ and $\omega\omega$, and also on $\bar{p}p \to \bar{K}K$, $\bar{K}K^*$ and $\bar{K}^*\bar{K}^*$, using antiprotons up to 2 GeV/c momentum. This report gives the physics motivation and objectives of the experiment, and it describes the experimental technique chosen. A detailed account is given of data around and above 2 GeV invariant mass, which were obtained by previous experiments using hadronic reactions and heavy quarkonium decays. Future possibilities include threshold studies in multi-kaon final states, as well as high-statistics studies of exclusive hyperon–antihyperon production.
Introduction

According to the present understanding of particle physics, Quantum Chromodynamics (QCD) is the candidate theory underlying hadronic interactions. The theory describes hadrons as bound states of quarks that interact through colour forces by exchange of gluons. However, the equations of motion in QCD have yet to be solved in an exact manner, and many phenomena experimentally observed in hadronic interactions at small momentum transfers have yet to be understood. One prominent example for such a phenomenon is called ‘colour confinement’. It points to the fact that the coloured quarks and gluons appear to exist not as free particles but only as colour-neutral bound hadronic states. Speaking in general terms, it is still one of the fundamental questions in QCD what the physical objects of the theory are.

Lacking a more elegant description, our theoretical understanding of the hadronic spectrum is largely based on the Constituent Quark Model (QM). This model treats baryons and mesons, i.e. the ‘conventional’ hadrons. Baryons are colour-neutral triplets of quarks, (qqq), and mesons are colour-neutral quark–antiquark pairs, (qq). But the conventional hadrons are only one class of physical objects that QCD is dealing with. The other class, which does not exist in the Constituent Quark Model, is characterized by the fact that, in addition to quarks, gluons too can play a structural role in hadronic states. Since gluons are coloured, they are subject to self-coupling, and so gluons themselves can be constituents of hadronic matter. This self-coupling of the mediators of the strong interaction is a peculiarity in Quantum Chromodynamics, and it is due to the non-abelian character of the theory. The situation in Quantum Electrodynamics (QED) is quite different, since the mediating photons are electrically neutral and hence do not self-interact.

For those states in QCD which cannot be explained in terms of conventional hadrons we may adopt the name ‘non-quark-model’ states (NQM). There are three types of such NQM states. Glueballs are quark-less states consisting of two or more real gluons, (gg) or (ggg). Hybrids – alternatively called meiletons – are composed of a quark–antiquark pair and a real gluon, (qg). Multi-quark states are colour-neutral combinations of four or more quarks and/or antiquarks, for instance (qqqq) or (qqqqq). Since QCD allows the existence of such states, by not giving arguments against it, their clear-cut experimental discovery would be of greatest importance for the verification of QCD in the low-energy regime. On the other hand, the proof of non-existence of NQM states could be a genuine problem with far-reaching consequences for our current understanding of hadronic interactions. Experimentally, the difficulty lies in the fact that there is almost no clear signature which would allow NQM states and conventional hadrons to be distinguished from each other. Therefore, some candidates have been established based mainly on the lack of consistency with our picture of the conventional hadronic spectrum.

The JETSET experiment (PS202) at CERN–LEAR studies hadronic states produced in the annihilation of in-flight antiprotons with protons at rest [1, 2]. The mass range covered in formation studies extends up to 2.43 GeV. The experiment uses a molecular hydrogen-cluster jet target inserted in the LEAR ring. A compact general-purpose detector surrounds the interaction region. One advantage of this technique is the possibility to perform fine-tuned momentum scanning of the circulating antiproton beam. This fully exploits the excellent beam-momentum resolution of LEAR, and it results in a correspondingly good mass resolution for states that may be observed in pp interactions. Another advantage is the high luminosity. It is achieved by making most efficient use of the antiprotons, and it cannot be reached in extracted-beam experiments with in-flight antiprotons.

The experiment initially focusses on the investigation of pp annihilations into \(\phi\phi\), \(K^+K^-\phi\) and \(K^+K^-K^+K^-\) from the respective reaction thresholds up to the 2.0 GeV/c beam momentum. This is to be complemented by studies of pp annihilations into \(\pi^+\phi\), \(\eta\phi\), \(\omega\phi\) and \(\omega\omega\), which involve the detection both of charged particles and of photons, and also by measurements of other ‘strange'
channels, such as neutral $\bar{K}K$, $\bar{K}K^*$ and $K^*K^*$. In order to have access to hadronic states with quantum numbers not available in $pp$ formation experiments, three-particle reactions such as $\bar{p}p \to \pi^0\phi\phi$ are to be measured which requires the highest possible beam momenta at LEAR.

In the following chapter we describe the experimental technique chosen. Then we discuss the physics objectives of the JETSET experiment and review previously obtained data relevant to the mass region around and above 2 GeV. We conclude with an outlook into the future in terms of a substantial improvement of the experimental boundary conditions and the subsequent widening of the physics programme.1

Experimental technique

LEAR and the internal jet target

A central feature of the JETSET apparatus (see figure 1) is the molecular hydrogen-cluster jet target. The system is installed in the straight section SL2 of the LEAR ring. The basic principle is the expansion of molecular hydrogen kept at low temperature and high pressure, which creates an intense supersonic flow of clusters of $H_2$ molecules. The jet is oriented in the horizontal direction and intersects the antiproton beam perpendicularly. In the interaction region the jet provides a low-mass pure gaseous hydrogen target. The jet has a density $\rho = 5 \times 10^{13}$ atoms/cm$^2$ and a diameter of 8 mm (FWHM). For the later stage of the experiment the operation of a polarized jet target is foreseen, which would make some spin observables such as spin-transfer parameters accessible.

Some considerations for the operation of LEAR with the jet target are discussed in refs. [4] and [5]. At a momentum of 1.5 GeV/c the antiprotons stored in the machine have a revolution frequency $f = 3.2$ MHz. With an unbunched beam initially consisting of $N_0 = 6 \times 10^{12}$ antiprotons, the peak luminosity is thus $L_0 = \rho f N_0 = 10^{31}$ cm$^{-2}$ sec$^{-1}$. The hadronic $\bar{p}p$ total cross-section being $\sigma \approx 100$ mb in the relevant energy range, we have a hadronic interaction rate of up to $\sigma L_0 = 10^9$ sec$^{-1}$. This is one of several factors which cause the luminosity to decrease exponentially in time, $L_L = L_0 \exp(-t/\tau)$, and which thus influence the beam lifetime $\tau$ in the machine. The angular acceptance of the machine for scattering from the hydrogen jet is limited by the size of the vacuum chamber. Without a special low-beta insertion the acceptance is of the order of a few mrad. A fraction of the Coulomb-scattered antiprotons can thus be recuperated. However, the presence of the hydrogen jet causes a local pressure bump in the machine, which would lead within some minutes to an unacceptably large blow-up of the beam. This must be compensated by continuous transverse stochastic cooling, so that the transverse dimensions of the beam are always kept smaller than those of the intersecting jet. The energy loss of up to a few keV/sec must be compensated by continuous longitudinal stochastic cooling, so as to maintain a good momentum resolution and to keep the beam on its nominal orbit. In view of a possible upgrade of the JETSET apparatus with a surrounding magnetic field, schemes for the compensation of such a field and the induced machine resonances have already been studied. The calculations seem to indicate that, except for very low beam momenta, LEAR can be safely operated with a solenoidal field up to about 1 T-m.

In the region where the JETSET detector system is located around the interaction volume, the LEAR ring is equipped with a special vacuum chamber. The size of the chamber is dictated by the machine parameters at the time of beam injection: it is an oval with horizontal and vertical half-axes

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1 Throughout this report some particle names [3] are shortened as follows: $\rho = \rho(770)$, $\omega = \omega(783)$, $K^* = K^*(892)$, $\eta' = \eta(958)$, $f_0 = f_0(975)$, $\phi = \phi(1020)$, $K^{*+} = K^{*+}(1430)$, $\eta_c = \eta_c(2980)$ and $J/\psi = J/\psi(3097)$.
of 78 and 38 mm, respectively. This limits the geometrical acceptance of the detector to angles $\theta > 10^\circ$. It also means that particles have to travel some distance and must traverse the chamber wall before they can reach the nearest detector. At present the best solution is a corrugated chamber made of 0.3 mm Inconal, the hope being that further material developments will lead to a reduced amount of matter or perhaps even to a smaller-sized vacuum chamber.

One may assume that the stochastic cooling systems work perfectly well and that they always keep the beam emittance below the machine acceptance. If, for reasons of simplicity, one further assumes that there are no losses in the machine other than due to hadronic interactions and (multiple) Coulomb scattering in the hydrogen jet, one can estimate the beam lifetime. The number of particles in the machine is then given by $N(t) = N_0 \exp(-\rho t)$, where $\rho$ denotes the total cross-section for 'absorption' or 'off-acceptance scattering' of antiprotons. For $\Sigma \approx 120\,\text{mb}$, the 1/e lifetime would be $\tau = (\rho \Sigma)^{-1} = 14.5\,\text{hr}$. The longitudinal stochastic cooling of the beam also allows the antiproton momentum to be scanned continuously across a band in $\sqrt{s}$, for instance a hadronic resonance that one may hope to find. The momentum resolution of the beam, $\Delta p/p \approx 10^{-3}$, and the low mass of the hydrogen jet would then translate into an experimental invariant-mass resolution of about 500 keV for such a state.

**Basic event signatures**

For the task of fast on-line triggering, the $pp$ reactions in the prime interest of the JETSET experiment can be grouped into three categories. The decay modes assumed for this are $\phi \rightarrow K^+ K^-$, $\omega \rightarrow \gamma \eta^0$, $K^0(S) \rightarrow \pi^+ \pi^-$, and $K^* \rightarrow \pi^0 K^0(S) \rightarrow \pi^+ \pi^- \pi^-$.  

- Channels $\phi \phi$, $K^+ K^- \phi$, $K^- K^+ K^-$, and $\pi^0 \phi \phi$:
  - final state with four charged $K$ and with zero or one $\pi^0$, featuring a topology due to near-threshold kinematics.
- Channels $\omega \phi$ and $\omega \omega$:
  - final state with one $\gamma \eta^0$ and two charged $K$, or with two $\gamma \pi^0$ and no charged particles.
- Channels $KK$, $KK^*$ and $K^* K^*$:
  - final state with four charged $\pi$, featuring a $2\pi^0$ topology of two delayed decays, and with zero or one or two $\pi^0$.

The fast on-line triggering schemes are thus based on the multiplicity of charged particles, on the discrimination of $\pi / K / p$, on the multiplicity of photons, and on the specific event topologies.

**Detection of charged-particle multiplicities**

The vacuum chamber of the LEAR machine is immediately surrounded by 2 mm thick scintillator strips running along the beam direction ($Z$). One set of 40 strips, each 10 mm wide, covers polar angles $\theta \leq 45^\circ$. Another set of 20 strips, each 20 mm wide, gives the complementary coverage for larger angles. These 'inner' scintillators with their fine azimuthal segmentation provide a fast trigger on charged-particle multiplicities and they also give the time reference for $pp$ interactions. The information obtained from them is not much distorted by particle decays, secondary interactions or time-of-flight effects. However, such effects can become large as one goes to low beam momenta or approaches a reaction threshold, so that these inner trigger counters then play a key role in keeping the acceptance at a reasonable level.

Additional sets of 5 mm thick segmented 'outer' scintillation counters are positioned 40 to 60 cm away from the interaction region. Charged-particle multiplicity information in the forward part is provided by 48 pie-shaped segments, each covering $\Delta \phi = 7.5^\circ$. This plane is overlaid by two other planes, each of which contains 24 segments curved with opposite sense. The three layers form a fine grid that can provide fast kinematical information on the events, for instance hit coordinates
and track angles, which are to be used in the higher-level trigger. Similarly, the barrel part comprises a layer of 12 straight segments running along the Z direction, each covering $\Delta \phi = 30^\circ$. This is overlaid with two layers of 12 helical pieces each; the layers are wound with opposite screw sense.

The combined information from the inner and the outer scintillation counters is used to establish a 'charged multiplicity step' trigger on particles that have relatively long decay lengths, such as $K_S$ or $\Lambda$. Generally speaking, one wants to discriminate particles pointing back to the interaction volume against those showing a finite impact parameter relative to that region.
**Gamma detection**

In the forward region the JETSET apparatus is equipped with an electromagnetic calorimeter. Its main purpose is to detect \( \gamma \)-rays coming from the decays of neutral mesons, such as \( \pi^0 \), \( \eta \) or \( \omega \), which may be produced in pp interactions. For measurements of the exclusive production of \( \phi \phi \) or \( \bar{K}K \), it provides an efficient veto on 'unwanted' events involving photons in the final state \( (\phi \rightarrow K^+K^-; K_S \rightarrow \pi^+\pi^-; K^* \rightarrow \pi K) \). But studies of other channels, such as \( \pi^0\phi \), \( \eta\phi \), \( \omega\phi \), \( \omega\omega \) or \( \pi^0\pi^0 \), require that the direction and energy of the photons be measured well \( (\pi^0 \rightarrow \gamma\gamma; \eta \rightarrow \gamma\gamma, \pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0, \omega \rightarrow \pi^+\pi^-\pi^0, \gamma\pi^0) \). The calorimeter is made in a technique employing lead and scintillating fibres. It consists of 300 individual modules ('towers') grouped in eight rings. There are 12, 24 or 48 modules per ring in the azimuthal direction, and the modules have nearly constant front-face areas. Each of these modules contains plastic fibres of 1 mm diameter, which are embedded between corrugated sheaths of lead-alloy glued on top of each other. The filling by volume is 50% fibres, 35% lead-alloy and 15% optical epoxy glue. The blocks are 12.5 radiation lengths thick. They are individually machined and oriented such that the fibres running along their depths approximately point to the interaction region. The energy resolution was measured with electron and photon beams ranging in energy from 0.035 to 5.0 GeV. The average energy resolution is \( \sigma/E = 0.063\sqrt{E} \) (with E in GeV). The angular resolution for \( \gamma \)-rays coming from the target is around 7 mrad.

A possible detector upgrade is the extension of the electromagnetic calorimeter into the barrel region of the apparatus. This upgrade is important for studies of reactions far above their respective thresholds, in particular in view of processes involving multiple photons in the final state. For the time being, however, the barrel part is equipped with simple \( \gamma \)-veto counters. They are also made of lead and scintillating fibres, but in this case the fibres run along the beam direction. The device is segmented into 24 elements, each covering \( \Delta\phi = 15^\circ \). For the calorimeter as well as for the \( \gamma \)-veto counters the geometrical match with the outer trigger scintillators makes sure that showers due to photons can be distinguished from those due to hadronic charged particles.

**Charged-particle identification by \( \beta \) and \( dE/dx \)**

For the reaction \( \bar{p}p \rightarrow \phi\phi \) and others, sets of threshold Cherenkov counters provide a fast and efficient rejection of the charged-pion background. There are 24 pie-shaped detector segments in the forward part and 24 straight elements in the barrel part, so that each of the pieces covers \( \Delta\phi = 15^\circ \) and thus matches the segmentation of the outer trigger scintillators. The 2 cm thick counters are filled either with liquid freon FC-72 (refractive index \( n = 1.26 \)) or with water \( (n = 1.33) \), depending on the beam momentum chosen. The detectors are thus sensitive to particles having velocities \( \beta > 0.79 \) or \( \beta > 0.75 \), respectively. This corresponds to \( \pi / K / p \) threshold momenta of 182 / 645 / 1225 MeV/c in the first case and 159 / 563 / 1070 MeV/c in the second case. These values are well-matched in particular to studies of \( K^+K^-K^+K^- \) final states.

A ring-imaging Cherenkov counter (RICH) for JETSET is under development. It hopefully will provide additional information about the momenta of charged particles by measuring their \( \beta \) values. The RICH is conceived to have a 1 cm thick quartz radiator \( (n = 1.46) \). This is followed by a 6 cm deep drift space that allows the Cherenkov light cone to broaden before detection. The detector is sensitive to particles having velocities \( \beta > 0.68 \), which corresponds to \( \pi / K / p \) threshold momenta of 131 / 464 / 882 MeV/c. The photons are detected by means of photon-electron conversion in TMAE gas that is carried in a helium-ethane mixture at room temperature. The detector employs a modular structure, the basic element being a miniature wire chamber with 8x8 mm\(^2\) cell size and a single wire running perpendicular to the radiator surface. A detector module is formed by a matrix of 64 such cells. The pattern of struck cells provides the information necessary to determine the \( \beta \) value. From Monte Carlo simulations one can estimate that under these conditions the measurement error in \( \beta \) will be below 10%.
Silicon pad counters measure the specific energy loss $dE/dx$ of charged particles and thus greatly help to distinguish $K^+K^-K^+K^-$ final states from backgrounds such as $p\pi^+\pi^-$. Their information is evaluated during the off-line event reconstruction. The silicon detector is a natural complement to the threshold Cherenkov counters and the RICH, as its best information is obtained at low particle energies. The 280 $\mu$m thick counters are arranged in two planes in the forward region and two layers in the lower-angle part of the barrel region. They consist of elements $2.0 \times 2.4$ cm$^2$ in area, each of which contains four individual pads. The $dE/dx$ signal resolution obtained from these measurements is 10 to 20% for particles having $\beta < 0.8$. This allows the particle momentum to be 'predicted', typical precisions for kaons being 10% at 300 MeV/c and 30% at 600 MeV/c. In addition to $dE/dx$ measurements, the fine segmentation of the silicon counters also provides geometrical information on charged-particle tracks.

**Tracking of charged particles**

The 'heart' of the detection system and the central element for the off-line track reconstruction of charged-particles is a wire chamber made of individual drift tubes. This chamber is the only tracking device in the apparatus, hence all kinematic filtering relies on it. The chamber is divided into a forward part covering polar angles $\theta < 50^\circ$ and a barrel part being sensitive to tracks with $\theta > 40^\circ$.

The barrel tracking chamber is composed of about 1500 individual drift tubes ('straws') running parallel to the beam direction (Z). The tubes are glued together in two self-supporting units which constitute the top and the bottom halves of the barrel chamber. The horizontal split facilitates the installation of the detector and allows for the entry of the jet target. The 300 tubes in the horizontal midplane of the jet are to be mounted at a later stage. Each of the barrel straws consists of an extruded aluminium tube with 60 $\mu$m wall thickness and 8 mm diameter. The tubes are 436 mm long. Each tube is equipped with a stainless steel wire of 30 $\mu$m diameter running down its centre. The wires are kept in position by precision plastic endpieces. Low-mass sandwich structures serve as endplates and gas manifolds, and they also provide the electrical connections to the wires. Such a construction reduces the amount of support material needed at the forward end of the assembly, and it thus reduces the multiple scattering of particles leaving the barrel and entering the forward tracking chamber. For this reason all connections to gas supply, high voltage and readout systems are made at the barrel rear endplate. Each wire is equipped separately with front-end electronics consisting of a charge-sensitive preamplifier, a postamplifier with differential analog drivers, and a discriminator with differential ECL drivers. The electrons' drift-times are read from each wire in order to measure the radial distance of impact ($\rho$). For the measurement of the longitudinal coordinate (Z) by means of charge division, two wires are connected to each other 'back-to-back' using resistors in SMD technology which are located at the forward end of the assembly. The combined information from TDC's (drift time) and ADC's (charge division) provides unambiguous three-dimensional information for track and vertex reconstruction. When operated with a gas mixture of 50% Ar and 50% CO$_2$ at atmospheric pressure, the average resolutions obtained are $\sigma(\perp) = 150$ $\mu$m from the drift-time information and $\sigma(\parallel) = 8$ mm from the charge-division information.

The forward tracking chamber uses basically the same drift tubes as described above, although the geometrical configuration and the endplate assembly are quite different. In this case the straws are directly glued head-on onto precision printed-circuit boards that fix the wire position and provide electrical connections. The straws are mounted in 12 planes perpendicular to the beam direction. The alternating 'X' and 'Y' modules, arranged as (3-X)(3-Y)(3-X)(3-Y), employ a total number of about 1000 straws. Such an arrangement provides complete tracking information on the basis of drift-time readout only.
Physics objectives of the JETSET experiment

Survey of phenomenological and theoretical approaches

The questions that are addressed in phenomenological and theoretical approaches to non-quark-model hadrons, such as glueballs, hybrids and multi-quark states, are the masses, the ordering of spin states, and the most likely modes of production and decay. The reader is referred to several excellent recent reviews on this subject [6–8]. As mentioned in the introduction, the identification of an NQM state as such goes largely by 'excluding' that it be a conventional hadron. It thus requires a very good understanding of the spectrum of (qq) mesons. However, a problem arises from the possibility that the real physical states, which we observe, are mixtures of conventional and non-conventional hadrons. Another difficulty for experimenters is that some NQM states, in particular light glueballs, are expected to lie in mass regions which are already densely populated with (qq) states.

A number of models have been developed to predict spectra of non-quark-model states, or they have been adopted from their original application to (qq) mesons. In Bag Models [9, 10] the massless spin-1 gluons are confined in a spherical bag of suitable size. Two types of eigenmodes with angular momentum $L$ are distinguished: transverse electric $(TE)_L$ with parity $P = (-1)^L$, and transverse magnetic (TM)$_L$ with parity $P = (-1)^{L+1}$. The two-gluon state with the lowest mass is of the type $(TE)_0(TE)_1$ with $J^{PC} = 0^{++}$ and a mass of 1 to 1.3 GeV. In order of increasing mass, the spectrum is expected to be $J^{PC} = 0^{++}, 0^{--} < 2^{++} < 2^{--}$ for two-gluon states, the highest mass being around 2.3 GeV. In Potential Models one takes gluons to be massive spin-1 particles, which interact through a long-range confining potential that is linearly increasing with distance. The assumed effective gluon mass is of the order of a few hundred MeV, which is similar to the effective masses of light quarks bound in hadrons. In QCD Sum Rule approaches one studies functions associated with a current carrying the same quantum numbers as a resonance. The extrapolation from the high-momentum regime down to the non-perturbative one allows the mass of such a resonance to be extracted. The Flux-Tube Model [11] is a QCD-based approach in which glueballs can be formed by removing the quarks from the colour-flux tubes and joining the end of those flux tubes together. The lightest glueball is predicted to have $J^{PC} = 0^{++}$ with a mass around 1.5 GeV, and most of the other states are expected above 2 GeV. In Lattice Gauge calculations [12] methods of Monte–Carlo simulations are used to evaluate Feynman path integrals on a lattice and to study two-point correlation functions. This numerical type of approach can provide, in principle, the most accurate description of non-perturbative aspects of QCD. For reasons of computational feasibility, however, the lattice must be of finite spacing and of finite box size. The goal is to choose conditions such that a perturbative treatment is applicable, so that the resulting mass spectrum is not much affected by the finite lattice spacing. Typical values compatible with today’s computing power are a lattice spacing of 0.1 fm and a box size of 2 fm. The $0^{++}$ scalar glueball again turns out to be the lightest one, and the $2^{++}$ tensor state is expected to be about 1.5 times heavier [8, 12]. However, in Lattice Gauge calculations as well as in the Flux-Tube Model there is a considerable uncertainty in the overall mass scale of hadrons containing gluonic degrees of freedom.

Whereas there is some consensus on the $J^{PC}$ ordering of glueballs, not much can be said about their widths. One may assume that processes like $pp\rightarrow\phi\phi$, in which the initial and the final states are not connected by quark lines, are dominated by multi-gluon intermediate states. Then a prediction can be made [13] that the width of such a glueball is of the order of 10 MeV. There is, however, considerable uncertainty about the justification for the above assumption, largely due to the lack of understanding of the dynamics underlying quark-disconnected processes. Another naive expectation concerns the decay modes of glueballs. A flavourless, electrically neutral two-gluon state should have no preferred quark flavour or charge for its decays to (qq) mesons. However, this flavour symmetry is broken at low energies due to the mass difference between the strange quark and
the lighter u- and d-quarks. There are, in fact, arguments derived from perturbation theory which favour a particularly strong coupling of gluons to strange quarks, rather than to u- or d-quarks [14].

Glueballs have been searched for in various hadronic reaction channels, such as ππ or pp, and in the decay of heavy quarkonia, in particular radiative J/ψ decays. Proton—antiproton annihilations at rest or in flight can provide a rich source of hard gluons. The production of final states containing one or more (ss) quark pairs is likely to proceed via the annihilation of one or more light (q̅q) pairs. In general, however, both annihilation and rearrangement mechanisms contribute to the production or formation of hadrons in pp interactions. The outstanding feature of radiative decays, J/ψ→γ +X, is the cleanliness and the conceptual ‘simplicity’ of this process: the (cc) quark pair must annihilate in order for hadrons to be created, and the photon provides an experimental tag for that. The decay is thought to be dominated by J/ψ→γgg→γ + hadrons, with J^PC = 0++ , 0−− and 2++ being the most important partial waves contributing. In fact, the two best glueball candidates, η(1430) with J^PC = 0−− and f2(1720) with J^PC = 2++ , were seen in radiative J/ψ decays. They seem to have no place in the spectrum of conventional (q̅q) mesons, and their parameters are now often used in theoretical calculations in order to fix quantities such as the gluon self-energies. The question as to how ‘glueish’ a glueball candidate is cannot be answered easily in a quantitative way. For the comparison of different candidates with the same J^PC, however, Chanowitz [10] has defined the ‘stickiness’ of a state X as S_X = [Γ(J/ψ→γX)/(phase space)]/Γ(X→γγ)/(phase space). This expresses the expectation that glueballs are copiously produced in radiative J/ψ decays and that they have, due to the lack of electric charge, very little coupling to photons.

Hybrids, being mixed states of quarks and gluons, have been studied theoretically in frameworks similar to those of glueball studies. Explicit calculations in the Flux-Tube Model have predicted a number of states around 2 GeV mass, which preferentially decay to two mesons with one of them being excited [15]. In the Bag Model the lightest hybrids arise from the coupling of a (q̅q) pair with L = 0 and S = 0 or 1 to a TE(J^P=1+) gluon [6, 7]. The resulting states, most of them below 2 GeV mass, are a spin singlet J^PC = 1−− and a spin triplet J^PC = 0−+, 1++, 2++. Excited states are due to a TM(J^P=1−) gluon. This gives rise to a singlet J^PC = 1++ and a triplet J^PC = 0++, 1++, 2++, with masses just below or well above 2 GeV. It should be noted that quantum numbers in the series J^PC = (odd)−− or (even)++ are not accessible for conventional (q̅q) mesons. The identification of a state such as J^PC = 1−−, a so-called J^PC-exotic, would thus be the most convincing evidence for the discovery of a non-conventional hadron.

A (q̅q) hybrid could, for instance, decay according to the following two-step scheme. The first step is (q̅q)→(q̅q)→(q̅q)→(q̅q), where the subscript refers to colour octet. Two mesons can then be formed either by rearrangement, (q̅q)→(q̅q), or by gluon exchange, (q̅q)→(q̅q), the subscript denoting colour singlet here. The second possibility is, due to disconnected quark lines, suppressed for the decay of any conventional meson, hence it may be taken as a decay signature of a hybrid. A speculative example for this is the state ξ(2230) seen in KK final states. Its yet unobserved ωω decay mode would be an indication for the (u̅u+d̅d)g hypothesis. An ‘ω-based’ hybrid with J^PC = 2++ is, in fact, predicted at 2.32 GeV mass, and it has therefore been suggested [14] to search for the decays of ξ(2230) to ωω and K^−K^+. Multi-quark states too have been the subject of many theoretical investigations. A prominent example is the six-quark object called H, which has been predicted to be a stable strangeness −2 dibaryon about 80 MeV below the ΛΛ invariant mass [16]. Other studies found that most (qqqq) configurations lead to two free mesons, rather than to bound four-quark states [17]. An exception are the so-called KK molecules, ‘deuteron-like’ systems, which have been predicted to exist as loosely bound states in the isospin 0 and 1 channels. Genuine multi-quark states, if they really exist and are observable, may have peculiar properties that cannot be carried by ordinary (q̅q) or (qqq) hadrons. Flavour-exotics, for instance, can be formed in K^*+→X^0, and the result would in this case be a doubly-positive charged object with strangeness +1.
A suggestion being of particular interest to the JETSET experiment has been made by Ioffe [18]. He expects hybrids and four-quark states made of s- and/or c-quarks (but without u- or d-quarks) to have rather small total widths of less than 50 MeV, which may lead to cleaner experimental signatures. At masses of \((2.3 \pm 0.1)\) GeV, hence close to the upper limit of LEAR, several \((ssss)\) states are predicted with \(J^{PC} = 0^{++}, 1^{+-}, 2^{++}\). The main decay mode of the \(2^{++}\) state at 2.3 GeV is \(\phi \phi\), and that of the \(1^{+-}\) state about 100 MeV lower is \(\eta \phi\) or \(\eta' \phi\). The cross-section for the formation of such states in pp annihilations is estimated to be only 10 to 100 nb, but the partial width for this channel would be well below 1 MeV.

The reactions \(\bar{p}p \rightarrow \phi \phi\), \(\bar{p}p \rightarrow \omega \phi\) and \(\bar{p}p \rightarrow \omega \omega\)

Before elaborating on possible mechanisms for the exclusive production of \(\phi \phi\), \(\omega \phi\) and \(\omega \omega\) in \(\bar{p}p\) annihilations, it is useful to examine the quantum numbers that are available both in the initial and in the final states. The quantum numbers \([3]\) of \(\omega\) and \(\phi\) mesons are the same, \(J^{PC}(1^{G}) = 1^{--}(0^{-})\), hence the selection rules are the same for all three channels considered here. In the following we use capital letters, \(L\) and \(S\), for the orbital and spin angular momentum quantum numbers of the final state; those of the \(\bar{p}p\) state are denoted by lower case, \(\ell\) and \(s\). The \(\phi \phi\) state restricts the quantum numbers of charge conjugation and of G-parity to be positive, \(C = +1\) and \(G = +1\), respectively. Since the charge conjugation is defined as \((-1)^{\ell + \frac{S}{2}}\) for \(\phi \phi\) and \((-1)^{\ell + \frac{1}{2}}\) for \(\bar{p}p\), it follows that both \((L+S)\) and \((\ell + s)\) must be even numbers. The parity of \(\phi \phi\) is \((-1)^{L}\), and it is \((-1)^{\ell + 1}\) for \(\bar{p}p\). Therefore, \(L\) must be odd when \(\ell\) is even, and \(L\) must be even when \(\ell\) is odd. The total spin of the \(\phi \phi\) system can have the quantum numbers \(S = 0, 1\) or \(2\); that of the \(\bar{p}p\) initial state is restricted to \(s = 0\) or \(1\). Finally, the only allowed values of the isospin quantum numbers are \((I_{3}) = (0,0)\). The conservation of parity and total angular momentum \((J = j)\) then leads to the following three sets of selection rules.

- \(\ell\) even, \(s = 0; J = \ell\)
  - \(L\) odd, \(S = 1; J = L \pm 1\) \(J^{PC} = 0^{-+}, 2^{--+}, 4^{---}, ...\)
- \(\ell\) odd, \(s = 1; J = \ell\)
  - \(L\) even, \(S = 2; J = L \pm 1\) \(J^{PC} = 1^{++}, 3^{++}, 5^{+++}, ...\)
- \(\ell\) odd, \(s = 1; J = \ell \pm 1\)
  - \(L\) even, \(S = 0; J = L\) \(J^{PC} = 0^{++}, 2^{++}, 4^{+++}, ...\)
  - \(L\) even, \(S = 2; J = L\) \(J^{PC} = 2^{++}, 4^{+++}, ...\)
  - \(L\) even, \(S = 2; J = L + 2\) \(J^{PC} = 0^{++}, 2^{++}, 4^{+++}, ...\)

In total there are 8 kinds of amplitudes connecting the \(\bar{p}p\) spin--parity initial state to the \(\phi \phi\) (or \(\omega \omega\), \(\omega \phi\)) spin--parity final state. We note that exotic quantum numbers, \(J^{PC} = 1^{--}\) for instance, are in principle possible for states decaying to \(\phi \phi\), but in \(\bar{p}p\) annihilations they can be accessed only through reactions involving more particles, such as \(\bar{p}p \rightarrow \pi^{0} \phi \phi\).

Physical states having the same \(J^{PC}\) and the same additive quantum numbers can mix because of SU(3) breaking. Examples where such mixing occurs [3] are given by pseudoscalar mesons, \(\eta\) and \(\eta'\), and by vector mesons, \(\phi\) and \(\omega\). Each of these particles can be thought of as a linear combination of the corresponding SU(3) octet and singlet states. For the vector mesons the octet and singlet states, written in terms of unsymmetrized quark wave functions, are \(\omega_{8} = (uu + dd - 2ss)/\sqrt{6}\) and \(\omega_{1} = (uu + dd + ss)/\sqrt{3}\), respectively. The physical states \(\phi\) and \(\omega\) are then constructed from the SU(3) states involving a 'vector-mixing' angle: \(\phi = \omega_{8}\cos\theta_{V} - \omega_{1}\sin\theta_{V}\) and \(\omega = \omega_{8}\sin\theta_{V} + \omega_{1}\cos\theta_{V}\). The mixing is said to be 'ideal' if \(\phi = (ss)\) and \(\omega = (uu + dd)/\sqrt{2}\). This is the case for \(\tan\theta_{V} = 1/\sqrt{2}\), which corresponds to \(\theta_{V} \approx 35.3^{\circ}\). The \(\theta_{V}\) value as determined from \(\phi \rightarrow \pi \rho\) is about 39°. It can thus be assumed that the non-(ss) admixture in the \(\phi\)-meson and the (ss) admixture in the \(\omega\)-meson are of the order of 1%.

The immediate consequence for the hadronic reaction \(\bar{p}p \rightarrow \phi \phi\) appears to be rather extreme. As the initial and the final states have no quark, the transition should proceed via an
'intermediate state' containing only mediators of the strong interaction, namely at least two gluons (see figure 2a). This would make the reaction an ideal hunting ground for glueballs. The cross-section to be expected for such a 'quark-disconnected' process is relatively small. If so, however, it would be explained by the Okubo–Zweig–Iizuka (OZI) rule [19]. This empirical rule was established to account for the small ratio of branching fractions, \( BR(\phi \rightarrow \pi^+ \pi^- \pi^0) / BR(\omega \rightarrow \pi^+ \pi^- \pi^0) \). The OZI rule basically states that quark-disconnected processes are suppressed with respect to quark-connected ones. As a consequence, the occurrence of \( \bar{p}p \rightarrow \phi \phi \) through a quark-disconnected diagram would have to be considered a violation of the OZI rule, or it could be a hint for a new phenomenon. It should be noted, however, that the OZI rule itself is not understood in the context of the underlying QCD, and neither are its limits of validity. The OZI suppression can be 'bypassed' if one considers that the reaction \( \bar{p}p \rightarrow \phi \phi \) may proceed via the \( \phi - \omega \) mixing. In this picture, the \( \bar{p}p \) initial state would couple to the \( (u\bar{u}) \) and \( (d\bar{d}) \) components of the mixed \( \phi - \omega \) system (mainly \( \omega \)), whereas the final charged kaon state would arise through the \( (s\bar{s}) \) component of the \( \phi - \omega \) system (mainly \( \phi \)). The probability for such a mechanism may be small, but it can nevertheless turn out to be important if the quark-disconnected process is strongly suppressed by the OZI rule.

![Diagram](https://via.placeholder.com/150)

**Figure 2:** Examples of quark-line diagrams. a) The reaction \( \bar{p}p \rightarrow \phi \phi \), and b) the reaction \( \bar{p}p \rightarrow \omega \phi \).  

For the hadronic production of \( \phi \phi \) states there are, in fact, several reaction mechanisms that seem to avoid the 'complication' of OZI suppression. The case due to \( \phi - \omega \) mixing discussed above shows that the reaction \( \bar{p}p \rightarrow \phi \phi \) may proceed in several steps each of which is quark-connected and thus not OZI-suppressed. Intermediate states relevant for the production of \( \phi \phi \) are obviously those that contain a sizeable amount of strangeness. Donoghue [20] has identified \( \eta \eta \) as an important intermediate state. As \( \eta \) mesons contain large components of all three quark types \( (u\bar{u}), (d\bar{d}) \) and \( (s\bar{s}) \), it is quite conceivable that the first reaction step, \( \bar{p}p \rightarrow \eta \eta \), proceeds through the non-strange component of \( \eta \) and the second step, \( \eta \eta \rightarrow \phi \phi \), through the strange one. Lipkin [21] has argued that in such a case there are additional contributions due to \( \eta \eta' \) and \( \eta' \eta' \), which may altogether tend to cancel. Similar considerations can be made for \( \bar{K}K \) as another possible intermediate state between \( \bar{p}p \) and \( \phi \phi \). Again, additional contributions due to \( \bar{K}K^* \) and \( K^* \bar{K} \) may have a cancelling effect.

The reaction \( \bar{p}p \rightarrow \phi \phi \) can also be seen to proceed via intermediate states consisting of two four-quark objects, \( (q\bar{q}s)(q\bar{q}s) \), with yet unknown identity. This has been argued for by Dover and Fishbane [22] in an attempt to explain the rates observed experimentally for \( \phi \) production in
nucleon–antinucleon annihilation. Roberts and Karl [23] have suggested a string-breaking mechanism for hadronic $\phi\phi$ production. After the creation of the first (ss) pair, the second one is produced by breaking the QCD string that joins the first pair. The sequential process is then seen as $q\bar{q} \rightarrow s_{1} \bar{s}_{1} \rightarrow s_{2} (s_{2} \bar{s}_{2}) \bar{s}_{2} \rightarrow (s_{2} \bar{s}_{2})(\bar{s}_{2} s_{2}) \rightarrow \phi\phi$. Recent data from deep-inelastic scattering of polarized muons on protons have revived interest in the question to what extent a sea of (qq) pairs ($q = u, d, s$) and gluons may contribute to the proton wave-function, even when larger distances or small momentum transfers are involved. Ellis et al. [24] have demonstrated that the coupling of an (ss) meson to a non-strange baryon via non-valence (ss) quark pairs is indeed conceivable. For $p\bar{p} \rightarrow \phi\phi$ this constitutes another possible mechanism in which the otherwise expected OZI suppression is not in action.

We have briefly discussed six different reaction modes with which to produce $\phi\phi$ meson pairs in $\bar{p}p$ annihilations. Clearly, a measurement of this reaction alone will not be sufficient for unravelling the various mechanisms involved, nor will it be sufficient for the identification of possible NQM states as such. Therefore, it is indispensable that additional channels complementary to $\phi\phi$, in particular $K^+K^-$ and $K^+K^-K^+K^-$ on one side, and $\omega\phi$ and $\omega\omega$ on the other, be investigated simultaneously by the experiment.

For the reaction $\bar{p}p \rightarrow \omega\omega$ the mechanism in the context of a simple quark picture is obvious, as there are no significant quark-disconnected contributions. But this means also that the ratio of resonant and non-resonant cross-sections may be very unfavourable. Ideally seen, however, measurements of the $\phi\phi$ and $\omega\omega$ channels together would allow the relative sizes of strange and non-strange components in a possible (qq) resonance to be extracted. In the case of a glueball, the flavour (in-)dependence of its decay could be tested.

The reaction $\bar{p}p \rightarrow \omega\phi$ is OZI-suppressed for intermediate (qq) states because of its quark-disconnected (ss) vertex. However, the gluons associated with that vertex and the (qq) nature of the $\omega$ seem to make the $\omega\phi$ channel very attractive for a hybrid search (see figure 2b). In a simple view the creation and decay of such a hybrid may be written as $\bar{p}p \approx (uud + uud) \rightarrow (u\bar{d} + d\bar{u})(u\bar{u} \rightarrow (u\bar{u} + d\bar{d})g \rightarrow (u\bar{u} + d\bar{d})(ss) \approx \omega\phi$.

**The reactions $\bar{p}p \rightarrow \bar{K}K$, $\bar{p}p \rightarrow \bar{K}K^*$ and $\bar{p}p \rightarrow K^*K^*$**

In ground-state kaons the spins of the quark–antiquark pair are antiparallel, giving rise to $J^P(1) = 0^+(1/2)$. Therefore the assignments are $S = 0, J = L$, and $P = C = (-1)^L$ for the $\bar{K}K$ systems. In the $\bar{p}p$ initial state, on the other hand, one has $P = (-1)^L + 1$ and $C = (-1)^L + 3$. The conservation of parity and charge conjugation is satisfied only for $s = 1$. In words this means that the annihilation $\bar{p}p \rightarrow \bar{K}K$ can proceed only from the spin-triplet state of the $\bar{p}p$ system. For the orbital angular momenta it must hold that $L = \ell \pm 1$. The isospin in the initial and the final states can have the values $(I, I_y) = (0, 0)$ or $(1, 0)$. In summary, the selection rules for $\bar{p}p \rightarrow \bar{K}K$ are the following.

- $\ell$ even, $s = 1; J = \ell \pm 1$
  - $L$ odd, $S = 0; J = L$ ($J^PC = 1^-, 3^-, 5^-, ...$)
- $\ell$ odd, $s = 1; J = \ell \pm 1$
  - $L$ even, $S = 0; J = L$ ($J^PC = 0^+, 2^+, 4^+, ...$)

For the $K^+K^-$ system there are no further restrictions. However, when considering the neutral-kaon final state, $K^0\bar{K}^0$, the short- and the long-lived components of $K^0$ and $\bar{K}^0$ introduce more constraints. In the limit of CP conservation we can identify these components with the CP eigenstates $K_1$ and $K_2$: $K_S \approx K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ and $K_L \approx K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$. For even $L$-values it is $P = C = + 1$. The corresponding part of the $K^0\bar{K}^0$ wave-function is thus symmetric with respect to $K^0 - \bar{K}^0$ exchange and it consists of $K_S K_S$ and $K_L K_L$ components only. For odd $L$-values one has $P = C = - 1$ with an antisymmetric wave-function containing only the $K_S K_L$
component of $\bar{K}^0 K^0$. If, as in the JETSET experiment, the detection of hadronically produced $K^0$ and $\bar{K}^0$ mesons proceeds via the two-pion decay of the short-lived component, the only accessible $\bar{K}^0 K^0$ states are in the series $J^{PC} = (\text{even})^{++}$.

In $K^*$ mesons the constituent quark–antiquark pair has the spins parallel, so that $J^P(I) = 1^-(1/2)$. In $\bar{K}K^*$ systems (and the charge-conjugated case $K^*K$) it must therefore be $S = 1$. Again, parity conservation requires that $L = \ell \pm 1$. The selection rules for $p\bar{p} \rightarrow \bar{K}K^*$ + c.c. are as follows.

- $\ell$ even, $s = 0; J = \ell \pm 1$
  - $L$ odd, $S = 1; J = L \pm 1$ ($J^{PC} = 0^{++}, 2^{++}, 4^{++}, ...$)

- $\ell$ even, $s = 1; J = \ell$
  - $L$ odd, $S = 1; J = L \pm 1$ ($J^{PC} = 2^{--}, 4^{--}, ...$)

- $\ell$ odd, $s = 0; J = \ell$
  - $L$ even, $S = 1; J = L \pm 1$ ($J^{PC} = 1^{--}, 3^{--}, 5^{--}, ...$)

- $\ell$ odd, $s = 1; J = \ell$
  - $L$ even, $S = 1; J = L \pm 1$ ($J^{PC} = 1^{++}, 3^{++}, 5^{++}, ...$)

- $\ell$ even, $s = 0; J = \ell$
  - $L$ even, $S = 1; J = L \pm 1$ ($J^{PC} = 0^{++}, 2^{++}, 4^{++}, ...$)


The reaction $p\bar{p} \rightarrow \bar{K}K^*$ involves even more partial waves because of the possibilities $S = 0, 1$ or 2 in the final state. From charge-conjugation invariance one has $(-1)^{s+L} = (-1)^{L+S}$. The selection rules are thus the following.

- $\ell$ even, $s = 0; J = \ell$
  - $L$ odd, $S = 1; J = L \pm 1$ ($J^{PC} = 0^{++}, 2^{++}, 4^{++}, ...$)

- $\ell$ even, $s = 1; J = \ell$
  - $L$ odd, $S = 2; J = L \pm 1$ ($J^{PC} = 2^{--}, 4^{--}, ...$)

- $\ell$ odd, $s = 0; J = \ell$
  - $L$ even, $S = 1; J = L \pm 1$ ($J^{PC} = 1^{--}, 3^{--}, 5^{--}, ...$)

- $\ell$ odd, $s = 1; J = \ell$
  - $L$ even, $S = 1; J = L \pm 1$ ($J^{PC} = 1^{++}, 3^{++}, 5^{++}, ...$)

- $\ell$ odd, $s = 0; J = \ell$
  - $L$ even, $S = 0; J = L \pm 1$ ($J^{PC} = 0^{++}, 2^{++}, 4^{++}, ...$)

- $\ell$ odd, $s = 1; J = \ell$
  - $L$ even, $S = 1; J = L \pm 1$ ($J^{PC} = 0^{++}, 2^{++}, 4^{++}, ...$)

The reactions $p\bar{p} \rightarrow \bar{K}K$, $p\bar{p} \rightarrow \bar{K}K^*$ + c.c. and $p\bar{p} \rightarrow \bar{K}^* K^*$ involve, in lowest order, the annihilation of two (qq) pairs and the creation of one (ss) quark pair. An alternative to this quark-connected process is the quark-disconnected one, in which all three (qq) pairs of the pp initial state annihilate. The reactions are thus open for various NQM states as intermediate resonances. In particular, the simultaneous measurement of these channels can provide stringent tests for the quark–gluon structure of intermediate resonances. For glueballs, the various possibilities of decays to strange-meson pairs are an 'analyzer' with respect to the charge-conjugation quantum number \cite{6}. A glueball having $C = +1$ can decay to $KK$, $K^*K^*$ or $KK_2^*$, whereas a $C = -1$ glueball would select the decay channels $KK^*$ or $K^*K_2^*$. In contrast to this, a nonet of 'ordinary' quarkonium states has all these channels open, provided \cite{15} is in the allowed series. In addition, the decays of a (qq) state are somehow restricted by the OZI rule as discussed above. A 'smoking gun' glueball candidate can thus be identified as such if it would decay, for example, into both (ss)-type channels such as $\phi \phi$ and non-(ss) channels like $\omega \omega$ or $\pi \pi$, but into only one of the two classes of strange-meson pairs.
Previous data on $\phi\phi$, $K^+K^-\phi$ and $K^+K^-K^+K^-$ states

In this section we attempt to give an account of data that have been obtained in $\phi\phi$ and states related to this. The reaction $p\bar{p}\to\phi\phi$, which constitutes the main physics objective of the phase-1 JETSET experiment, has been measured only once. In the CERN–ISR experiment R704 an energy scan was performed in order to detect $p\bar{p}\to\eta\phi$ formation [25]. As a part of this, the reaction $p\bar{p}\to\phi\phi\to K^+K^-K^+K^-$ was also studied. On the basis of 83 events centered around $\sqrt{s} = 2.989$ GeV, and after correction for the branching fraction $\text{BR}(\phi\to K^+K^-) = 0.495$, the resulting production cross-section is $\sigma(p\bar{p}\to\phi\phi) = (25.0 \pm 8.3)$ nb. Besides the direct coupling of $p\bar{p}$ to $\phi\phi$, the formation and decay of an intermediate $\eta_c$ might also contribute to the measured cross-section. In an earlier bubble-chamber experiment on $p\bar{p}\to K^+K^-K^+K^-$ between 1.6 and 2.2 GeV/c incident momentum only six events were identified [26]. These also included $K^+K^-\phi$ and $\phi\phi$ intermediate states. The production cross-section $\sigma(p\bar{p}\to K^+K^-K^+K^-) = (3.8 \pm 1.7)$ $\mu$b was calculated from the data.

Prominent information on $\phi\phi$ hadronic production stems from measurements of $\pi^-p\to\phi\phi n$, which were performed in four generations of experiments using a 22 GeV/c beam and the MPS facility at BNL–AGS. The $\phi$-mesons were identified through their decays into $K^+K^-$, and the analysis required the mass of the $K^+K^-$ pairs close to the $\phi$ mass. In the first of these experiments [27], 102 events were obtained. The $\phi\phi$ invariant-mass spectrum showed an enhancement between threshold and 2.4 GeV. The data also revealed the ratio of cross-sections to be $\sigma(K^+K^-\phi)/\sigma(\phi\phi) \leq 10$, which was interpreted as a violation of the expected OZI suppression. In fact, when taking into account decay modes other than $\phi\to K^+K^-$, this ratio is probably more like 5. With the second experiment [28], the event statistics was increased to 1203, which allowed a partial wave analysis of $\phi\phi$ production to be performed. All permitted values of $J\leq 4$ and $L\leq 3$ were included, resulting in 52 waves. The $\phi\phi$ mass spectrum was found to be essentially reproduced by only two amplitudes, both having $J^{PC} = 2^{++}$, from which the following resonance parameters were extracted: $M_1 = (2.16 \pm 0.05)$ GeV with $\Gamma_1 = (0.31 \pm 0.07)$ GeV for the S-wave, and $M_2 = (2.32 \pm 0.04)$ GeV with $\Gamma_2 = (0.22 \pm 0.07)$ GeV for the D-wave. The sensitivity of this analysis was then increased by the third experiment [29], which led to a total of 3652 events. As a consequence, a strongly dominant S-wave and two D-waves, again all with $J^{PC} = 2^{++}$, were found to comprise all of the observed cross-section. The resonance parameters of the S-wave were $M_1 = (2.05 \pm 0.07)$ GeV with $\Gamma_1 = (0.20 \pm 0.11)$ GeV; those for the two D-waves were $M_2 = (2.30 \pm 0.06)$ GeV with $\Gamma_2 = (0.20 \pm 0.06)$ GeV, and $M_3 = (2.35 \pm 0.03)$ GeV with $\Gamma_3 = (0.27 \pm 0.11)$ GeV. In contrast to this the $K^+K^-\phi$ background was seen to be mostly structureless. Finally, the fourth experiment [30] doubled the statistics, which now included a total of 6658 events (see figure 3). The refined partial wave analysis included all 114 waves with $J\leq 6$ and $L\leq 4$. Again three $2^{++}$ resonances contained all of the observed $\phi\phi$ strength. The dominant S-wave accounted for 45% of the data; its resonance parameters were determined to be $M_1 = (2111 \pm 69)$ MeV with $\Gamma_1 = (202 \pm 65)$ MeV. The two D-waves comprised 20% and 35% of the data; their parameters were $M_2 = (2297 \pm 28)$ MeV with $\Gamma_2 = (149 \pm 41)$ MeV, and $M_3 = (2339 \pm 55)$ MeV with $\Gamma_3 = (319 \pm 75)$ MeV, respectively. The production of $K^+K^-\phi$ was evaluated simultaneously. Two thirds of its strength were found to be structureless and incoherent, whereas one third exhibited $J^{PC} = 1^{--}$, and a few percent $J^{PC} = 2^{++}$.

The view of $\pi^-p\to\phi\phi n$ as an OZI-suppressed process and the unexpectedly large signal seen in ($\phi\phi$) vs ($K^+K^-\phi$) led the BNL experimenters to strong conclusions. The OZI suppression was seen to be broken down due to the annihilation of ($q\bar{q}$) pairs into resonating gluons. The three broad resonances that were un unravelled in the amplitude analysis were thus interpreted as tensor glueballs. The authors labelled the states $g_T$, however, in ref. [3] they are listed as $f_T$. The strong and uncompromising claim for the discovery of at least one glueball has caused a great deal of controversy, for which ref. [31] gives illustrative examples. It has also inspired much theoretical work on $\phi\phi$ hadronic production as discussed previously. It appears unsatisfactory that none of the
three resonances is clearly visible in the \( \phi\phi \) mass spectrum, but they only showed up, as broad and overlapping as they are, resulting from a complicated amplitude analysis. Another problem, which is actually more challenging, is that the states have not been seen in the decay \( J/\psi \rightarrow \gamma\phi\phi \), a channel that is certainly quark-disconnected and thus supposed to be gluon-enriched, so that the glueball interpretation of the BNL data becomes less likely. However, there do exist some experimental results consistent with the observations made at BNL. After the first experiment there, the same reaction \( \pi^- p \rightarrow \phi\phi n \) was studied at CERN–SPS using the OMEGA spectrometer in a 16 GeV/c beam [32]. The \( \phi\phi \) mass distribution, based on 153 event candidates, exhibited a threshold enhancement falling off at 2.5 GeV. From a spin–parity analysis the background-reduced event sample was found to be consistent with two interfering \( J^P = 2^+ \) resonances.

Experiment WA67 at CERN–SPS measured, also using the OMEGA spectrometer, the inclusive production \( \pi^- \text{Be} \rightarrow \phi\phi + X \) at 83 GeV/c beam momentum [33]. The ratio of (\( K^+K^-\phi \) or \( K^+K^-K^-K^+ \)) vs \( \phi\phi \) production turned out to be of the order of one. From the \( \phi\phi \) spectrum, comprising 13088 events up to 3.2 GeV, two broad resonances were extracted: \( M_1 = (2231 \pm 10) \text{ MeV} \) with \( \Gamma_1 = (133 \pm 50) \text{ MeV} \), and \( M_2 = (2392 \pm 10) \text{ MeV} \) with \( \Gamma_2 = (198 \pm 50) \text{ MeV} \) as a mixture of S- and D-waves, and \( M_2 = (2392 \pm 10) \text{ MeV} \) with \( \Gamma_2 = (198 \pm 50) \text{ MeV} \) as a pure D-wave (see figure 4). Moreover, from the analysis of angular correlations in \( \phi\phi \) decays it was found that the mass spectrum up to 2.5 GeV was consistent with a dominance of \( J^P = 2^+ \), and a signal observed in the higher mass range was attributed to \( \pi^- \text{Be} \rightarrow \eta_c + X \rightarrow \phi\phi + X \).

Using a 400 GeV/c proton beam from the FNAL main ring, experiment E623 looked at the inclusive channel \( pN \rightarrow \phi\phi + X \), where each \( \phi \) decays into a \( K^+K^- \) pair [34]. The events were found to be concentrated at low invariant masses of the \( \phi\phi \) system. This region was investigated further. The spectra of the above reaction were compared with other spectra obtained in the same experiment [35]:

\[ pN \rightarrow (K^+K^-) + X, \quad pN \rightarrow (\phi\phi)K^+K^- + X, \quad pN \rightarrow (K^+K^-)K^+K^- + X, \quad \text{and} \quad pN \rightarrow (\pi^+\pi^-\phi)K^+K^- + X. \]

A global fit to the data, comprising nearly 400 events above background, revealed a narrow enhancement with mass \( M = (2141 \pm 16) \text{ MeV} \) and width \( \Gamma = (49 \pm 28) \text{ MeV} \) (see figure 5). Also determined were the ratios of branching fractions for this state, the results being

\[ \frac{BR(M \rightarrow \phi\phi)}{BR(M \rightarrow K^+K^-\phi)} = 0.39 \pm 0.24 \text{ and } \frac{BR(M \rightarrow K^+K^-\phi)}{BR(M \rightarrow \pi^+\pi^-\phi)} = 0.49 \pm 0.16. \]

In view of the latter number, the observed state was found to be inconsistent with being of
(q\bar{q}) nature. It also appeared to be not identifiable with any of the broad $\phi \phi$ resonances discussed above, nor with narrow structures seen in KK channels that are discussed further below.

The reaction $K^- p \rightarrow \phi \phi Y^0$, with $Y^0$ being a $\Lambda$ or a $\Sigma^0$ hyperon, was measured for the first time at CERN using the OMEGA spectrometer in a 18.5 GeV/c beam [36]. The about 100 events were found to be concentrated in the low-mass region of the $\phi \phi$ spectrum. More recently, the $K^- p \rightarrow \phi \phi \Lambda$ reaction was also measured at SLAC using the LASS spectrometer in a 11 GeV/c beam [37]. Near 2.2 GeV a structure was visible in the $\phi \phi$ mass spectrum. An angular analysis then showed that the distributions were essentially consistent with a pure S-wave or a combination of waves giving $J^P = 2^+$, but the authors found the data to be inconsistent with a dominant $J^P = 0^-$ assignment.

The central production of neutral states was extensively studied with experiment WA76 using the OMEGA spectrometer at CERN−SPS. Exclusively produced states $X^0$ were investigated in $\pi^+ p \rightarrow \pi^+ (X^0) p$ at 85 GeV/c and also in $p p \rightarrow p (X^0) p$ at 85 and 300 GeV/c. Of particular interest in the context here is the production of those states that were identified as $\phi \phi$, $K^+ K^- \phi$ or $K^+ K^- K^+ K^-$. The central system ($X^0$) is characterized by small values of the Feynman variable, $x_F = 2p_F/\sqrt{s}$. It is presumed to be produced by a double exchange process, which, at high centre-of-mass energies, is dominated by double Pomeron exchange. As the Pomeron is believed to be a multi-gluon state, Pomeron−Pomeron scattering may be a source of states other than (q\bar{q}). The events from the $\pi^+$ and $pp$ experiments performed at 85 GeV/c showed similar features, so they were considered together [38]. By plotting $K^+ K^-$ mass spectra the production of one or two $\phi$-mesons could be demonstrated. Although the statistics of $\phi \phi$ events was very low, there was an apparent accumulation of events near threshold. After correction for decay modes other than the detected $\phi \rightarrow K^+ K^-$, the ratios of cross-sections were determined to be $\sigma(K^+ K^- \phi)/\sigma(\phi \phi) = 1.5 \pm 0.6$ and $\sigma(K^+ K^- K^+ K^-)/\sigma(\phi \phi) = 0.3 \pm 0.2$. From the pp data taken at 300 GeV/c the ratio $\sigma(K^+ K^- \phi)/\sigma(\phi \phi) = 1.0 \pm 0.3$ was extracted [39]. Combining the 85 GeV/c and the 300 GeV/c data into one $\phi \phi$ mass distribution, a shape similar to the one obtained from the $\pi^- p$ experiments at BNL was found (see figure 6). The angular distribution of the $K^+ K^- K^+ K^-$ system was used to
determine the spin and parity of the intermediate $\phi\phi$ state. As a result, $J^P = 2^+$ was favoured over $J^P = 0^-$, although other waves could not be ruled out.

All of the data obtained in hadronic production of $\phi\phi$ pairs up to about 2.5 GeV invariant mass appear to indicate the dominance of $J^P = 2^+$ or, at least, are not inconsistent with such an assignment. This has been challenged by some of the results from radiative decays $J/\psi \rightarrow \gamma \phi\phi$. The experiments DM2 at Orsay−DCI and MARK III at SLAC−SPEAR both studied various hadronic and radiative decay modes following the resonance formation $e^+e^- \rightarrow J/\psi$. The data sample collected by DM2 consisted of $8.6 \times 10^6$ events. For the study of $J/\psi \rightarrow \gamma \phi\phi$, the decay mode $\phi\phi \rightarrow K^+K^-K^+K^-$ was evaluated [40]. A spin−parity analysis of the $\phi\phi$ mass spectrum was performed in order to search for intermediate states (see figure 7a). The region up to 2.5 GeV was found to agree with the hypothesis of an S-wave giving $J^P = 2^+$. However, the probabilities for other waves were also significant in some cases, and the possible mixing between different waves was not taken into account. Near 2.2 GeV an enhancement of events was seen in the mass spectrum. Here a P-wave and $J^P = 0^-$ was the preferred assignment, and, moreover, even parity appeared to be strongly disfavoured. The mass region above 2.9 GeV revealed presence of the sequential decay $J/\psi \rightarrow \gamma \eta_c \rightarrow \phi\phi$. A spin−parity analysis confirmed the assignment $J^P = 0^-$ for the $\eta_c$, whereas adjacent events between 2.68 and 2.9 GeV did not fit with the $J^P = 0^-$ hypothesis. More recently, the DM2 group also performed an analysis of the decay mode $\phi\phi \rightarrow K^+K^-K_SK_L$ [41]. This confirmed the presence of an enhancement in the $\phi\phi$ invariant-mass spectrum near threshold (see figure 7b). Taking the sum of the efficiency-corrected mass spectra of both decay modes, the extracted resonance parameters were $M = (2238 \pm 7)$ MeV and $\Gamma = (80 \pm 30)$ MeV. The new
analysis was consistent with the pseudoscalar assignment for this state as concluded from final states with four charged kaons.

The \( J/\psi \) sample evaluated by MARK III consisted of \( 4.9 \times 10^6 \) produced events [42, 43]. In the decays \( J/\psi \to \gamma \phi \phi \), both the \( \phi \phi \) final states \( K^+ K^- K^+ K^- \) and \( K^+ K^- K_S K_L \) (with \( K_S \to \pi^+ \pi^- \)) were studied. The efficiency-corrected mass spectra of \( \phi \phi \) for each of the two modes exhibited the same two structures, one being the \( \eta_c \) and the other one located near 2.2 GeV (see figure 8). The parameters extracted for the low-mass state [42], when averaged over the two decay modes, were \( M = (2222 \pm 27) \) MeV and \( \Gamma = (150 \pm 190) \) MeV. A spin-parity analysis was performed, in which the angle between the \( \phi \phi \) decay planes in the \( \phi \phi \) rest frame and the polar angle of the decay kaon in its \( \phi \) rest frame were evaluated. The resulting distributions showed the characteristics of a pseudoscalar, \( J^P = 0^- \), for this state and also for the \( \eta_c \). No indication for the presence of a \( J^P = 2^+ \) state in the \( \phi \phi \) spectrum was found. In fact, and somewhat contrasting the DM2 result, the entire region below 2.4 GeV appeared to be dominantly \( J^P = 0^- \).

Pseudoscalar structures near threshold produced in radiative \( J/\psi \) decays were seen, besides \( \phi \phi \), also in other vector–vector meson channels [42–45]: \( \rho \rho \), \( \omega \omega \), and \( K^* K^* \). In view of the quark content of \( \omega \) and \( \phi \)-mesons and the \( \omega - \phi \) mixing, the channel \( J/\psi \to \gamma \phi \phi \) is naturally complemented by studies of \( J/\psi \to \omega \omega \phi \) and \( J/\psi \to \omega \omega \omega \). Suffering from very low statistics, however, no significant structures were observed in the \( \omega \omega \phi \) invariant-mass spectrum [43]. Radiative \( J/\psi \) decays to \( \omega \omega \) appear to be an order of magnitude stronger. A prominent threshold enhancement near 1.8 GeV, again featuring \( J^P = 0^- \), was seen in the \( \omega \omega \omega \) spectrum, but no structures were observed at higher masses [46].

The GAMS collaboration studied the reaction \( \pi^- p \to \omega \omega \omega \) using a 38 GeV/c beam [47]. The \( \omega \)-mesons were identified through their \( \gamma \pi^0 \) decay mode. Near 2 GeV invariant mass of the \( \omega \omega \omega \)
system, two states were identified by an analysis that intentionally emphasizes different spin states (see figure 9). One of the states was measured to have the parameters $M = (1924 \pm 14)$ MeV with $\Gamma = (91 \pm 50)$ MeV, and the assignment $J^P_C = 2^{++}$ was determined from the data. The other state occurred at $M = (2060 \pm 20)$ MeV with $\Gamma = (170 \pm 60)$ MeV, and it was identified with the $4^{++}$ candidate $f_2(2050)$ listed in the data tables of ref. [3].

**Previous data on $K^*K^*$ states**

Having dealt mostly with $\phi \phi$ states in the previous section, we now turn to $K^*K^*$ as another very interesting channel that involves a pair of vector mesons. The associated production of neutral $K^*$ and $\bar{K}^*$ mesons can be identified through the decays $K^+\pi^-$ and $K^-\pi^+$, respectively. It was observed in central hadronic collisions, namely in $\pi^-p \rightarrow \pi^+(K^*\bar{K}^*)p$ measured at 85 GeV/c, and also in $pp \rightarrow p(K^*\bar{K}^*)p$ at 85 and 300 GeV/c [48, 49]. Experiment WA76, which studied these processes, reported a production cross-section ratio $\sigma(K^*\bar{K}^*)/\sigma(\phi\phi) \approx 10$ from the 85 GeV/c data. In all spectra obtained, the $K^*\overline{K}^*$ events were found to be concentrated in a relatively narrow non-resonant enhancement near threshold. A similar threshold behavior was also observed in the LASS experiment investigating the reaction $K^-p \rightarrow K^*\overline{K}^*\Lambda$ at 11 GeV/c [37]. Here, both neutral ($K^-\pi^+\pi^-\pi^-$) and charged ($K_S\pi^+K_S\pi^-$) modes were measured. The angular distributions of $K^*\overline{K}^*$ were found to be consistent with $L = 0$ production, giving rise to $J^P = 2^+$, and inconsistent with the assumption of $J^P = 0^-$ dominance.

Studying various vector–vector meson states, the MARK III group also looked at the radiative decays $J/\psi \rightarrow \gamma K^*\overline{K}^*$ in the charged mode [44, 45]. A fit to the $K^*\overline{K}^*$ invariant-mass spectrum revealed some interesting structures below 2.5 GeV, their parameters being $M_1 = (1930 \pm 9)$ MeV with $\Gamma_1 = (75 \pm 21)$ MeV, $M_2 = (2067 \pm 12)$ MeV with $\Gamma_2 = (113 \pm 30)$ MeV, and $M_3 = (2335$
Results [42] from $J/\psi \to \phi \phi \phi$ of the MARK III experiment. Shown are the $\phi \phi$ mass spectra, a) obtained from the $K^+K^-K^+K^-$ decay mode, and b) from the $K^+K^-K_SK_L$ decay mode. The shaded area is the estimated background; the dashed curve shows the acceptance. The efficiency-corrected spectra for the two final states with fits to Breit–Wigner resonances are shown in c) and d), respectively.

$\pm 31 \text{ MeV with } \Gamma_3 = (180 \pm 64 \text{ MeV}).$ The $\bar{K}^*K^*$ spectrum appeared to be dominated by $J^P = 0^-$, as it was the case in radiative decays to $\phi \phi$. It is interesting to note that enhancements occurring in channels like $\bar{K}^*K^*$ and $\phi \phi$ close to their respective thresholds seem to be a universal feature of vector–vector meson states, as observed through several different production mechanisms. The nature of these enhancements, however, has yet to be understood. Possible explanations include radial excitations of pseudoscalar mesons. Another interesting feature is that radiative $J/\psi$ decays seem to favour the assignment $J^P = 0^-$, whereas hadronic production channels are consistent with $J^P = 2^+$. 

**Previous data on $\bar{K}K$ states**

The past years have seen a wealth of spectroscopic information provided by studies both of $\bar{K}^0K^0$ and $K^+K^-$ final states produced from various initial states. In this section we summarize experimental results that have been obtained in $\bar{K}K$ and related channels above $2 \text{ GeV}$ invariant mass. In the context of the JETSET experiment, the channel $pp \to K_SK_S$ is of prime interest. One reason for this is a narrow resonance originally called $\zeta(2230)$ and now tabulated in ref. [3] as $X(2220)$ because of its yet unconfirmed identity. The $\zeta(2230)$ was first seen by the MARK III experiment [50] in the radiative decays $J/\psi \to \gamma KK$, where both the $K^+K^-$ and $K_SK_S$ modes were
looked at (see figure 10a). The resonance parameters extracted from fits to the invariant-mass spectra are, averaged over the two modes, $M = (2231 \pm 13)$ MeV and $\Gamma = (22 \pm 23)$ MeV. The significance of the signal in the $K^-K^-$ and $K_SK_S$ channels was 4.5 and 3.6 standard deviations, respectively, and the product branching fractions $\text{BR}(J/\psi \rightarrow \gamma \zeta) \cdot \text{BR}(\zeta \rightarrow KK)$ were $(4.2 \pm 1.7) \times 10^{-5}$ and $(3.1 \pm 1.6) \times 10^{-5}$ for the two modes. The ratio of these fractions, $1.3 \pm 0.9$, is consistent with the value 2 expected for an isoscalar state. The quantum numbers of $\zeta(2230)$ must lie in the series $J^{PC} = (\text{even})^{++}$ due to its observation in $K_SK_S$. A spin-parity analysis yielded $J \geq 2$ as a lower limit [43]. No $\zeta(2230)$ signal was seen by MARK III in other two-meson decay modes. However, the great interest in this narrow state stems from the possibility that it may be a non-(qq) object. The DM2 experiment [51], by investigating the same production and decay channels as MARK III, did not find evidence for the $\zeta(2230)$ resonance (see figure 10b). Based on the parameters extracted by MARK III, the upper limits for the product branching fractions as determined by DM2 were $2.3 \times 10^{-5}$ for $K^+K^-$ and $1.6 \times 10^{-5}$ for $K_SK_S$ (corresponding to 95% C.L.).

Three things are interesting to note here, which appear to make the observations by the two experiments not inconsistent. Firstly, the MARK III values and the DM2 upper limits for the product branching fractions are consistent within one standard deviation. Secondly, a spike is visible in the $K_SK_S$ mass spectrum of DM2, which is basically one bin below the $\zeta(2230)$ mass value from MARK III. Thirdly, the $K_SK_S$ spectra obtained by the two experiments look very much alike over the entire mass region (see figure 10b and d), and the channel contains very little background due to its restriction to $J^{PC} = (\text{even})^{++}$. In particular, both $K_SK_S$ spectra exhibit an excess of events between 2 and 2.4 GeV, which is not explained by any known source of background. A fit
performed by DM2 using a Breit–Wigner curve in this region revealed the parameters $M = (2197 \pm 17)$ MeV and $\Gamma = (201 \pm 51)$ MeV, the product branching fraction being as large as $1.5 \times 10^{-4}$. Coherent fits by MARK III to $\xi(2230)$ and the broader 2.2 GeV structure were also reported [52]. The resonance parameters extracted for the latter, $M = (2184 \pm 64)$ MeV and $\Gamma = (413 \pm 211)$ MeV, are consistent with the DM2 data.

An earlier observation in the $K^+K^-$ channel of a structure near 2.2 GeV with a width of the order of 200 MeV stems from a measurement [53] of $\pi^-p \to K^+K^-n$ at 10 GeV/c using the
OMEGA spectrometer at CERN - PS. The complementary reaction \( \pi^- p \rightarrow K_S K_S n \) was measured in a 22 GeV/c beam at BNL - AGS, but no structure was observed in \( K_S K_S \) above 2 GeV [54]. This latter null result has been contrasted by studies of the same reaction, \( \pi^- p \rightarrow K_S K_S n \), measured at 40 GeV/c with the MSS facility at Serpukhov [55]. A little structure could be seen in the \( K_S K_S \) mass spectrum near 2.2 GeV. Based on an amplitude analysis, the authors identified this to be a D-wave resonance having \( J^{PC} = 2^{++} \) with parameters \( M = (2230 \pm 20) \) MeV and \( \Gamma = (60 \pm 30) \) MeV, and, moreover, they identified it with the \( \xi(2230) \) resonance of MARK III.

Using the LASS spectrometer at SLAC, the reactions \( K^- p \rightarrow K_S K_L \Lambda \) and \( K^- p \rightarrow K^+ K^- \Lambda \) were studied at 11 GeV/c incident momentum, the main motivation being to investigate the spectrum of \((s\bar{s})\) strangeonium states. The final data samples from these two reactions contained 441 and 12294 events, respectively. The analysis of the \( K_S K_S \) angular distribution [56] in terms of spherical harmonic moments in the t-channel helicity frame indicated the presence of a structure near 2.2 GeV with \( J \geq 2 \), so that \( J^{PC} = 2^{++} \) or \( 4^{++} \) became most likely (see figure 11a). For the \( K^+ K^- \) final state a similar analysis was performed [57], more detailed in terms of helicity amplitudes, which confirmed this structure (see figure 11b). It appeared to be most pronounced in the \( L = 4 \) wave and, even more so, when plotting the sum of interference terms between \( L = 4 \) and \( L \leq 3 \). The peak strikingly visible in this latter plot is, however, not easily to be traced back to the invariant-mass spectrum from which it essentially originates. A resonance fit to this G-wave amplitude yielded the parameters \( M = (2209 \pm 16) \) MeV and \( \Gamma = (60 \pm 82) \) MeV. For this state the \( 4^{++} \) assignment was the most likely one. The conclusion was that it be mostly of \((s\bar{s})\) nature and a member of the \( ^3F \) ground-state nonet. Furthermore, it seemed possible that the state observed here and the \( \xi(2230) \) state seen in \( J/\psi \rightarrow \gamma KK \) are one and the same. Both \( J^{PC} = 2^{++} \) or \( 4^{++} \) would be possible in such a case, since from the Constituent Quark Model one expects both \( ^3F \) \((s\bar{s})\) states in this mass region.

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**Figure 11:** Results [57] from \( K^- p \rightarrow KK \Lambda \). a) Acceptance-corrected mass spectrum for the \( K_S K_S \) mode and comparison with \( J/\psi \rightarrow K_S K_S \) data from ref. [50]. b) Mass dependence of interference terms between particular partial waves in the \( K^+ K^- \) mode.
It was also attempted to detect the direct formation of $\xi(2230)$ in $p\bar{p}$ interactions. The reaction $p\bar{p}\to K^+K^-$ was studied at BNL-AGS [58] and by experiment PS170 at LEAR [59]. Evaluating the ratio of cross-sections for $(K^+K^-)$ vs $(\pi^+\pi^-)$, no evidence for $\xi(2230)$ formation was found. Upper limits for the product branching fraction $\text{BR}(p\bar{p}\to\xi)\cdot\text{BR}(\xi\to K^+K^-)$ were typically around $2\times10^{-4}$, when $\Gamma \approx 30$ MeV and $J = 2$ were assumed for $\xi(2230)$. The reaction $p\bar{p}\to K_SK_S$, investigated by experiment PS185 at LEAR, contains a non-resonant background by a smaller order of magnitude compared with $K^+K^-$, hence this channel is expected to be more sensitive to a $K\bar{K}$ resonance. Still, no evidence for $\xi(2230)$ formation has been found in the excitation function or the angular distributions [60]. Assuming, for instance, $\Gamma \approx 30$ MeV and $J = 2$ for the state, an upper limit $\text{BR}(p\bar{p}\to\xi)\cdot\text{BR}(\xi\to K_SK_S) \approx 2\times10^{-5}$ was calculated from the data.

Previous data on $\eta\eta'$ and $\pi\pi$ states

In addition to $K\bar{K}$ states discussed in the previous section, channels containing other pairs of pseudoscalar mesons, such as $\eta\eta'$ or $\pi\pi$, can provide information that allows the flavour-dependent decay of intermediate states to be probed. The production of neutral hadrons in $\pi^-p\to X^0n$ and their subsequent decays into multi-photon final states was studied by joint CERN-HEP experiments using the GAMS electromagnetic calorimeters. Data at 38 GeV/c beam momentum were taken at Serpukhov, those with a 100 GeV/c beam at CERN-SPS. A structure centered at $(2220 \pm 10)$ MeV decaying into $\eta\eta'$, seen as a sub-sample of $4\gamma$ events, was observed in both data sets [61]. The statistics being very low, the width of this state appeared to be comparable to the instrumental resolution of about 100 MeV at this energy. From anisotropic angular distributions the lower limit $J\geq 2$ was concluded. In view of the strange-quark content of $\eta$ and $\eta'$ it is tempting to identify this structure with the state $\xi(2230)$ seen in $J/\psi\to \gamma K\bar{K}$ and/or with the 2.2 GeV structure seen in $K^-p\to KKA$.

From an early experiment using a missing-mass spectrometer in order to study the inclusive reaction $\pi^-p\to p+X^0$, the observation of three resonances originally called $S$, $T$ and $U$ was reported in the mass region between 1.9 and 2.4 GeV [62]. Also in $p\bar{p}$ interactions enhancements were seen in the energy dependence of the total cross-section, as well as in that of the elastic, the inelastic, and the annihilation cross-sections. One experiment, by investigating these structures in high-statistics studies, extracted the following resonance parameters for the $T$- and $U$-meson regions from the data [63]: $M_T = (2193 \pm 1)$ MeV with $\Gamma_T = (98 \pm 7)$ MeV, and $M_U = (2359 \pm 1)$ MeV with $\Gamma_U = (165 \pm 13)$ MeV. Another experiment studied specifically the annihilation channels $p\bar{p}\to\pi^+\pi^0$ and $p\bar{p}\to\pi^0\eta$ in these energy regions [64]. The latter process did not exhibit any energy-dependent structure in the differential cross-section. The $\pi^0\pi^0$ channel, however, was analyzed in terms of partial-wave amplitudes. Here, the results suggested the presence of a $2^{++}$ resonance with mass $M = 2.15$ GeV and width $\Gamma = 0.25$ GeV. From a comparison of $\pi^0\pi^0$ and $\pi^+\pi^-$, the authors interpreted this resonance as the isospin-0 contribution to the $T$-meson region. Data obtained in measurements of $\pi^-p\to\pi^+\pi^0\pi^0p$ were analyzed in terms of $\pi^+\pi^-\to\pi^0\pi^0$ scattering amplitudes. This again gave some evidence for a resonance in the energy region just above 2 GeV [65], the parameters extracted from the fits being $M = (2015 \pm 28)$ MeV and $\Gamma = (186 \pm 81)$ MeV.

A high-mass structure decaying into $\pi^+\pi^-$ was seen by MARK III in studies of $J/\psi\to \gamma \pi^+\pi^-$ (see figure 12a). The parameters of this resonance with yet ambiguous interpretation [66] were determined as $M = (2086 \pm 15)$ MeV and $\Gamma = (210 \pm 63)$ MeV. However, the higher-statistics data from MARK III reported in ref. [43] led to the values $M = (2089 \pm 18)$ MeV and $\Gamma = (127 \pm 106)$ MeV. The DM2 measurements of $J/\psi\to \gamma \pi^+\pi^-$ also revealed a relatively broad structure in the $\pi^+\pi^-$ invariant-mass spectrum [67]. Its resonance parameters were somewhat dependent on the number of Breit-Wigner curves introduced to fit the entire mass spectrum (see figure 12b). The fits gave average values $M = (2024 \pm 27)$ MeV and $\Gamma = (290 \pm 50)$ MeV. The authors suggested to identify this state with the $4^{++}$ candidate tabulated as $f_{4}(2500)$ in ref. [3].
Figure 12: Results from $J/\psi \rightarrow \gamma \pi^+\pi^-$ of the MARK III and DM2 experiments. Shown are the $\pi^+\pi^-$ invariant mass spectra, a) with a four-resonance fit obtained by the MARK III experiment [66], and b) with a five-resonance fit obtained by the DM2 experiment [67].

Outlook: Enriched physics with an improved machine

In the preceding chapters we have demonstrated the richness of the physics to be pursued with the JETSET experiment, in particular by measurements of $p\bar{p}$ annihilations into $\phi\phi$, $\omega\omega$, $\omega\omega$ and $\pi^0\phi\phi$, and into $K\bar{K}$, $\bar{K}K^*$ and $K^*\bar{K}^*$. Although these studies take full advantage of the high luminosity and the good final-state mass resolution obtainable in a jet-target experiment, there are some limitations due to the machine parameters to be encountered. The main deficiencies of the LEAR accelerator in its actual configuration are the large size of the vacuum chamber and the upper limit of the beam momentum. Improvements in these respects, however, may be impossible without severe negative consequences in other areas, such as the acceptance of the machine or the availability of low-momentum beams. The advantage of beam momenta higher than the present LEAR limit, say 4 GeV/c, is obvious. An increase of the invariant-mass range up to $\sqrt{s} \approx 3$ GeV or higher would open the window to a largely unexplored regime in the spectroscopy of conventional and non-conventional hadrons. Formation studies such as $pp \rightarrow \phi\phi$ and, even more so, production experiments like $pp \rightarrow \pi^0\phi\phi$ would greatly profit from such an 'energy upgrade'.

There are several strong arguments in favour of a small-sized and correspondingly thin-walled beam pipe. Firstly, the innermost tracking device ('vertex detector') can be positioned close to the interaction region, which leads to a better precision in the reconstruction of production vertices. Secondly, triggers for 'long-lived' neutral particles such as $K_S$ or $\Lambda$ can be established more efficiently. Thirdly, the detection of charged particle tracks can be extended down to small angles. This last point becomes more and more important as one approaches the threshold of the reaction under study, since in that case all particles are emitted within a narrow forward cone centered around the beam axis. Moreover, in many cases the early decays of low-momentum particles make both triggering and tracking difficult.
In the following two sections we briefly discuss two experiments, both of which would take full advantage of a small-sized and thin-walled vacuum chamber. Both cases would need very high luminosities as available only in internal jet-target experiments. For instrumental reasons, however, they are both beyond the scope of the phase-I physics programme of JETSET. They are being discussed here as interesting possibilities — among others — for later stages.

**Threshold studies and KK molecules**

The dynamics of a reaction close to its threshold is simplified in that only a few partial waves are expected to contribute. But this region is always a particularly interesting one, because the excitation function may reveal structures near threshold due to quasi-bound states, or the excitation function of another reaction may exhibit a structure due to the opening of the first channel ("cusp"). At and around the K⁺K⁻K⁺K⁻ threshold we encounter seven closely spaced thresholds (see table 1), which call for a detailed investigation.

<table>
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<td>559.09</td>
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<tr>
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</tr>
<tr>
<td>K⁺K⁻a₀</td>
<td>1970.29</td>
<td>630.53</td>
</tr>
<tr>
<td>K⁺K⁺K⁺K⁻</td>
<td>1974.58</td>
<td>646.56</td>
</tr>
<tr>
<td>K⁺K⁺φ</td>
<td>2006.70</td>
<td>760.25</td>
</tr>
<tr>
<td>φφ</td>
<td>2038.82</td>
<td>866.03</td>
</tr>
</tbody>
</table>

The f₀ and a₀ particles have masses only a few MeV below the K⁺K⁻ invariant mass. As these 0⁺⁺ states are almost degenerate and seem to differ only by isospin, they have been subject to many speculations as to their origin. The theoretical investigation of (qqqq) spectra showed that the only bound states of this kind are those having a KK-like structure [17]. It has been suggested that the f₀ and a₀ are such KK 'molecules' or 'dimesons', one argument being that the measured and calculated widths agree rather well but a (q̅q̅) state would be much broader [68]. Both f₀ and a₀ seem to be strongly coupled to the KK channels. If they are of non-(qq) nature, one may eventually expect enhanced branching fractions for φ→γf₀ or φ→γ a₀. A continuous scan in √s for all channels and across all thresholds listed in table 1 would certainly help to unravel many mysteries and open questions related to multi-kaon final states — even though it may be difficult for any experiment to differentiate between the four-quark and the KK-molecule interpretation of the f₀ and a₀ states.

**High-statistics ¯p→ΛΛ for a CP violation search**

Up to here all discussion in this report has focussed on strong interactions and the underlying theory of QCD. But also aspects of electroweak interactions can be addressed, which constitute the other building block of the Standard Model. A fundamental question in this context is the physical origin of CP non-conservation, since no system, other than the K⁰–K̅⁰ system, has exhibited CP violation so far. An experimental programme that can be devoted to this [69–71] is the
The non-leptonic weak decay $\Lambda \rightarrow p\pi^-$ ($\bar{\Lambda} \rightarrow \bar{p}\pi^+$) is parity-violating. For a sample of $\Lambda$ hyperons with polarization $P$, the angular distribution of the decay protons in the $\Lambda$ rest frame is given by $W(\theta_P) = (4\pi)^{-1} [1 + (\alpha P) \cos \theta_P]$, where $\theta_P$ is measured between the normal to the production plane and the proton momentum vector, and $\alpha = 0.642 \pm 0.013$ is the $\Lambda \rightarrow p\pi^-$ decay asymmetry parameter. An interesting observable is $A = (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$, which would signal CP violation if measured to be non-zero. The absolute size of this signal, as predicted in the framework of the Standard Model, is small. Typical values [74, 75] are of the order of a few $10^{-4}$, and are somewhat dependent on yet poorly known quantities such as hadronic matrix elements, the $t$-quark mass, and the 'direct' CP violation parameter $|\epsilon|/|\epsilon^\prime|$. 

Experimentally the ratio $A$ is relatively easy to determine. The best result obtained so far stems from experiment PS185 at LEAR, where data taken at 1.546 GeV/c (4063 events) and 1.695 GeV/c (11427 events) were used to evaluate the ratio $A$. The statistics of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^+\pi^- \pi^-$ events combined from the two beam momenta [72] gave the average value $\langle A \rangle = (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) = -0.024 \pm 0.057$. On the basis of statistical arguments one can estimate how many events must be accumulated and analyzed in order to reach the level of sensitivity at which a CP violation effect can conceivably be expected. For a number of $N$ events, the statistical uncertainty on the ratio $A$ is $\sigma_A = (\alpha P)^{-1}\sqrt{[3/(2N)]]}$. Assuming $|P| = 0.3$ as the average of the angular dependent polarization, the uncertainty $\sigma_A \approx 10^{-4}$ corresponds to $N > 4 \times 10^6$ events. It is interesting that the result from PS185 as quoted above is consistent with this estimate and an average polarization $|P| = 0.27$.

The question arises how such a huge number of events can be accumulated within a reasonable running time [69 - 71].

- The optimum beam momentum in a jet-target experiment on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is 1.65 GeV/c, which is just below the $\bar{\Lambda}\Sigma^0$ threshold. The production cross-section is $\sigma(\bar{\Lambda}\Lambda) \approx 80 \mu$b.
- The 'overall efficiency' of the experiment is about 10%. This number is a little lower than what has been learned from PS185 in 'real life'. It includes the double-branching fraction $BR(\Lambda \rightarrow p\pi^-)BR(\bar{\Lambda} \rightarrow \bar{p}\pi^+) = 0.41$, the on-line trigger efficiency of 0.6, the data-acquisition live-time of 0.7, and the off-line reconstruction efficiency for four-track ($2\pi^0$) events of 0.6.
- With at least $10^{11}$ antiprotons stored in the machine, a revolution frequency of 4 MHz, and a jet-target density of $10^{12}$ atoms/cm$^2$, the peak luminosity is $4 \times 10^{31}$ cm$^{-2}$sec$^{-1}$.

From the above numbers one calculates an acquisition rate for 'good' events of 320 sec$^{-1}$ at peak luminosity. The accumulation of $4 \times 10^8$ events would thus require an effective data-taking time of $1.25 \times 10^7$ sec. This is not far from the 'canonical' value of $10^7$ sec, which is often assumed as the equivalent to being 'on-beam' for one full year. Preliminary studies indicate that the detector elements suited for the triggering and for the recording of charged particle tracks do not require much R&D effort, the main difficulties of the experiment being in the areas of fast data acquisition and pre-processing. The availability of computing power, however, continues to grow rapidly.
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