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Facilities for formation and production of light mesons are considered and the advantages of meson spectroscopy using $\bar{p}$ annihilations at LEAR are discussed. Atomic and nuclear physics effects in protonium, which provide new tools for meson spectroscopy in $p\bar{p}$ annihilations at rest, are illustrated. LEAR results in meson spectroscopy are rewiewed. The APPLE experiment has made good statistics measurements of the antiproton electromagnetic form factor in the timelike region, which are sensitive, at threshold, to the atomic and nuclear physics of protonium, and to the presence of $N\bar{N}$ resonances and of vector mesons radial excitations. The exploitation of the new tools in $p\bar{p}$ annihilations at rest has led to the discovery of the 2^{++} resonance AX(1565) that could be a $q\bar{q}$ radial excitation or an exotic structure. It has also permitted a new determination of the 0^{-+} quantum numbers of the E/ι resonance, which is a glueball candidate. The AX has been discovered by ASTERIX and has been observed recently by the new LEAR experiments Crystal Barrel and OBELIX. ASTERIX has also observed a $2\pi^+2\pi^-$ structure at 1500 MeV in five-prong $\bar{p}n$ annihilations. That structure was formerly seen in bubble chamber experiments for which a recent spin-parity data reanalysis finds $J^PI^G = 0^+0^+$. The new spectroscopy experiments at LEAR (Crystal Barrel, OBELIX and JETSET) are described. Prospects of further major developments are discussed.

1. INTRODUCTION

The spectroscopy of light mesons and the search for exotics, and eventually their spectroscopy, have been among the main physics motivations for the Low Energy Antiproton Ring (LEAR)[1]. In these fields, experiments of the first generation have made original contributions. They are a top priority in the current LEAR research programme[2], where the largest investments are being made on the scale of the facility.

In Section 2 of this review we discuss the specific and distinctive advantages of LEAR in the study of light mesons and exotics in the context of the numerous facilities where meson spectroscopy work is being actively pursued.

In Section 3 first we show the results of the studies of the atomic and nuclear physics of protonium, which offer new possibilities of investigating meson spectroscopy. Subsequently we consider, in turn, results in the sectors of vector mesons, scalars, tensors, and pseudoscalars, where resonances have been observed. Further

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work is required to establish their nature, that is to say whether they are radial excitations, four-quark states, baryonium, glueball or hybrid.

Section 4 introduces the new spectroscopy experiments at LEAR. Their installation started after the beginning of the construction of the Antiproton Collector (AC); they are at different stages of completion, but some have already produced interesting results.

In Section 5 prospects of the development of the study of the spectroscopy of exotics at LEAR and the context of long-term continuation of that work are discussed. Conclusions are given in Section 6.

In the course of this review, reference is often made to contributions in the Proceedings of the LEAR Workshops[3–6], of the Erice Low-Energy Antiproton School dedicated to meson spectroscopy[7], and of recent International Hadron Conferences[8,9].

2. FACILITIES FOR MESON SPECTROSCOPY AND THE ROLE OF LEAR

2.1. *Experimental approaches to light meson spectroscopy*

Recent experiments dedicated to the study of the spectroscopy of light mesons and to the search for exotic mesons use different formation and production mechanisms including:

i) *For production*

a) decays of J/ψ formed in e^+e^- colliding beams (XB, MARK II, MARK III at SPEAR, DM2 at DCI, BES at the BEPC Beijing Charm Factory);

b) $\gamma\gamma$ and $\gamma\gamma^*$ interactions in e^+e^- colliding beams (PLUTO, JADE, TASSO, and CELLO at PETRA; DELCO, MARK II, and TPC $\gamma\gamma$ at PEP; XB and ARGUS at DORIS II);

c) central production in pp, πp, and Kp interactions at high energies (AFS at the ISR, OMEGA at SPS, GAMS at Serpukhov and at the SPS, MPS at BNL);

d) peripheral production in charge-exchange reactions at high energies (LASS at SLAC, MPS at BNL, BENKEY at KEK, GAMS);

e) $\bar{p}p$ annihilations at rest (ASTERIX, Crystal Barrel, OBELIX at LEAR);

f) $\bar{p}n$ annihilations of $\bar{p}$'s stopped in a gas D_2 target (ASTERIX, OBELIX).

ii) *For formation*

$\bar{p}p$ annihilations in flight of cooled stored antiprotons colliding with a H_2 gas-jet target with a scan of the $\bar{p}$ beam momentum (JETSET at LEAR).

In the near and not-too-far-distant future the following additions will occur:

i) *For production*

a) decays of ϕ formed at e^+e^- colliding beams (DAΦNE at LNF and possibly other projects);

b) $\bar{p}p$ annihilations in flight with extracted beams (Crystal Barrel, OBELIX);

c) $\bar{p}p$ annihilations in flight with a $\bar{p}$ beam stored in LEAR and a (eventually polarized) H_2 gas-jet target (JETSET);

d) $\bar{p}n$ annihilations in flight with a $\bar{p}$ extracted beam, a D_2 gas target, and measurement of the spectator proton (OBELIX);

ii) *For formation*

$\bar{n}p$ annihilations with $\bar{n}$'s produced by charge exchange of $\bar{p}$'s extracted from LEAR (OBELIX).

Most of the detectors quoted above and operating at facilities other than LEAR are illustrated in the LBL compilation by Gidal et al.[10], which gives references to original descriptions of the experiments.

2.2. *Aspects that make LEAR competitive in meson spectroscopy*

The various production and formation approaches feature different advantages and limitations. LEAR is competitive in light meson spectroscopy because it combines the following advantages:

α) For $p\bar{p}$ *production experiments with* $\bar{p}$*'s at rest in a gaseous* H_2 *target*

a) extremely high annihilation rates (10^4–10^6 s^{-1} in operation, 10^7 s^{-1} feasible),

b) c.m. of the annihilating system at rest in the laboratory,

c) possibility of using an extremely thin target container,

d) possibility of selecting sets of initial states of annihilation that have different distributions of orbital angular momentum (S- and P-wave)

e) possibility of searching for new structures and probably also for broad states by differential measurements to be performed by varying the S- and P-wave distributions of the initial states.

β) For $\bar{p}n$ *production experiments with* $\bar{p}$*'s at rest and a gaseous* D_2 *target*

a) extremely high annihilation rates (10^4–10^5 s^{-1} in operation, 10^7 s^{-1} feasible);

b) possibility of determining the energy and momentum of the annihilating system by measurement of the recoil proton down to very low momenta (> 50 MeV);

c) possibility of selecting sets of initial states of the $\bar{p}d$ atom that have different distributions of the S- and P-wave orbital angular momentum between the $\bar{p}$ and the deuteron nucleus;

d) possibility of comparing I = 1 $\bar{p}n$ annihilations with I = 0 and I = 1 $\bar{p}p$ annihilations to search for new (eventually also broad) structures by differential measurements.

γ) For $\bar{p}n$ *production experiments in flight with a gaseous* D_2 *target and an extracted* $\bar{p}$ *beam*

a) fairly high annihilation rates (up to 10^4 s^{-1});

b) possibility of determining the energy and momentum of the annihilating system by measurement of the recoil proton down to very low momenta;

c) possibility of comparing I = 1 $\bar{p}n$ annihilations with I = 0 and I = 1 $\bar{p}p$ annihilations to search for new (eventually also broad) structures by differential measurements.

δ) for $\bar{p}p$ *formation experiments with a* H_2 *target and an extracted* $\bar{p}$ *beam*

a) high interaction rates (up to 10^4 s^{-1});

b) excellent energy resolution (well suited to discovering new narrow states and to measuring their widths).

η) for $\bar{p}p$ *formation experiments with a gas-jet target and a cooled stored* $\bar{p}$ *beam*

a) extremely high interaction rates (up to 10^7 s^{-1});

b) excellent energy resolution ($\Delta E < 1$ MeV);

c) well-defined and small interaction volume.

2.3. *Comments*

In what concerns the event rate we can make the following remarks. Low-energy $\bar{p}$ beams extracted continuously from LEAR with intensities adjustable from some 10^4 to 10^6 $\bar{p}$'s per second are a current routine operation. Up to 10^7 $\bar{p}$'s per second could eventually become available by exploiting the full potentiality of the CERN $\bar{p}$ source, since the CERN antiproton complex can produce more than 10^{12} $\bar{p}$'s per day, which can be transferred to LEAR with high efficiency in bunches of some 10^{10} $\bar{p}$'s per transfer. With a H_2 target and an extracted beam, rates of up to 10^7 annihilations per second at rest and of some 10^4

annihilations per second in flight are therefore achievable. With a H_2 gas-jet target intersecting the beam stored in LEAR, rates of up to 10^7 interactions per second in flight are attainable[11]. At rest all p̄'s annihilate and, apart from the extremely rare annihilations into lepton pairs, each p̄ annihilation produces light mesons. In this mode, LEAR therefore provides the brightest source in the world for studying light $q\bar{q}$ and exotic mesons. For comparison, consider, for instance, that i) the DM2 experiment exploited in total less than 10^7 e^+e^- interactions with the DCI machine tuned at the J/ψ resonance, ii) the MARK III experiment at SPEAR exploited a comparable number of e^+e^- interactions, iii) less than 4×10^6 J/ψ's have been formed so far at the Beijing e^+e^- Storage Ring (and the peak design luminosity of 1.7×10^{31} cm^{-2} s^{-1} would provide some tens of interactions per second tuning the machine on the J/ψ resonance), and iv) the DAΦNE Storage Ring will provide at the initial luminosity of 10^{32} cm^{-2} s^{-1} some hundreds of interactions per second with the machine tuned on the ϕ resonance.

Concerning points (α), (β) and (γ), the reader is referred to previous papers[12–16] regarding p̄p physics at rest and p̄d/p̄p physics at low momenta, where we have discussed the experimental advantages and suggested new physics possibilities related to the combined use of:

i) a low-momentum extracted p̄ beam,

ii) a H_2 or D_2 gas target surrounded by a projection chamber and separated from it by a very thin window,

iii) an XDC/SPC large-acceptance low-threshold X-ray detector[17] and vertex detector surrounding the gas target and capable of detecting and identifying the L radiative transitions of the p̄p and p̄d atom, and

iv) an SPC/XDC large-acceptance low-threshold vertex detector[18] capable of identifying spectator protons in p̄n annihilations in a D_2 target, and measuring their momentum or range.

Some of the advantages and ideas behind part of the possibilities mentioned above[19–25] have been the source of a part of the physics motivations for LEAR[1,3,20,21]. They have been the basis of the main physics motivations[26–28] for the ASTERIX[29] and OBELIX[30] proposals.

ASTERIX has demonstrated experimentally[31–36] the existence of what we have called Angular Momentum Polarization (AMP) in p̄p at rest[14], namely that the branching ratios of exclusive annihilation channels and of intermediate resonant states depend on the ratio between S- and P-waves in the distribution of atomic states from which annihilations occur, and that, when using a gas target, it is possible to change the distribution of initial states by selecting the annihilation events with a soft X-ray (1-4 keV) in coincidence. This point is discussed in Section 3.1.

Differential measurements in p̄p at rest, by comparing data with different AMPs, are a new tool in meson spectroscopy, proposed and advocated by the speaker for a long time. I fear that, if low-mass states of glueballs and hybrids are too large, differential measurements are probably the only way to assess their existence. Differential measurements performed in the ASTERIX experiment have permitted the discovery of a new meson, the AX(1565)[37], and offer a new way to constrain the J^{PC} quantum numbers of the E/ι meson[38], which was discovered in pp̄ at rest in liquid hydrogen 27 years ago[39,40] and that is a serious glueball candidate. These items are discussed in Sections 3.4 and 3.5.

The p̄ form factor in the timelike region has been measured at LEAR by the APPLE Collaboration[41,42] in the reaction $p\bar{p} \to e^+e^-$. At threshold the form factor is sensitive to AMP effects and to the existence of vector mesons coupled to $p\bar{p}$ and decaying into e^+e^-. This point is discussed in Section 3.2.

The following comments concern items (δ) and (η). Production experiments can give access to states with exotic quantum numbers, which would be an uncontroversial signature of a glueball or of a hybrid that cannot be mimicked by a $q\bar{q}$ state. Formation experiments with $p\bar{p}$ cannot form states with exotic quantum numbers, but, unlike experiments with e^+e^- colliding beams (where only 1^{--} states are formed in e^+e^- annihilations), $0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}$ and others states with higher orbital excitations can be directly formed. This point and its relevance for charmonium spectroscopy was stressed[43] at the time of the launching of the $\bar{p}$ project[44] and of the LEAR proposal[20]. It was one of the main motivations for the proposal of LEAR, in view of the high resolution attainable in formation experiments with cooled antiproton beams. It was the reason for extending up to 2 GeV/c the maximum storage momentum of the beams circulating inside the ring and was at the source of the successful jet-target experiments R704 at the ISR and E760 at the Fermilab accumulator[45]. A jet-target option was suggested[46,47] and became an integral in part of the design of LEAR[48,49] for formation experiments in order to combine maximum luminosity and energy resolution. The JETSET experiment[50] concretizes at LEAR that option in the energy region with beam momenta between 600 and 2000 MeV/c and is introduced in Section 4.

Pre-ACOL LEAR experiments designed to search for new states in formation at intermediate and low energies with extracted beams have not found any. However, the region very near to threshold, below 300 MeV/c, has not been explored; the energy scans performed with good mass resolution have been concentrated only in two regions, at intermediate momenta around 600 and 1200 MeV/c; there the former claims for the S meson and the $\xi(2200)$ were not confirmed by experiments at LEAR, which were able to look at two-body final states such as $p\bar{p}$, $n\bar{n}$, $\pi\pi$, and $K\bar{K}$. These results are not covered here. The momenta explored during 1986 are listed in Ref. 51.

In the very low momentum region, where jet target operation may not be practical, the Crystal Barrel and OBELIX will have the possibility of doing a good job with extracted beams tuned at lower and lower momenta. Below 100 MeV/c OBELIX will have the possibility of doing energy scans, exploiting its 60 cm long gas target and improvements over the schemes first suggested for this purpose[52,53].

In Section 5 we discuss extensions of the LEAR programme of meson spectroscopy with $\bar{p}$'s in flight. One extension requires a polarized $\bar{p}$ beam and a polarized H_2 jet target for production and formation experiments, which could do differential measurements by varying the total spin to also identify broad structures[14,15]. The second extension is SuperLEAR, which has been discussed on several occasions[54] and is not covered here. These extensions could well coexist with the use of LEAR: i) to complete the physics programme of present experiments at the extracted beams with upgraded detectors, and ii) for testing LHC detectors (with $\bar{p}$'s stopped in H_2 gas filling their beam pipe) under quasi-realistic conditions in terms of event rates and longitudinal vertex spread[15].

3. PHYSICS RESULTS AT LEAR

3.1. $p\bar{p}$ annihilation at rest: S- and P-wave branching ratios and Angular Momentum Polarization

Table 1 summarizes values of the absolute branching ratios of $p\bar{p}$ annihilations at rest into some exclusive final states measured under the following three different experimental conditions:

i) liquid H_2 target[55],

ii) gaseous H_2 target at normal conditions of temperature and pressure (NTP),

iii) gaseous H_2 target at NTP and the requirement that an X-ray in the energy window 1–4 keV was detected in coincidence with the mesons observed in the final state.

TABLE 1: Branching ratios for pp annihilations at rest in liquid target (BR_L), in NTP gas target(BR_G), and NTP gas target with 1-4 KeV X-rays in coincidence (BR_X). See Refs. 31, 32 and 55 for refs. to original data.

Branching ratios $\times 10^3$

Final state	BR_L	BR_G	BR_X
$\pi^+\pi^-$	3.33 ± 0.17	4.30 ± 0.14	4.69 ± 0.50
K^+K^-	1.01 ± 0.05	0.69 ± 0.04	0.34 ± 0.05
K_SK_L	0.76 ± 0.04	0.36 ± 0.06	0.073 ± 0.056
K_SK_S	0.004 ± 0.004	0.03 ± 0.01	0.037 ± 0.014

These data show that the branching ratios of exclusive final states of $p\bar{p}$ annihilations at rest do not have absolute values, but depend on the target density and on the requirement of the presence of X-rays in coincidence (emitted via radiative transitions in the atomic cascade of protonium atoms and via internal bremsstrahlung in protonium annihilations with charged particles present in the final state). This has caused no surprise because the changes of experimental conditions indicated above reflect the variations of the distribution of S- and P-wave initial states of protonium from which annihilations take place. Actually, as suggested long ago by Day, Snow and Sucher[56], the high density of liquid H_2 targets favours annihilations in S-wave from levels of protonium with high principal quantum number n. These nS levels are populated from levels with the same n and higher angular momentum quantum number L, via Stark mixing, during collisions of the $p\bar{p}$ atom with nearby H_2 molecules. In a NTP H_2-gas target the frequency of collisions is about three orders of magnitude lower than in a liquid target. Therefore the combined action of Stark mixing and S-wave annihilation in high-n levels is much reduced. Low-n P-wave levels of protonium are then populated by the atomic cascade and a substantial amount of P-wave annihilations occur, since the P-wave annihilation rates are competitive with the atomic transition rates in low-n states. Finally, annihilations in coincidence with 1–4 keV X-rays occur dominantly in P-wave from one of the four sublevels of the 2P state for two main reasons: i) in the 1–4 keV energy window L X-ray transitions from nD levels to 2P sublevels of protonium are more intense than the X-ray emission by internal bremsstrahlung, and ii) the annihilation width of the 2P level is 100 times greater than its radiative width[57].

The scenario of pp annihilations at rest in the three experimental conditions mentioned above is qualitatively as follows: dominant S-wave annihilation in liquid-H_2 targets; comparable fractions of S- and P-wave annihilations in NTP gaseous H_2 targets; dominant P-wave annihilation in gaseous targets and 1–4 keV X-rays in coincidence.

Establishing the exact ratio between S- and P-wave annihilations in a given experimental condition is not exciting when the attention is focused on elementary particle physics; however it is a necessary task in order to determine the distribution of initial states, which, in turn, is an important issue in connection with particle physics topics, such as the $\bar{p}$ form factor in the time-like region, CP violation experiments using $\bar{p}p$ annihilations at rest as sources of tagged kaons, and glueball searches. Indeed, speaking in terms of ratios between S- and P-wave initial states is already a simplification, since $\bar{p}p$ annihilations at rest take place from the singlet 0^{-+} and the triplet 1^{--} nS levels and from the 1^{+-} singlet nP and the $0^{++}, 1^{++}, 2^{++}$ triplet nP levels that are populated by the atomic cascade. The fraction of S- and P-wave annihilations in liquid and in a NTP gas H_2 target has been derived by the ASTERIX Collaboration via the simplification just mentioned, by using the data listed in Table 1 plus data on the $\pi^0\pi^0$ channel in a liquid target[58], the constraints that the branching ratio for the $K_S K_L$ channel is zero in pure P-wave and that the branching ratio for the $K_S K_S$ channel is zero in pure S-wave[redacted] The derivation of the ratios between S- and P-wave annihilations has been made under tacit assumptions discussed in Ref. 16. A generalization of that discussion is being worked out[59]. Figure 1 displays the 1σ band of the measured absolute branching ratio plotted against the fraction of P-wave annihilation over total S- plus P-wave annihilation for the measurements under one of the three sets of experimental conditions explored by i) bubble chambers and counter experiments, and ii) and iii) by ASTERIX. The value of the abscissa for the $\pi^+\pi^-$ point in liquid H_2 is controlled by the relative values of the $\pi^0\pi^0$ and $\pi^+\pi^-$ branching ratios, which have both been measured in liquid H_2, although by different experiments. The value for the $\pi^+\pi^-$ branching ratio at 100% P-wave annihilation was obtained from the two values measured i) in gas and ii) in gas with X-rays in coincidence, and from the measurement of the relative yields of protonium L X-rays and internal bremsstrahlung.

Fig. 1. Branching ratios (BR) of $\bar{p}p$ annihilations at rest into two body channels measured in liquid H_2 (BR_L), in NTP H_2 gas (BR_G), and with 1-4 keV X-rays in coincidence in NTP H_2 gas (BR_X)

The absolute branching ratio for a given exclusive annihilation channel measured in one of the three above-defined experimental conditions is the sum of the absolute branching ratio for S-wave and that for P-wave annihilation in that experimental condition. A straight line connects the two points giving the branching ratios for pure S- and pure P-wave annihilation, and it must intercept the absolute branching ratio values measured in the three different physical conditions (provided of course that the tacit assumptions mentioned in Ref. 16 are justified to first order). The ratio of S- and P-wave annihilations in gas can then be extracted from the relation

$$\frac{BR_{liquid} - BR_{gas}}{BR_{gas} - BR_{gas+X-ray}} = \frac{\%S_{liquid} - \%S_{gas}}{\%S_{gas} - \%S_{gas+X-ray}}$$

where %S represents the percentages of S-wave annihilations.

The quantitative information that emerges from the data and this type of analysis is relevant in two aspects. First, one learns that the fraction of annihilations in S-wave is about 10% in liquid H_2; it is about 50% in H_2 gas; and it is from 80 to

90% in gas with X-rays in coincidence (this last value depends on the type of final state because each final state is accompanied by its yield of internal bremsstrahlung). Secondly, one gets the pure S-wave and pure P-wave absolute branching ratios values for the exclusive channels examined.

Notice that some branching ratios increase with an increasing percentage of P-wave annihilations, while others decrease. This feature has been observed also in other, more complex, exclusive annihilation channels with three and more mesons in the final state and, for a given exclusive final state, also for the branching ratio for the production of resonances in the intermediate state. A recent compilation gives the branching ratios of annihilations at rest in various experimental conditions[60].

In experiments with a NTP gas H_2 target, the relative contribution of annihilation channels that occur only from P-wave initial states is enhanced by a factor of between 1.6 and 1.8, and the relative contribution of annihilation channels that occur only from S-wave initial states is depressed by a factor of 2.5–5 when 1–4 keV X-rays are required in coincidence.

This feature is at the basis of the idea of differential measurements in light meson spectroscopy with $p\bar{p}$ at rest that has been discussed in detail in Refs. 14 and 15. Given a final exclusive annihilation channel, one can pick up mesons present in the final state and proceed with the usual explorations to see if they originate from the decay of a resonance (or of another structure present in the intermediate state). The key point is that this exploration can and has to be done for the two different distributions of initial states given by data in gas without and with the requirement of 1–4 keV X-rays in coincidence. In this way two types of spectra can be obtained, where i) narrow resonances are visible in both and the variation of their production rate can be studied according to the variation of the distribution of angular momenta of the initial states, and ii) broad resonances can be identified by differential comparison of these spectra. The great advantage is that in this differential comparison nearly all experimental aspects regarding the final state factorize away: phase space, detector features, acceptances and efficiencies; trigger biases; data collection time; reconstruction and analysis software; data selection cuts. The only remaining difference is the distribution of initial states and, if a resonance in a intermediate state can be produced only or dominantly from S- or P-wave initial $p\bar{p}$ atomic states, this causes major differences in the two sets of plots with different AMPs. Examples of this comparison for mass plots, Dalitz plots, and decay angular distributions are shown in Ref. 16. Annihilation dynamics (whose simplest manifestation is in selection rules requiring C or P or I conservation) controls the branching ratios of each J^{PC} I^G initial state of protonium into the various exclusive final states with their intermediate resonant states. This topic has an intrinsic interest, since at an unknown future date it should be possible to obtain a computation of the hadronization into the various possible final states subsequent to the close encounter in a J^{PC} state of the two complex systems p and $\bar{p}$. These systems are made respectively of three quarks with accompanying gluon fields and of three antiquarks with their accompanying gluons; they are bound together by the long-range Coulomb force and survive the $p\bar{p}$ atom formation for several nanoseconds[61,62] during which atomic and molecular transitions bring them into more and more bound Coulomb states, until annihilation takes place in some n J^{PC} state. Several approaches and models, which are not covered here and originate from the attempt to connect present nuclear physics knowl-

Fig. 2. Wolinsky diagrams for $N\bar{N}$ interactions

Fig. 3. Annihilation of $q\bar{q}$ pair (a) and of $p\bar{p}$ pair (b), where up to to three pairs of contituent q and $\bar{q}$ can annihilate (b')

edge in the sector of low-energy $N\bar{N}$ interactions to NN interactions, are used in the tentative to describe $N\bar{N}$ strong interactions before real annihilation takes place and also—more recently — to try to describe annihilation on a microscopic basis. The task is formidable. Once executed completely, if should be possible to compute, for instance, for any chosen J^{PC} state of protonium, its probabilities of annihilation into all accessible final states with their intermediate resonances, just as it is possible for positronium annihilations. Wolinsky diagrams, shown in Fig. 2 for very simple final states, give a pictorial idea of the complexity of the problem.

It should be stressed that, no matter the difficulties of computing Wolinsky amplitudes, experiment has already demonstrated two essential points. The first point is that, insofar as the basic diagram of meson spectroscopy one is interested in is as shown in Fig. 3a (in which a q and a $\bar{q}$ annihilate into a gluon [#1]), $p\bar{p}$ interactions offer up to three $q\bar{q}$ annihilations per $p\bar{p}$ annihilation; this can be visualized by turning Fig. 3a and getting ~~three times~~ Fig. 3b, or—more prosaic by considering that in annihilation processes not dominated by recombination, one $q\bar{q}$ pair at least has to annihilate and/or a new $q\bar{q}$ pair has to be pulled out of the vacuum. Notice that annihilations at rest, which do not come from pure recombination, are at least those with kaons in the final state, which amount to more than 5% of the events in liquid-H_2 targets. The second point is that the $p\bar{p}$ atomic levels are extremely close on the mass scale of hadrons, quite differently from the spacing of charmonium levels. This implies that the phase space for annihilations from all the levels of protonium is practically the same, unlike for charmonium. Moreover we get 'χ' and 'J/ψ' states of protonium by using a gas-H_2 target at NTP and dominantly 'χ' states by requiring 1–4 keV X-rays in coincidence; we can thus compare the annihilations from the 'J/ψ' states and from the 'χ' states, in order to search for broad new structures, and to have clues in order to assign quantum numbers both to narrow structures (which are easy to see), and to broad ones.

#1 This gluon can in turn interact with other gluons and form glueballs, or interact with near-by $q\bar{q}$ pairs with non-zero total colour charge and form hybrids

Fig. 4. Data from the LEAR experiment APPLE (PS 170) compared to the curve for the antiproton electromagnetic form factor in the timelike region based on VDM

3.2. Vector mesons

Experiment PS170 (APPLE Collaboration[41]) has studied the proton form factor in the timelike region via the reaction $p\bar{p} \rightarrow e^+e^-$. This reaction was suggested long ago[63] and has been first explored, at threshold and near it, with modest statistics by a pre-LEAR experiment with slow antiprotons[64]. At e^+e^- colliding rings the low momentum transfer region $3.8 < -q^2 < 5.8$ GeV^2 has been explored via the inverse reaction $e^+e^- \rightarrow p\bar{p}$, but the statistics are again modest and the experiments cannot measure the point at threshold since the $\bar{p}$ stops in the beam pipe. The preliminary results of PS170 [42] are shown in **Fig. 4.** These results are not compatible with the curve based on vector dominance, whose parameters are adjusted to fit the accurate data existing in the spacelike region, and include known $1^{--}\rho$, ω, and ϕ radial excitations. Structure(s) in the 1^{--} channel strongly coupled to the $p\bar{p}$ initial state might be responsible for the behaviour of the form-factor points. The determination of the value of the electromagnetic form factor at zero momentum requires the knowledge of the total fraction of $p\bar{p}$ annihilations at rest that occur in 1^{--} states[63]. The experiment was performed with a liquid-H_2 target. The fraction of S-wave annihilations was taken from the ASTERIX analysis, and the usual assumption of a statistical distribution of singlet and triplet S-wave initial states was made[65]. One can appreciate, in this case, the major role that is played by the complex blend of atomic, nuclear, and particle physics which controls the protonium cascade, by considering that, if the e^+e^- branching ratio had been measured with a NTP gaseous H_2 target, the branching ratio of the e^+e^- signal would have been about half that measured by experiment PS170. A gas target would be convenient to explore with good resolution the form factor in the timelike domain in the region between rest and the lowest point in flight measured by PS170.

3.3. Scalar mesons

The ASTERIX experiment has observed a structure decaying into $2\pi^+2\pi^-$ in $\bar{p}n$ annihilations at rest in D_2 gas in the final state $2\pi^+3\pi^-$ with recoil protons with momentum below 200 MeV/c identified via missing mass. For spectator protons with momentum below 200 MeV/c the structure has its peak at 1500 MeV and a width of 210 MeV. For recoil protons with momentum above 200 MeV/c, the structure has its peak at 1360 MeV and a width of 260 MeV. No quantum number determination was made[66]. ASTERIX has not observed a prominent state decaying into $2\pi^+2\pi^-$ in $p\bar{p}$ annihilations at rest in the final state $2\pi^+2\pi^-\pi^0$. A prominent signal in $2\pi^+2\pi^-$ had been observed formerly in five-prong $\bar{p}n$ annihilations in liquid D_2 in the Padua–Pisa data at CERN[67] with parameters M = 1410 MeV, Γ = 90 MeV, $J^{PC} = 0^{++}$, I = 0 or 2 as well as in the Rome–Syracuse data at BNL[68] with parameters $M = 1477$ MeV, $\Gamma = 116$ MeV, $J^{PC} = 2^{++}$, $I = 0$, and prominent decay channel $\rho^0\rho^0$. A recent re-analysis[69] of the Padua–Pisa data has established the following parameters: $I^G J^P = 0^+0^+$, $M \simeq 1.40$ GeV, $\Gamma \simeq 300$ MeV, decay channels $\rho^0\rho^0$ and $\epsilon^0\epsilon^0$, 25% contribution of the $\rho^0\rho^0$ decay channel, and zero relative phase between the $\rho^0\rho^0$ and $\epsilon^0\epsilon^0$ decay amplitudes. The dependence of the mass shift from the cut on the momentum of the spectator proton observed by ASTERIX has been explained[70] in terms of rescattering.

3.4. Tensor mesons

The ASTERIX experiment has observed a new isoscalar structure[37], called AX(1565), with a mass of 1565 MeV, a width of 170 MeV, $J^{PC} = 2^{++}$, $I^G = 0^+$, produced dominantly from P-wave protonium states and decaying into $\pi^+\pi^-$ in the study of the exclusive annihilation channel $p\bar{p} \rightarrow \pi^0\pi^+\pi^-$ in $p\bar{p}$ annihilations at rest in H_2 gas at NTP. The experimental evidence of the new meson, the detailed study of $p\bar{p}$ S- and P-wave annihilations into three pions, and various possible interpretations of the AX state are discussed in detail in the relevant publications[37,33,34] of the ASTERIX Collaboration. We should like to underline here the crucial role of the differential analysis of the data mentioned in Section 2 because i) the evidence that the observed signal was not due to instrumental effects, but to physical reasons, came from the comparison between data in gas and data in gas with 1–4 keV X-rays in coincidence (see Fig. 5), and ii) the evidence that the signal observed was not due to effects of interferences of amplitudes of other channels came from the combined analysis of the full Dalitz plots of both sets of data[33,34].

Fig. 5. $\pi^+\pi^-$ invariant mass in $p\bar{p}$ annihilations at rest into $\pi^+\pi^-\pi^0$ measured in liquid H_2 (a), in NTP H_2 gas (b), and with 1-4 keV X-rays in coincidence in NTP H_2 gas (c)

The Crystal Barrel experiment has observed, in the final state $\pi^0\pi^0\pi^0$ of $p\bar{p}$ annihilations at rest in liquid H_2, a prominent signal called AX(1520) in the decay mode $\pi^0\pi^0$. The mass is 1520 MeV, the width is 120 MeV, and the angular distributions are consistent with $J^{PC} = 2^{++}$. The experiment has not yet shown, in the $\pi^+\pi^-\pi^0$ final state, the signal from the AX(1520) in the $\pi^+\pi^-$ decay mode. Furthermore they observe a prominent peak in the $\eta\eta$ decay mode at a mass of ~ 1560 MeV with a width of < 200 MeV in the final state $\pi^0\eta\eta$ [71–73].

The OBELIX experiment has observed the AX in $p\bar{p}$ annihilations at rest in H_2 gas at NTP in the $\pi^+\pi^-$ decay mode. The AX signal is the main background source in data collected with a trigger requiring two prongs coplanar to the beam axis, which was employed to collect $\pi^+\pi^-$ and K^+K^- final states useful for the absolute calibration of the magnetic spectrometer. If present, a signal in the K^+K^- decay channel is lower by about two orders of magnitude than in the $\pi^+\pi^-$ one. OBELIX has no data yet to look for the $\pi^0\pi^0$ decay channel of the AX.

Figure 6 shows the signals in the AX energy region observed at LEAR.

In the following some points are discussed concerning the physical interpretation of the AX, investigations of other decay channels, and matters regarding production of the AX.

In view of the facts that the 2^{++} nonet is already full, that the AX has no charged partners, and that it has not been observed in J/ψ radiative decays, the AX is a candidate for a $qqq\bar{q}\bar{q}\bar{q}$ baryonium state, or a $qq\bar{q}\bar{q}$ multiquark state, or a 2^{++} $q\bar{q}$ radial excitation. This last possibility is the most economical one and it is compatible with the lower bound for the 2^{++} continuum computed in the framework of QCD sum rules[74], if other important decay modes of the AX, besides the $\pi^+\pi^-$ and $\pi^0\pi^0$ ones, are not observed. The 2^{++} radial excitation hypothesis is not in agreement with a quark-model expectation for the mass of the lightest isoscalar radial excitation of the 2^{++} nonet, which is about 200 MeV higher than the AX mass[75].

If the AX is a baryonium or a $qq\bar{q}\bar{q}$ state, decay modes with several pions present in the final state should be dominant and similar to what happens in the annihilations of protonium in 2^{++} initial states. Experiments with $\bar{p}$ at rest in liquid-D_2 targets[76–79] gave indications of structures in the $\pi^0\pi^0$ and $\pi^+\pi^-$ decay channels in the mass region of the AX, but in the $\bar{p}n$ annihilation final state $\pi^+\pi^-\pi^-$ a resonant nature of the signal was not established by a study of the phase movement, and whether the spin was 0 or 2 was not resolved. The signal in the $\pi^+\pi^-\pi^+\pi^-$ invariant mass of $\bar{p}n$ annihilations into five charged pions, obtained at BNL, has been attributed a branching ratio[68] of $(3.7 \pm 0.3) \times 10^{-2}$. Gray et al.[79] also had a spike in the $\pi^+\pi^-$ invariant mass spectrum of $\bar{p}n$ annihilations into $\pi^+\pi^-\pi^-$, attributed to a structure with mass centred at 1530 MeV and with a branching ratio of $(2.6 \pm 0.4) \times 10^{-3}$. Comparison of the two branching ratios quoted above indicates that, if the decays into two and four charged pions are from the same object—called ζ —, the decay probability of the ζ into $\pi^+\pi^-\pi^+\pi^-$ is 14 times higher than into $\pi^+\pi^-$. The experimental branching ratio for producing AX decaying into $\pi^+\pi^-$ in a NTP gas target in $p\bar{p}$ annihilations into $\pi^+\pi^-\pi^0$ with 1–4 keV X-rays in coincidence is[37] $(3.7 \pm 0.6) \times 10^{-3}$. If AX and ζ are the same resonance and interference effects are negligible, then one would expect an experimental branching ratio of about 5.2×10^{-2} for decays into $2\pi^+2\pi^-$ of AX produced in gaseous H_2 at NTP with 1–4 keV X-rays in coincidence. Taking into account the ratio of about 1/2 of the AX production in gas to that in gas with X-rays in coincidence in $p\bar{p}$ annihilations into $\pi^+\pi^-\pi^0$, and the ratio of production of the exclusive channel $\pi^+\pi^-\pi^0$ in gas and in gas with X-rays in coincidence, one would expect a branching ratio of about 2×10^{-2} for $2\pi^+2\pi^-$ decays of AX produced in gas in the exclusive final state $2\pi^+2\pi^-\pi^0$. The branching ratio for the $2\pi^+2\pi^-\pi^0$ channel in gas is[35,38] 19×10^{-2}. Therefore the AX signal should amount to 10% of all the $2\pi^+2\pi^-\pi^0$ events in gas. Since the branching ratio for only four prongs in $p\bar{p}$ annihilations in gas is[80] around 6.5×10^{-2}, the AX $\rightarrow 2\pi^+2\pi^-$ signal should contribute in the four-prong invariant-mass spectrum a signal with an area of about 1/3 of that of the peak of the events with four prongs only (after acceptance corrections). To summarize, the expected signal of the AX in the four-prong data is rather large under the hypothesis that $\zeta(1480)$, $\zeta(1530)$, and AX(1565) are the same thing. Inspection of the ASTERIX four-prong invariant mass spectrum for gas data reveals no peak in the AX mass region; the shape of the spectrum does not change visibly for the data in gas with 1–4 keV X-rays in

Fig. 6. Signals in the AX energy region observed at LEAR in $p\bar{p}$ annihilations at rest. a) AX(1565) in the $\pi^+\pi^-$ invariant mass in events $p\bar{p} \rightarrow \pi^+\pi^-\pi^0$ with 1-4 keV X-rays in coincidence in a NTP H_2 gas target (ASTERIX [37]). b) AX in the $\pi^+\pi^-$ invariant mass in a NTP H_2 gas target with a trigger requiring two prongs only and coplanar or quasi coplanar to the magnetic field direction (OBELIX preliminary data, n.b. the peak at $\sim$ 1860 MeV is due to the annihilation channel $p\bar{p} \rightarrow \pi^+\pi^-$). c) AX(1520) in the $\pi^0\pi^0$ invariant mass in events $pp \rightarrow \pi^0\pi^0\pi^0$ in liquid H_2 target (Crystal Barrel[72,73]). d) Signal in the $\eta\eta$ invariant mass in $p\bar{p} \rightarrow \pi^0\eta\eta$ events in liquid H_2 target (Crystal Barrel[72,73])

coincidence. Under these circumstances the assumptions made recently[81,82] that the AX and the ζ are the same thing seem not to be justified. In any case, a complete differential analysis of the four-prong ASTERIX data in gas and of those in gas with X-rays in coincidence is necessary to give an upper limit on the presence of the AX in the four-prong spectra. This is because the AX signal would not be narrow, because there is activity in the mass region where the AX would contribute, and because it might occur that this mass region is populated only by AX events in both types of data. A preliminary glance at four-prong OBELIX data in gas shows that the ratio between the total amount of events in the AX energy region and the number of only-four-prong events seems not to be below the 1/3 boundary computed above.

The assumption of the identity of AX(1565) and of the signal in $2\pi^+2\pi^-$ present in $\bar{p}d$ annihilations is obviously also not supported by the recent 0^+ determination of the J^P quantum numbers of the $2\pi^+2\pi^-$ signal[69].

A further remark on the interpretation of the AX and of the state $2\pi^+2\pi^-$ in $\bar{p}d$ is that, if one of them is a baryonium state, the probability that it is reached via radiative transitions with emission of a γ of about 200 MeV should be appreciable and related to the probability of being reached via the pionic transitions that have led to its observation[82]. To confirm the baryonium hypothesis it will therefore be crucial to observe the AX in the reaction $p\bar{p} \rightarrow \pi^0 2\pi^+2\pi^-$ and in the reaction $p\bar{p} \rightarrow \gamma 2\pi^+2\pi^-$. This last reaction can be selected with the spectrometers on the floor at LEAR. Indeed their missing-mass resolution is not sufficient to discriminate a γ from a π^0, however the γ's of transitions to the AX would have a much higher momentum than the π^0's of pionic transitions to the AX and can be selected with a cut on the missing momentum. The background from four-prong events with $2\pi^0$'s is low and can be suppressed by a cut on the missing mass. The background from four-prong events with one π^0 feeding through the cut on the missing momentum can be suppressed, by requiring one and only one γ to be detected (with energy equal to the energy missing from the four prongs) and by applying a cut on the angle between the direction of the momentum missing to the four-prong and the direction of the detected γ.

The AX(1520) gives a beautiful signal in the $\pi^0\pi^0$ decay channel[71] in liquid H_2. Instead the AX signal in the $\pi^+\pi^-$ decay channel was not visible in the $\pi^+\pi^-$ invariant mass plot from bubble chamber data[83] and has not yet been shown in the same plot by the Crystal Barrel Collaboration. The signal of the AX in the $\pi^+\pi^-$ channel is hard to detect with a liquid-H_2 target because the background due to annihilations in S-wave is too high (in particular that due to the large $\rho^+\pi^-$ and $\rho^-\pi^+$ production). The background from annihilations in S-wave does not interfere with the signal of the AX from P-wave annihilations; however it simply covers the AX signal from the 10% or so P-wave annihilations at high n of protonium that occurs in liquid. The fact that the Crystal Barrel sees the AX so nicely in liquid, where it is produced in such scarce quantities, underlines the importance of the new detection techniques, which allow the reconstruction of exclusive final states with several gammas or only neutrals. These techniques are independent of the new techniques to change the populations of the nS and nP waves of the initial state and can be used in conjunction. Had a good detector for exclusive final states with only π^0's present been employed to study $p\bar{p}$ annihilations at rest before LEAR, the AX could have been discovered 15 years ago! Hints of an AX(1520) signal may indeed have been present in pre-LEAR data[78,79]. The Crystal Barrel data indicate that the f_2 is produced dominantly from 1^{++} initial states of protonium and marginally from 0^{-+} S-wave states [that have respectively a $\cos^2\theta + \frac{1}{3}$ and a $(\cos^2\theta - \frac{1}{3})^2$ angular distribution of the two decay pions relative to direction of motion of the f_2], while the AX is produced from 2^{++}, 1^{++}, and 0^{-+} states with comparable rates. When $\pi^0\pi^0\pi^0$ annihilation data will have been collected in gaseous H_2, it will be interesting to see what will happen. We can already anticipate that the absolute branching ratio for the $\pi^0\pi^0\pi^0$ exclusive final state will increase, since the total P-wave annihilation will increase from about 10% to about 50%, and f_2 and AX production from P-states are the dominant component in the $3\pi^0$ dynamics already in liquid. Data with X-rays in coincidence will have an even higher $\pi^0\pi^0\pi^0$ branching ratio since about 90% of the annihilations will be from P-wave. Comparison of the three sets of data could give indications about the possibility of spin polarization in $p\bar{p}$ annihilations at rest[59], because it might be that the relative fraction of 2^{++} and 1^{++} annihilations is not the same for: i) annihilations from the $n = 2$ protonium P levels (tagged by the L X-rays), ii) annihilations from all the P levels populated by the atomic cascade of protonium in gaseous H_2 at NTP, and iii) annihilations from all the P levels populated by the atomic cascade of protonium in liquid H_2. Spin polarization in $p\bar{p}$ annihilations at rest is one new piece of information we may hope to get from the high-energy part of the $\pi^0\pi^0$ invariant mass spectrum by inspecting the variations of the relative yields of AX and f_2. Inspection of what will happen in the low-energy part of the spectrum, which cannot be populated by the decay of 1^{--} objects (such as the ρ^0), could give new information about 0^{++} low-mass states, which are of extreme interest[54].

By the way, note that for the study of light structures decaying into $\pi^0\pi^0$, other channels accessible with the Crystal Barrel and OBELIX appear more convenient, since they do not suffer from combinatorial background: the channel $\eta\pi^0\pi^0$ has already been explored by the Crystal Barrel and the channel $\pi^-\pi^0\pi^0$ can be studied very well by OBELIX in $\bar{p}n$ annihilations in a D_2 gas target with slow spectator protons measured in the SPC vertex detector.

3.5. Pseudoscalar mesons

The ASTERIX experiment has observed again the E meson in the decay channel $K^0_{miss}K^\pm\pi^\mp$ in the exclusive final state $K^0_{miss}K^\pm\pi^\mp\pi^+\pi^-$. This particle is a serious candidate to be a pseudoscalar glueball state.

The E was discovered at CERN by Armenteros and co-workers[39], in 1963, in $p\bar{p}$ annihilations at rest, in liquid H_2, in the decay channel $K_SK^\pm\pi^\mp$ in the exclusive final state $K_SK^\pm\pi^\mp\pi^+\pi^-$ with the K_S decaying into $\pi^+\pi^-$. The first measurement of the E featured a bump centred at 1410 MeV with a width of about 60 MeV (see Fig. 7). The 80 cm Saclay Bubble Chamber, where the discovery was made, was operating with a low-energy conventional $\bar{p}$ beam in the South Hall of the CERN PS, where the LEAR complex was installed twenty years later. The quantum numbers $I^GJ^{PC} = 0^+0^{-+}$ of the state, which was labelled E for Europe, were subsequently established from the analysis of a larger data sample of 1.4×10^6 events[40]. The values of mass and width obtained from a Breit-Wigner fit of the peak, obtained by subtracting the double-charge combination $K\bar{K}\pi$ spectrum from the zero-charge one, were 1415 ± 5 MeV and

Fig. 7. First observation of the E meson[39] in $p\bar{p}$ at rest in liquid H_2 in 1963. Invariant mass of K_S $K^\pm\pi^\mp$ neutral combinations (top) and of K_S $K^\pm\pi^\pm$ double charge combinations (bottom) in $p\bar{p} \rightarrow K_S$ $K^\pm\pi^\mp\pi^+\pi^-$ events. The bottom spectrum gives the combinatorial background present in the top curve

77 ± 12 MeV, respectively; the values obtained by fitting the experimental spectrum with a Monte Carlo spectrum accounting for the quantum numbers and decay modes of the E were 1421 ± 8 MeV and 80 ± 15 MeV, respectively. The branching ratio of the annihilation channel $p\bar{p} \rightarrow E\pi^+\pi^-$ in liquid H_2 with E decaying into $K_SK^\pm\pi^\mp$ was $(7.1 \pm 0.7) \times 10^{-4}$. This branching ratio was derived from measurements with the neutral kaon decaying into $\pi^+\pi^-$, with about 600 events in the peak[40,55]. The E observed in the 80 cm bubble chamber was seen also in the $K^+K^-\pi^0$ and in the $K_SK_S\pi^0$ decay channels. The events observed by ASTERIX in the mass region of the E show a strong $K\bar{K}$ threshold effect. The decay Dalitz plot does not permit discrimination between a 0^{-+} E decaying dominantly via $a_0\pi$ and a 1^{++} E decaying dominantly via $a_0\pi$. The data are not compatible with the hypothesis of a dominant $K^*\bar{K}$ decay mode of the E.

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The E has been observed by the ASTERIX experiment[38] using a gaseous H_2 target at NTP, where the fraction of P-wave annihilations is about 50%. However the four-prong data used for the E study (11.2×10^6 events) were collected with simultaneous use of a multiplicity-4 trigger and of the trigger (called 1-gap trigger) used to enrich the data samples with X-rays in coincidence[85]. The 1-gap trigger had an efficiency of 25% for selecting events with a true X-ray in the 1–4 keV window. The data set of four-prong events collected with the 1-gap trigger active then had a fraction of 61% of the events with annihilation from P-wave. The subset of events with an X-ray in coincidence in the 1–4 keV window, ascertained in the off-line analysis, had instead 86% of the events with annihilation from P-wave (the 14% of events with annihilation from S-wave had a 1–4 keV X-ray from internal bremsstrahlung in coincidence). [Notice, in passing, that the two-prong data used by ASTERIX for the discovery of the AX comprised two distinct data sets : one with the 1-gap trigger active simultaneously with the two-prong trigger, and one with the two-prong trigger alone.] The $KK\pi$ invariant mass spectra from all four-prong events collected with the 1-gap trigger and from four-prong events with a true X-ray in coincidence are reproduced in Fig. 8a and 8b.

By using four-prong 1-gap trigger events and after subtraction of background events with a false missing neutral kaon, ASTERIX has observed the E with a mass 1413 ± 8 MeV and a width of 62 ± 16 MeV from a Breit-Wigner fit of the E region of the spectrum obtained by subtracting the double-charge combination $KK\pi$ spectrum from the zero-charge one (see Fig. 8c). The branching ratio of the annihilation channel $p\bar{p} \rightarrow E\pi^+\pi^-$ with E decaying into $K_LK^\pm\pi^\mp$ is $(3.0 \pm 0.9) \times 10^{-4}$ for the four-prong 1-gap data sample, where there is 61% P-wave annihilation.

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Fig. 9. Production of E decaying into $K_SK^\pm\pi^\mp$ or into $K_LK^\pm\pi^\mp$ in $p\bar{p}$ annihilations at rest into $K_{S/L}K^\pm\pi^\mp\pi^+\pi^-$ displayed versus the fraction of P-wave annihilations. The decay channel $K_SK^\pm\pi^\mp$ was measured in liquid H_2 (see Refs. 39,40). The decay channel $K_LK^\pm\pi^\mp$ was mesured in a NTP gas target

This branching ratio was derived from measurements with the neutral kaon decaying into neutrals and selected by a cut in the missing-mass spectrum around the peak of the K^0. About 500 events are present in the E peak of Fig. 8c. The small signal present in the ASTERIX spectrum at 1280 MeV is rather likely to be due to the D meson [f_1(1285)] 1285

The reduction in the E production from 7.1×10^{-4} to 3.0×10^{-4}, which appears when comparing the branching ratios measured in liquid and in gas (see Fig. 9) is consistent with the E being produced only from protonium states in P-wave. Thus the measurement of the angular distribution of the two pions recoiling against the E (which is flat and compatible with an $l = 0$ relative angular momentum of the two pions), and the measurement of the angular momentum L of the E with respect to the two-pion system (which is consistent with $L = 0$) permit one to establish[38] that the J^{PC} of the E is 0^{-+}. In order to come to this conclusion it is essential to make shift to pg 16 at the beginning

Fig. 8. Observation of the E meson in $p\bar{p}$ at rest in the NTP gas H_2 target of the ASTERIX experiment[38]. The figure shows different $(K^0)_{missing}K^{\pm}\pi^{\mp}$ invariant mass distributions for $p\bar{p} \rightarrow (K^0)_{missing}K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ annihilations. a) All events collected with the trigger 4-prongs + 1-gap; there are two entries per event; for these events the fraction of S-wave annihilations is ~ 40%. b) Subset of events of spectrum a) that have a 1-4 keV X-rays in coincidence; for these events the fraction of S-wave annihilations is ~ 14%. There are two entries per event. c) Spectrum a) after remotion of background events (that give a poor fit to the kinematical hypothesis $(K^0)_{missing}K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ and subtraction of the $(K^0)_{missing}K^{\pm}\pi^{\pm}$ invariant mass spectrum to remove the combinatorial background. The E signal gives a prominent peak and a 3σ effect appears at the D (f_1) mass. d) This empty frame should contain spectrum b) after remotion of background events and subtraction of the combinatorial background, or the subset of events of spectrum c) with 1-4 keV X-rays in coincidence. Spectrum d) has not been produced, also because of the comparatively large statistical errors introduced by the backgound subtraction. Spectrum d) should feature a strong depression of the signal in the E region, since the S-wave contribution drops from 40% to 14%, and survival of the signal in the D region. These features are already suggested by spectrum b). Spectrum d) is missing for a complete and selfconsistent differential analysis of the E meson data of ASTERIX

the observation that the production of E reduces with an increasing fraction of P-wave annihilations. This could have been established with the ASTERIX data alone, if the production branching ratio of the E had been measured directly also for the data with protonium X-rays in coincidence and if one would have observed a drop there. In this last case, the variation of the S-wave annihilation fraction is from 39% to 14%, and systematic errors in the sign determination of the slope of the curve in Fig. 9 would factorize away. This would have discarded the possibility that the decrease of the E production branching ratio with the increase of the P-wave fraction is due to systematical errors in the branching ratio measurement in either or both BC and ASTERIX measurements. The data sample with true X-rays in coincidence had about 4 times less events than the full data sample of four-prong 1-gap events, but a different fraction of P-wave annihilations. For the subset of data with true X-rays detected in coincidence, the same analysis as was carried out for the four-prong 1-gap data was not repeated exactly. If this had been done

Fig. 10. ι signal as seen by the DM2 experiment[91] in radiative decays $J/\psi \to \gamma K K \pi$. a) $K_S K^\pm \pi^\mp$ invariant mass spectrum. b) $K^+ K^- \pi^0$ invariant mass spectrum

the procedure of differential measurements[14,15] could have been completed and most likely we could have clearly seen also the D signal in spite of the moderate statistics.

The signal in the E energy region for structure(s) with $KK\pi$ decay modes was seen 17 years after the first observation by Armenteros et al. in radiative decays of the J/ψ by the MARK II[86] and Crystal Ball[87] experiments at SPEAR, and successively studied in more detail by the MARK III[88,89] and DM2 experiments[90,91] respectively at SPEAR and at DCI Orsay. The $KK\pi$ signal in the E region observed in radiative J/ψ decays was called ι. The ι turned out to be dominantly 0^{-+}, but broader than the E observed in $p\bar{p}$ at rest, and to have a shape (see Fig. 10) that requires at least two components centred at 1420 and 1460 MeV to give acceptable fits. The $\iota(s)/E$ provide a major candidate for a glueball state because of the following main features

i) ι has the highest production rate of all radiative decays of the J/ψ,

ii) there is no $\iota(s)/E$ production in $\gamma\gamma$ interactions,

iii) there are at least three candidates [$\eta(1295)$, $\iota/E(1420)$, and $\iota(1460)$] for two positions available for the two isoscalar 0^{-+} radial excitations of $q\bar{q}$ mesons.

There is evidence for an E/ι signal in $KK\pi$ decay modes, in reactions with pion beams[92], and there are several pieces of evidence for 1^{++} resonances in the E/ι mass region[93]. For instance, in central production with π^+ and p^+ beams and in $\gamma\gamma^*$ interactions, a clear 1^{++} structure is seen at 1425 MeV in decay modes $KK\pi$[94-96]. The central production experiments see also very neatly the D in $KK\pi$ decay modes at 1285 MeV, which is likely to be present in $p\bar{p}$ annihilations at rest in P-wave.

The situation in the 0^{-+} sector is very interesting in view of the serious possibility that the E or the other part of the ι signal be a glueball; however, a number of points are not clear and detailed analyses require much higher statistics than available, as well as studies of other decay channels, such as $\eta\pi\pi$. Looking at the experiments that have contributed to the E/ι, one notices that the number of events in the peak was about 500 in $p\bar{p}$ experiments at rest (which had modest detection capabilities for final states with gammas, but where the angular momentum distribution of the initial states could be changed to switch from prominent E to prominent D production), whereas it was less than 2000 in MARK III and DM2 (which were powerful detectors but were limited by the relatively low interaction rates). These detectors are no longer in operation, now that data analyses emphasize the interest of the physics and the need for larger statistical samples[97]. Work in the E/ι region is in progress at the Beijing Charm Factory with the BES detector[98] whose design was inspired by the MARK III one. More than 3×10^6 e^+e^- annihilations at the J/ψ energy have been collected so far.

At LEAR about 100 E's per second are produced by stopping 10^5 $\bar{p}$'s per second in a H_2 target. The Crystal Barrel and OBELIX experiments can gather substantial statistics on E/ι production and decay from three different distributions of initial states with three different fractions of P-wave annihilations. The design performances of the two detectors are comparable to or better than those of detectors that have been phased out. The two experiments will be able to measure the production branching ratios of the E and its decay branching ratio in $K\bar{K}\pi$, $\eta\pi\pi$, and $\eta\eta\pi$, and to check for the presence of new structures in the E/ι region in $p\bar{p}$ P-wave annihilation. First, low or minimum-bias triggers should be used to establish and compare as safely as possible the absolute production branching ratios. The two experiments then have the possibility of activating triggers that can enrich final states where K's or η's are present, and making high-statistics studies of selected excusive final states. It will be possible to determine the biases introduced by the triggers by comparison with data collected with the less selective triggers.

4. SPECTROSCOPY EXPERIMENTS ON THE FLOOR

4.1. Production experiments

The **Crystal Barrel**[99] and OBELIX[30] experiments **have been designed** to work in production with $p\bar{p}$ **annihilations** at rest and in flight. OBELIX has been designed to also study $\bar{p}n$ annihilations with $\bar{p}$'s annihilating at rest and in flight in a D_2 gaseous target. The CPLEAR experiment[100] might contribute with $p\bar{p}$ annihilations at rest. The JETSET[50] experiment might contribute with $p\bar{p}$ annihilations in flight in an advanced stage of the experiment with an upgraded version of the detector.

Fig. 11. Side cut view (top) and front cut view (bottom) of the Crystal Barrel detector. 1) iron added to the DM1 original joke, 2) DM1 iron joke, 3) coil, 4) CsI Barrel, 5) Jet Drift Chamber, 6) MWPC, 7) Liquid H_2 target

Fig. 12. View of the Crystal Barrel experiment in the LEAR experimental hall. The downstream end-cap of the solenoidal magnet is open and the downstream half of the CsI barrel has been slid out of the magnet for maintenance and access to the JDC

4.2. The Crystal Barrel

Figures 11 and 12 illustrate the Crystal Barrel experiment, which realizes the goal of con-

insert these pictures in pg 20 after 4.2 has started structing a complete experiment with a good detector for neutrals in $p\bar{p}$ annihilations[101,102]. The successful operation of GAMS[103] and Crystal Ball[104] at other facilities showed the feasibility of a good detector for neutrals. The Crystal Barrel is a large-acceptance spectrometer for charged particles and γ's. A set of two cylindrical multiwire proportional chambers (MWPC's) surrounds the liquid-H_2 target and provides a trigger on the multiplicity of charged particles. The JDC is a drift chamber of JET design[105] with 30 azimuthal sectors and 23 sense wires per sector, which are equipped with FADC electronics with 10 ns sampling time. There are 1380 caesium iodide crystals positioned in a barrel configuration with 60 azimuthal segments closed by two end-cap sectors. The barrel is segmented longitudinally into 16 rings. Each end-cap comprises five rings, of which the two nearest to the barrel axis have 30 crystals, while the other three rings have 60 crystals as the barrel. A conventional 2 MW solenoid provides a uniform 1.5 T magnetic field inside all the barrel volume. The JDC measures the momentum of charged particles and provides K/π separation up to 500 MeV by combined dE/dx and momentum measurements. The CsI crystals are tapered and 30 cm long ($16X_0$) and permit a measurement of the energy of a γ-ray converting in one of the crystals, with σ_E = 25 MeV at 1 GeV, and of the centre of gravity (in two dimensions) of the energy deposited by the electromagnetic shower, in the crystals surrounding the one where the conversion took place, with an angular resolution $\sigma = 1.2°$. The JDC is 40 cm long; it has an external diameter of 51 cm and covers a solid angle of 93% of 4π (84% of 4π for tracks with at least 9 hits). The solid angle of the gamma detector is 97% of 4π (95% of 4π for gamma detection without leakage of showers in the regions along the beam axis which are not instrumented with active elements)[71]. The gamma detector permits the reconstruction of events with 6 γ's detected, as well as the selection and analysis of $\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$, and $\omega\omega$ final states, with all the mesons decaying into γ's.

A 200 MeV/c $\bar{p}$ beam has been used for $p\bar{p}$ annihilations at rest. With this incoming beam momentum the energy straggling in the degrader causes a longitudinal spread of the annihilation vertices of about 1 mm in liquid H_2, less than the JDC resolution in the z direction for vertex reconstruction. In order to have a higher fraction of P-wave annihilation there are plans to use a gaseous-H_2 target[73] in the Crystal Barrel. A 200 MeV/c $\bar{p}$ beam may be convenient for scheduling reasons; however, with a NTP gas-H_2 target and a 200 MeV/c incoming beam momentum, the annihilation vertices would be spread longitudinally over more than twice the length of the vertex detector. Therefore when using the H_2-gas target, the Crystal Barrel would run at 100 MeV/c incoming beam momentum with a range straggling of about 12 cm, which would give a distribution of annihilation points well contained inside the JDC.

A minimum-bias trigger (incoming $\bar{p}$ giving a signal in a thin silicon counter betveen the beam pipe window and the target) and a zero-prong trigger (incoming $\bar{p}$, no signal in the MWPCs and no hits in the first layers of the JDC) have been used for data taking. More sophisticated final-state multiplicity triggers (fast charged multiplicity, barrel-cluster multiplicity, total energy, π^0 and η triggers) are under test.

During 1990, the Crystal Barrel has collected some millions of events at rest with the minimum-bias trigger and more than 10^7 events with the all-neutrals trigger, and has done a first run with annihilations in flight at 600 MeV/c beam momentum.

Send these figures to pg 22 after 4.3 has started

Fig. 13. Overall view (top) and side cut view of the OBELIX detector in the configuration for meson spectroscopy. 1) OAFM magnet, 2) Spiral Projection Chamber and X-ray Drift Chamber SPC/XDC vertex detector, 3) tof hodoscope, 4) AFS JET drift chamber, 5) Tof hodoscope, 6) HDSPC, 7) High Angular Resolution Gamma Detector HARGD

Fig. 14. View of the OBELIX experiment in the LEAR experimental hall. The south wing of the Tof is raised for access to the south AFS JET chamber, that in turn is shifted transversally away from the axis of the experiment for access to its front-end electronics. On the right is visible one extremity of the south HARGD supermodulus, that is shifted downsteam of the experiment in order to raise the Tof wing. At the two extremities of the AFS JET chamber are visible the poles of the OAFM magnet. The return joke of the magnet is two meters below the visible floor level. The metallic floor covers the garage position of the bottom HARGD supermodulus, that moves on air pads

It is planned that the Crystal Barrel will collect data samples in excess of 10^7 events for $p\bar{p}$ annihilations at rest in liquid and, later on, in a gas target with the minimum-bias trigger, with the all-neutrals trigger, and with more specialized triggers. The experiment also plans to collect data at rest with a liquid-D_2 target and to collect $p\bar{p}$ annihilation data in flight at 700 and 1900 MeV/c. Pile-up in the CsI crystals limits the rate of annihilations to a few 10^4 s^{-1}. The typical data-acquisition rate is 10 Hz. Appropriate beam intensities are then around 10^4 $\bar{p}$'s per second at rest and 10^6 $\bar{p}$'s per second or more in flight.

4.3. OBELIX

Figures 13 and 14 illustrate the OBELIX apparatus. This has been designed[28,106,107,30] to complete and extend the physics programme on light-meson spectroscopy, initiated with ASTERIX, with a detector superior both for the identification of the initial states and for identification, measurement and trigger of final exclusive states. The physics programme of the collaboration includes also studies of antinucleon interactions with nucleons and nuclei[30].

The OBELIX spectrometer has a large acceptance and consists of the open axial field magnet (OAFM) plus the AFS JET drift chambers recuperated from the AFS experiment[108] at the ISR and equipped with new electronics, of the central detector SPC, of two concentric hodoscopes of plastic scintillators called toffino (tof) and Toffone (Tof), and of four large moduli of gamma detectors called HARGD. The SPC contains, along its axis, a gaseous H_2 target at NTP separated by a very thin Mylar membrane from the

The 0.75 MW magnet ~~provides~~ generates a 0.5 T field in the centre of the experiment.

active volume of the vertex detector, so that L X-rays of protonium and low-momentum spectator protons are detected with high efficiency. The vertex detector is a spiral projection chamber (SPC)[17,18,109,110] (gas drift chamber with radial drift field and axial magnetic field). Ninety resistive sense wires, equipped on both sides with 10 ns sampling-time 8-bit FADC readout electronics, and 90 strips, equipped on one side with the same electronics as the anode wires, define inside the SPC about 10^7 pixels usable for the X-ray absorption-point and track-point localization and for dE/dx measurements. The target has a diameter of 6 cm. The SPC is 60 cm long and covers a solid angle exceeding 98% of 4π around the centre of the detector. It measures the direction of prongs coming from the target volume before they suffer multiple scattering inside any lumped amount of material. It provides typically 7 track points and more than 200 dE/dx samples per track reaching the surface of the strips. It will enable vertex reconstruction within 1 mm^3, detection and localization of protonium L X-rays, K/π separation from 300 MeV/c down to 50 MeV/c and triggering on L X-rays in the initial state and on K_S in the final state. The tof is a barrel of 30 plastic scintillators, 1 cm thick and 80 cm long, which surrounds the SPC and covers a solid angle of about 80% of 4π. The two AFS JET chambers are the drift chambers of the jet geometry with the largest azimuthal segmentation ever built: each of them contains 41 azimuthal sectors, 4° wide, with 48 resistive sense wires per sector, of which 40 are equipped at each extremity, with 10 ns sampling-time 8-bit FADC readout electronics.

The active volume of the two AFS JET drift chambers has 40 cm inner diameter, 160 cm outer diameter, and 128 cm length. These chambers measure accurately the momentum of prongs that have traversed the tof hodoscope, with up to 10 track points and dE/dx samples. Best-performance parameters for a single track reaching the chamber periphery are $\sigma_p = 2 - 3\%$ at 1 GeV/c and $\sigma(dE/dx) = 11\%$, permitting π/K separation up to 600 MeV/c. The Tof is a barrel of 90 plastic scintillators, 4 cm thick, 300 cm long, and positioned at a diameter of 250 cm. The tof and Tof arrays permit K/π identification by a time-of-flight (TOF) technique up to 800 MeV/c and triggering on charged kaons with momenta above 200 MeV/c. The four HARGD moduli have dimensions of 4 × 3 × 1 m^3 each. They contain 20 layers of lead foils with a total thickness of $10X_0$, that sandwich 26 planes of 1 cm^2 cross-section Iarocci tubes read out by planes of x and y strips, and planes of pads organized in towers pointing to the centre of the spectrometer. The HARGD provides i) a tridimensional picture of each shower, which allows good γ identification and eventually will allow checking its direction; ii) a modest, but useful, energy resolution by hit counting, and iii) a good three-dimensional localization of a γ conversion point with high segmentation. The minimum distance of a γ originating in the target and converting in one module of the calorimeter is 150 cm. This and the 1 cm pitch of the readout strips will allow an angular resolution on the γ direction of about 3 mrad. The pad towers are foreseen to enable triggers on the total hit multiplicity and eventually on the total γ multiplicity.

A beam of 105 MeV/c has been used for test runs with $p\bar{p}$ and $\bar{p}d$ annihilations at rest during August 1990, with all detectors for charged particles in operation and two HARGD supermoduli installed. About 10^5 $p\bar{p}$ and 5×10^4 $\bar{p}d$ events have been collected with the minimum-bias trigger (incoming antiproton firing a thin scintillator positioned between the beam pipe and the target windows). Other simple triggers have been used for debugging and calibration purposes (e.g. no hits in tof, multiplicity 2 and 4 in the TOF system, two prongs coplanar to the beam or quasi-coplanar). The electromagnetic calorimeter will be completed in the first half of 1991 and the full apparatus and a global reconstruction program should become operational in the course of that year.

A 105 MeV/c or lower-momentum $\bar{\text{p}}$ beam is necessary for production runs at rest to have the annihilation points distributed around the centre of the detector with a longitudinal spread of less than 10 cm. The detector can stand interaction rates in excess of 10^5 s^{-1}.

A strategy for data taking of OBELIX for meson spectroscopy in production with $\bar{\text{p}}$'s has been discussed extensively[14,15,111] by the author (see, in particular, pp. 337 and 338 of Ref. 14). The detector is capable of identifying all prongs emitted in $\text{p}\bar{\text{p}}$ and $\bar{\text{p}}\text{d}$ annihilations and of reconstructing completely and with high resolution final states with prongs and up to two π^0's (or one π^0 and one η, or two η's) decaying into four detected γ's. These features permit the search for objects produced in $\text{p}\bar{\text{p}}$ or $\bar{\text{p}}\text{d}$ annihilations, recoiling against one or two prongs and decaying into one or more of the following sets of light mesons: $\pi\pi$, πK, $\pi\eta$, KK, $\eta\eta$, ηK, $\omega\pi$, ωK, $\omega\eta$, $\phi\pi$, $\phi\eta$, $\pi\pi\pi$, $\pi\pi\eta$, $\eta\eta\pi$, $\pi\pi$K, KKπ. For some of these sets of decay particles, it is allowed by conservation rules that they be the daughters of an intermediate resonance with exotic quantum numbers. The trigger system will permit large data samples, with K_S, K^+, and K^- in the final state, to be collected. Unique strong points of the experiment are the possibilities of changing the ratio of S- to P-wave initial states of $\bar{\text{p}}$ annihilations at rest, without affecting the measurement of the final state, and of fully reconstructing $\bar{\text{p}}\text{n}$ annihilations with very low momentum spectator protons. This permits differential measurements where most, if not all, factors affecting the reconstruction and the measurement of the final state can be factorized away and where the difference in the distribution of the initial states may reflect, for a given exclusive final state, in different productions of the intermediate states. This has been demonstrated very clearly in the ASTERIX study of the $\pi^0\pi^+\pi^-$ final state and has led to the discovery of the AX, which is however not exceptionally broad and was directly visible in the data with X-rays in coincidence. For broader structures, which might emerge only from the differential analysis, it will be crucial to have the stability of the apparatus and of the analysis procedures well under control. The measurement and the monitoring of the stability of the branching ratios of simple exclusive channels of annihilation such as $\pi\pi$, KK, 4π, and 2π2K in $\text{p}\bar{\text{p}}$ annihilations with two and four prongs will be necessary. The measurement of these branching ratios and of other channels in gas at a few target pressures, with and without X-rays in coincidence, will permit us to find out if the atomic cascade of protonium causes spin polarization via the combined effect of collisions and annihilations in high-n atomic levels[59].

The OBELIX experiment will also exploit annihilations in flight for meson spectroscopy in order to extend the accessible mass range. For this purpose, it is advantageous, in production, to run at the highest external beam momentum available from LEAR. The drawback is that annihilation can occur from several angular momentum initial states and the data analysis becomes very complex. Nevertheless, OBELIX will have the unique opportunity of comparing, at the same total energy, annihilations of $\bar{\text{p}}\text{p}$ and $\bar{\text{p}}\text{n}$ studied in the same experimental conditions and with the spectator p of $\bar{\text{p}}\text{n}$ annihilations in $\bar{\text{p}}\text{d}$ interactions measured down to very low momenta. Obviously the non-interacting part of the beam will have to be disposed of well outside and downstream of the apparatus.

4.4. Comments

A nice feature of the present generation of production experiments at LEAR is the presence of two powerful and complementary detectors, which can cross-check their results in several annihilation channels (collected at the same target density for annihilations at rest, and at the same beam momentum for annihilations in flight). When we consider that the E and the AX have branching ratios at the 10^{-3} level and are among the most solid candidates for exotics; that the AX could have been discovered even without LEAR by using a powerful gamma detector; that the AX has been seen by ASTERIX because of the XDC technique[17,85], allowing a selection of P-wave annihilations, in the simplest production channel accessible with a magnetic spectrometer; and that the differential-analysis approach has not been applied systematically even by ASTERIX, it is clear that remarkable possibilities of discovery are present already with a minimum-bias trigger (where cross-check is easy). For any structure appearing in the analysis of the first, say, 10^7 minimum-bias events, it will then be possible to seriously enhance the statistics in one or more decay channels, by introducing specialized triggers, where the Crystal Barrel and OBELIX have substantially different performances depending on the annihilation final state selected.

4.5. Formation experiments

The JETSET experiment is the main one designed to work in formation at LEAR at momenta above 600 MeV/c. It will study initially selected annihilation channels without γ's in the final state. At low momenta, the Crystal Barrel and OBELIX will be able to contribute valuably in formation measurements. The OBELIX experiment will be able to contribute also at very low momenta (below 200 MeV/c) by using a gas target of convenient length and a downstream vacuum tube before the beam dump. The studies of $\bar{n}p$ interactions, which are part of the OBELIX proposal, will be able to contribute in formation to the search for I = 1 objects since the $\bar{n}$ beam obtained by the p — nn charge-exchange reaction has a continuous momentum spectrum[112]. Since formation experiments do not give access to exotic states with quantum numbers not allowed to $q\bar{q}$ states, their main interest, in the framework of meson spectroscopy, is focused on the $p\bar{p}$ — $\phi\phi$ reaction, which features only gluons in the intermediate state. This is the main reaction that will be studied by JETSET, since a glueball state coupled to $\phi\phi$ and with quantum numbers accessible to $p\bar{p}$ could give a signal in the $\phi\phi$ partial cross-section resonating with the beam-momentum variation, with a good signal-to-background ratio.

4.6. JETSET

Figures 15 and 16 illustrate the JETSET apparatus[50,113]. The experiment has been designed having in view, as the main task, measuring the $p\bar{p}$ — $\phi\phi$ — $K^+K^-K^+K^-$ and the $p\bar{p} \rightarrow K_SK_S$ — $\pi^+\pi^-\pi^+\pi^-$ reactions with the same detector configuration; later on, the programme could be expanded to measuring final states containing γ's.

In the following we summarize the main design figures of the experiment[113]. The internal gas-jet target provides, together with the beam circulating in LEAR and continuously cooled by stochastic cooling, an interaction volume of about $10 \times 2 \times 1$ mm^3. The beam momentum

Fig. 15. Overall scheme of the JETSET experiment. 1) Scintillators, 2) Straw chambers trackers, 3) Si counters for dE/dx, 4) Threshold Cherenkov counters, 5) RICH, 6) Gamma veto, 7) Forward electromagnetic calorimeter, 8a) Jet target production, 8b) Jet target sink

Fig. 16. Views of the LEAR ring and of the JETSET experiment. Top: JETSET seen from upstream with the Jet target production station on the right. Bottom: JETSET seen from downsream with the two halves of the electromagnetic calorimeter opened away from the LEAR beam pipe. On the top right and bottom left of this picture are visible two of the four bending magnets of LEAR. The staight pipe that connects the entrance of these two magnets is part of the stochastic cooling system of LEAR

can be set at any pre-prepared momentum in the range 0.6–2.0 GeV/c and permits scanning of the mass range 1.96–2.43 GeV. With a target density of 8×10^{13} atoms per cm^3, a fill of LEAR with 4×10^{10} $\bar{\rm p}$'s, and a revolution frequency of 3.2×10^6 s^{-1}, the peak luminosity will be around 10^{31} cm^{-2} s^{-1} and the beam lifetime will be about 11 hours. With a beam momentum spread kept at a value of $\Delta p/p = 10^{-3}$, the mass resolution ΔM is better than 1 MeV, i.e. 20 times better than the mass resolution characteristic of experiments that have so far studied $\phi\phi$ pairs in production with magnetic spectrometers. The possibility exists of continuously varying the LEAR beam momentum within a small window during the same fill of the storage ring, so as to enable small energy scans that exploit the exceptional mass resolution. The JETSET program foresees a first exploratory scan in momentum steps of about 100 MeV/c in order to make a first high-statistics exploratory study of the $\bar{\rm p}$p — $\phi\phi$ cross-section with high resolution scans possible around the nominal step values. The detector surrounds the LEAR beam pipe and is traversed horizontally by the jet beam pipe. Its barrel part opens vertically, as it embraces the jet beam pipe as well as the LEAR one, and its forward part opens sideways. It is composed of hodoscopes of scintillators for multiplicity triggering and for fast timing, a central detector made of thin aluminium straw chambers for tracking and for triggering on K$_{\rm S}$, Si dE/dx counters for identification and triggering of low-momentum kaons, threshold Cherenkov counters for identification of higher momentum kaons, and a gamma detector for vetoing events with γ's in the final state. A fast ring-imaging Cherenkov (RICH) counter is in construction for better kaon identification. The forward gamma detector is segmented in moduli made of lead and scintillating fibres and built with a projection geometry pointing at the interaction region, in view of later applications where π^0 and η reconstruction will be required. The interaction rate will be typically 10^6 s^{-1}. The trigger system will be based on the prong multiplicity and fast kaon identification for the $\phi\phi$ channel, and on the variation of prong multiplicity by 4 for the $K_S K_S$ channel.

In later stages of the experiment the use of a polarized jet target is also foreseen. The JETSET experiment is in an advanced stage of completion and test runs with the joint operation of LEAR, the jet target, and most parts of the detector have been carried out during 1990 with p's and p̄'s circulating in LEAR at several beam momenta. A luminosity of $\sim 3 \times 10^{29}$ has been achieved at momenta $p > 1000$ MeV/c.

5. PROSPECTS

On the experimental side the main lines of development and expansion for meson spectroscopy with p̄'s at CERN are represented by i) upgrading of the detectors that are presently on the floor, ii) extension, if possible, of the control of the discrete quantum numbers of the initial state necessary for differential measurement, and iii) extension of the energy range accessible.

5.1. Upgrading of detectors

For all the detectors on the floor, upgradings are envisaged explicitly in the proposals (polarized jet target, segmentation of the barrel gamma detector in JETSET), or are in the course of realization (optical fibres in the Crystal Barrel[114], in order to get a fast annihilation timing signal when using a gaseous target at rest, where the time spread of the atomic cascade of protonium measured[62] by OBELIX is about 4 ns), or are realized and in the course of optimization (the introduction of the strips equipped with FADC electronics in the SPC of OBELIX has improved the resolution in the beam direction by one order of magnitude over the design value[109]), or are embedded in the general design of the apparatus when not explicitly foreseen (magnet for momentum analysis in JETSET, space between the AFS JET chambers and the Tof array for z chambers and a Cherenkov array in OBELIX).

5.2. Differential measurements via spin polarization?

In my view, if means could be found to investigate and compare spin-triplet and spin-singlet p̄p annihilations with differential measurements, this would represent the major qualitative boost of physics possibilities at LEAR. The relative merits of differential measurements using spin polarization, angular-momentum polarization, and isospin polarization have been discussed by the author elsewhere[14,15,111]. Annihilation with spin-polarized p̄p initial states requires a polarized jet target and a polarized stored p̄ beam. The technique for producing polarized jet targets is established[115,116]. The difficult new part is the p̄ beam polarization. Two groups are trying different techniques for that purpose. One group aims at obtaining spin polarization via a multipass Stern Gerlach effect[117,118]. The second group aims at filtering out one polarization state via interactions of cooled stored p̄'s with a polarized high-density internal gas-H_2 target[119]. The studies of beam polarization are being made respectively at the low-energy storage ring IUCF at Indiana and at the TSR at Heidelberg. Should they prove the viability of one or the other method, then this should be tried with p̄'s at LEAR. The impact in meson spectroscopy of differential measurements with spin polarization of pp̄ would be dramatic, both in production and in formation measurements, and it would also be important to extend differential measurements at energies higher than those accessible at LEAR.

Consider, for instance, that in charmonium spectroscopy, when switching to initial singlet states, J/ψ and χ states would be completely suppressed for 100% polarization. Remarkably, the groups that are actively pursuing the work on developing polarized $\bar{p}$ beams are driven by the physics motivation of using polarized $\bar{p}$'s in order to study polarization effects in elastic scattering, charge exchange, and total cross-sections. These last topics have been given low priority at the Cogne meeting[2]; nevertheless, a working technique for polarizing stored $\bar{p}$'s would be a superb spin-off of this research motivated by $N\bar{N}$ reaction dynamics. This would be an example of the usefulness of having a composite user population at the LEAR facility. This could be similar to the evolution of the use of the techniques that were necessary for studying $N\bar{N}$ interactions via protonium spectroscopy[120], which have developed[85,121] and permitted the meson spectroscopy work described in Section 4 and will plausibly allow the uncovery of new broad states in $p\bar{p}$ annihilations at rest.

In Ref. 111 we stated that spin polarization cannot be achieved in $p\bar{p}$ at rest. This may be partially wrong and we are at present considering ways to measure whether the combination of atomic collisions and annihilation widths (which might be different for same n, same L, different J^{PC} atomic levels) could cause the ratios between the populations of low n (e.g. $n = 2$), same L, different J^{PC} levels to vary as a function of the target density. According to the extent that this would occur, spin polarization for annihilation in P-wave would become available; its effects should be taken into account and corrected for in the analysis of differential measurement, and might eventually be directly exploited.

5.3. *Extension of the LEAR energy range*

The LEAR machine was designed with a collider-mode option so as to enable access to the charmonium states. The maximum design luminosity of 10^{29} cm^{-2} s^{-1} and the bunch length exceeding 1 m are not competitive nowadays for charmonium spectroscopy. The possibility of using the collider mode at lower luminosities, say 10^{28} cm^{-2} s^{-1}, but with shorter bunch length for meson spectroscopy in production was considered at the Tignes Workshop of 1985, in the context of the presentations of OBELIX[107] and the Crystal Barrel[102]. However, this option is not competitive with production experiments at the SPS and elsewhere. Moreover, it is also not convenient in the context of the ongoing programme, where the straight section of LEAR is occupied by JETSET, whose programme features unique possibilities in terms of energy resolution, which require beam time to be exploited fully.

Various versions of a new ring called SuperLEAR have been suggested and discussed on several occasions[54] to extend the energy regime for meson spectroscopy up to the charmonium region and beyond, and for other physics topics. Spectroscopy at SuperLEAR energies is beyond the scope of this review.

5.4. *LEAR for LHC*

The LEAR beam will be very useful for testing Large Hadron Collider (LHC) detectors viewing the interaction vertex (vertex detectors, tracking chambers, pre-shower detectors and crystal detectors) by using $p\bar{p}$ annihilations at rest in H_2 gas in the centre of the detector[15] because of several concurrent factors:

- high rates of interactions tunable from 10^4 to 10^9 s^{-1},

– absolutely isotropic distribution of the annihilation products probing all parts of the detector uniformly,
– fixed-target operation mode (easiness of access, several test stations possible),
– several calibration reactions available (e.g. $\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, K_SK_S, K_SK_L, $KK\pi$, $2\pi^+2\pi^-$, ...) for testing spatial resolution, vertex reconstruction, secondary vertex reconstruction, γ energy resolution, trigger systems, and data-acquisition systems,
– rare calibration reactions available (e.g. $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$) for testing trigger systems.

6. CONCLUSIONS

LEAR was proposed in 1977, approved in 1980, started operation in 1983 with the Antiproton Accumulator (AA) $\bar{p}$ source, and in 1987 the Antiproton Collider was added to the AA.

In a survey of LEAR physics given in 1987 at the PANIC Conference[51], we gave the following assessment of the results obtained up to that time:

'From the results listed it emerges that most of the new experimental features anticipated and hoped for at the time of the proposal of LEAR are verified experimentally: access to P- and S-wave annihilation in $p\bar{p}$ at rest in a H_2-gas target, access to the low-momentum unexplored energy region below 400 MeV, extremely high resolution for formation and threshold experiments. Exciting results are still missing in the field of exotics and meson spectroscopy, and pre-LEAR baryonium candidates (which indeed had weak statistical significance) have not been confirmed. However, the analysis of experiments capable of identifying clearly exclusive final states of annihilation at rest and in flight is generally not yet at the level of mastering fully the behaviour of detectors and of the associated reconstruction programs, and the regions immediately above and below the $2m_p$ threshold have not yet been explored even in inclusive channels. In the sector of NN interactions and meson spectroscopy the completion of the analysis of the large data sets collected by production and formation experiments can lead to a solid experimental input for the phenomenology of dynamics of strong interactions, to establish decay channels not yet measured of known mesons and possibly to identify new structures.'

In the same survey we drew the following conclusions: 'The analysis of pre-ACOL experiments is entering the phase of producing stable results. Important ones have emerged and exciting ones may be in the pipeline... The physics to come from LEAR may be commensurate to the unique opportunities offered by $\bar{p}$'s at low energies and by the CERN environment.'

In the following years LEAR indeed began to produce exciting results in the field of meson spectroscopy and is now instrumented with a new generation of spectrometers, which are initiating operations, which have performances for the measurement of final states of annihilation by far superior to the ones that have been phased out, and which have a chance of approaching the high-quality standards of the machine.

The possibility of studying P-wave annihilations with little S-wave contamination permits the production and easy identification of high-spin mesons such as the f_2 and the AX, which are not produced or are scarcely produced in S-wave annihilations.

In $\bar{p}p$ annihilations at rest, it is possible to change the distribution of the angular-momentum quantum numbers of the initial states. This allows one to study annihilation dynamics and, more important, i) to constrain the quantum numbers of not too broad structures by studying, in differential measurements, the variation of their production branching ratios, and ii) hopefully to identify broad structures otherwise unnoticeable in mass spectra (this might be the case for the ground-state scalar glueball). This feature, together with the extremely large event rate at rest is at present the most competitive one of LEAR in light-meson spectroscopy.

A new meson, the AX(1565), has been discovered and studied in $p\bar{p}$ annihilations at rest. It is produced in P-wave annihilations, mainly from 1^{++} initial states, and copiously in a H_2-gas target at NTP; it has been observed in its $\pi^+\pi^-$ decay channel by the ASTERIX experiment first, and then by OBELIX in the $\pi^+\pi^-\pi^0$ final state. The ASTERIX experiment has determined the following characteristics of the AX(1565): $I^G = 0^+, J^{PC} = 2^{++}, M = 1565$ MeV, $\Gamma = 170$ MeV. The Crystal Barrel experiment has observed and studied, in the $\pi^0\pi^0\pi^0$ final state of $p\bar{p}$ annihilations at rest in liquid H_2, a very clear structure AX(1520) in the decay mode $\pi^0\pi^0$ with most likely $J^{PC} = 2^{++}$ and a width $\Gamma = 120$ MeV. Moreover, the Crystal Barrel experiment observes in the final state $\pi^0\eta\eta$ a prominent $\eta\eta$ signal centred at 1560 MeV with a width less than 200 MeV. Whether the three states seen in the $\pi^+\pi^-$, $\pi^0\pi^0$, and $\eta\eta$ decay channels, or two of them, are the same or not is a matter to be assessed.

The AX mass region is full of structures seen at LEAR and in $\bar{p}d$ pre-LEAR experiments with bubble chambers in different decay channels. The mass differences reach 100 MeV for reported mass accuracies of 10 MeV or better, and the J^{PC} quantum numbers are in some cases different. The assumption that all these structures seen in $p\bar{p}$ and in $\bar{p}d$ are the manifestations of a single resonance is not justified at present. However, these structures have the characteristics of authentic signals and not of spurious effects, and do not need artificial confirmation. Instead, it is necessary to have several decay channels measured in the same conditions by the same apparata to see if one or more structures are present.

Let us go back to the AX seen in $\pi\pi$, which is a different state from the $f_2'(1525)$, and assume with caution that AX(1565) and AX(1520) are the same object. The fraction of P-wave annihilation in liquid H_2 is less than 10%, and the AX, which turns out to be produced mainly in P-wave annihilations, is seen in the $\pi^0\pi^0$ decay mode only because the $3\pi^0$ final state turns out to be nearly background-free. The fraction of P-wave annihilations rises to about 50% in gas at NTP and to about 90% in annihilations in gas at NTP with X-rays in coincidence. This makes the AX the dominant source of signal for the $\pi\pi$ channel in the mass range above 1500 MeV in $p\bar{p}$ annihilations at rest into three pions in low-density targets.

The physics interpretation of the AX is open, since the two isoscalar partners of the 2^{++} nonet are well established. Since the AX has not been seen in radiative J/ψ decays, the glueball hypothesis is not favoured, but it is not possible with the available experimental information to tell whether the AX is a radial excitation of a 2^{++} isoscalar or a $qq\bar{q}\bar{q}$ four-quark state or a baryonium ($p\bar{p}$ state strongly bound by attractive nuclear forces).

If the AX is a $q\bar{q}$ meson, it may have one preferred dominant decay channel, and its isoscalar partner should probably be found somewhere near to the $p\bar{p}$ threshold.

If the AX is a $qq\bar{q}\bar{q}$ state or a baryonium it must have other and more frequent decay channels than the $\pi\pi$ ones.

If the AX is a baryonium, the reaction $p\bar{p} \rightarrow \gamma$ + AX should be observed.

If the AX is a glueball it might happen that the ratio of the decay probabilities of AX into $\pi^0\pi^0$ and $\pi^+\pi^-$ no longer be 1/2[74].

The following experimental questions therefore require answers from the Crystal Barrel and OBELIX experiments:

ii) What is the value of the product of production branching ratio times decay branching ratio $BR(p\bar{p} \to \pi^0 AX) \cdot BR(AX \to \pi^0\pi^0)$ in a liquid target?

ii) What is $BR(p\bar{p} \to \pi^0 AX) \cdot BR(AX \to \pi^+\pi^-)$ in a liquid target?

iii) What is $BR(p\bar{p} \to \pi^0 AX) \cdot BR(AX \to \pi^0\pi^0)$ in a gas target?

iv) What is $BR(p\bar{p} \to \pi^0 AX) \cdot BR(AX \to \pi^0\pi^0)$ in a gas target with X-rays in coincidence?

v) The ratios $BR(AX \to \pi^0\pi^0)/BR(AX \to \pi^+\pi^-)$ measured in liquid, in gas, and in gas with X-rays in coincidence are equal?

vi) Same questions as (i)–(iv) for the K^+K^-, K_SK_S and $\eta\eta$ decay channels in $\pi^0 KK$ and $\pi^0\eta\eta$ annihilations.

vii) Same questions as (i)–(iv) for reactions $pp \to \gamma AX$, $AX \to 2\pi$.

viii) Are there other decay modes of the AX, and with which branching ratio? And, the same questions as (i)–(iv) for reactions $pp \to \gamma AX$, $AX \to 2\pi^+2\pi^-$.

ix) Is there a KK state in the reaction $pd \to p_{spect}\pi^- K^+K^-$ at rest?

x) Is there an enhancement of the ratio of the partial cross-sections of the two-body annihilation channels K^+K^-, K_SK_S, $\pi^+\pi^-$, $\pi^0\pi^0$ just above threshold?

The OBELIX experiment can and should study better the state observed at 1500 MeV in $\bar{p}d$ by ASTERIX and search in deuterium for the AX. This can be done by selecting low-momentum recoil protons measured in the SPC central detector and measuring $\bar{p}n$ annihilations into $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$, and $\pi^-\eta\eta$ (which can be equally well measured since the annihilation vertex and the (γ conversion points can be reconstructed accurately), and into $\pi^-K^+K^-$, $\pi^-K_SK_S$, and $3\pi^-2\pi^+$.

Concerning the E/ι, the situation is more and more interesting. A crucial feature shown by the XB data is that the signal in the E/ι energy region is the most intense of all signals in the inclusive single-gamma spectrum of J/ψ radiative decays. This is strong support for the glueball hypothesis. Moreover, the shape of the E/ι signal of the most recent MARK III and DM2 data indicates that the 1400–1460 MeV mass region contains more than one single 0^{-+} object. The ASTERIX experiment has given a confirmation of the 0^{-+} interpretation of the E discovered by Armenteros and co-workers, with a new method that exploits the possibility of changing the angular-momentum distribution of the initial state, by requiring protonium X-rays in coincidence and by applying, although only in part, the method of differential analysis. It is clearly very important to better understand the E/ι signal. The statistics of MARK III and DM2 are insufficient for complete partial-wave analysis. At LEAR, the Crystal Barrel and OBELIX will be able to collect large statistical data samples investigating the $KK\pi$ and the $\eta\pi\pi$ decay channels. It will be necessary first to collect data samples with low trigger bias, which permit measuring in more than one decay channel, and in the same detector, the absolute production times decay branching ratios for two different distributions of initial-state quantum numbers (liquid and gas targets for the Crystal Barrel, gas target and gas target + X-ray in coincidence for OBELIX). In data with X-rays in coincidence the D, which is at the limit of being believable in the ASTERIX data in gas, should rise up and the E be depressed by one order of magnitude with respect to data in liquid H_2. Subsequently, each experiment will be able to enhance seriously the statistics in decay channels where selective and efficient triggers will be available. The Crystal Barrel experiment will be able to trigger on charged, π^0, and η multiplicities. The OBELIX experiment will be able to trigger on charged multiplicities, on charged kaons, and on K_S's decaying into $\pi^+\pi^-$. If the E (or one of the signals in the E/ι region) is really a glueball, then the 0^{++} glueball state should lie at a lower mass and should be found. Since it has not been observed in radiative J/ψ decays, it may be rather broad, and then the differential measurements that are feasible with $p\bar{p}$ at rest will be crucial in order to identify the glueball ground state.

The LEAR facility is now instrumented with modern detectors. The Crystal Barrel and OBELIX are the main instruments for studying mesons produced in $p\bar{p}$ and $\bar{p}d$ annihilations, while JETSET is the main detector for formation measurements in the mass range 2000–2400 MeV.

Major developments have also been made or are in progress in order to better prepare or identify the initial state of annihilation:

i) For $p\bar{p}$ annihilation at rest, OBELIX has a new version of an SPC to be used as a vertex detector and X-ray drift chamber for protonium X-rays, which improves by one order of magnitude the granularity and the spatial resolution in the beam direction over the ASTERIX XDC/SPC, which permitted the observation of the AX state.

ii) In order to select $I = 1$ initial states, $\bar{p}n$ annihilations must be studied in $\bar{p}d$ interactions with full kinematical reconstruction of annihilation final states and a selection of events with low-momentum recoil protons. The hardware developments implemented successfully in the SPC of OBELIX and the software ones in progress aim at measuring accurately slow spectator protons down to below 100 MeV/c (by range and/or momentum combined with dE/dx measurements).

iii) The use of the jet-gas target allows a very good energy resolution of the initial state of $p\bar{p}$ annihilations in flight, which reflects in an extremely high energy resolution for formation experiments.

iv) Experiments are in progress at TSR and Indiana to assess the possibility of polarizing a $\bar{p}$ stored beam. If this turns out to be successful and a p beam can also be polarized, it will be possible to prepare spin singlet and spin triplet initial states of $p\bar{p}$ annihilation. This development is very challenging, but if it works it will be possible then to perform differential measurements acting on the spin of the initial state, and this would represent a major advance for meson spectroscopy with antiprotons. This advance would be superior to the one achieved with the XDC technique because differential measurements would become feasible in production with high rates at all energies. This would permit both access to and identification of ggg glueballs, which can have exotic quantum numbers.

We can anticipate a very productive future for light-meson spectroscopy with the new detectors at present on the floor. Some 10^7 minimum-bias events at rest, at two or three target densities, are necessary for determining the branching ratios of all exclusive annihilation channels that can be fully reconstructed, for establishing the product of production times decay branching ratios for all accessible intermediate states with a production branching ratio in excess of 10^{-3}, and for establishing their dependence on the distribution of initial states (which changes by varying the target density and by requiring X-rays of protonium in coincidence). Extrapolating from what occurred in ASTERIX, and considering that $BR_{AX} > 10^{-3}$, it is very likely that new states will emerge already from these data. Data samples of some 10^7 events should then be collected with more selective triggers that will accept events containing K or η in

of annihilation final states

the final state, and with and without the requirement of the presence of an X-ray in coincidence, independently of the request for the final state. The efficiency, the rejection power, and the biases of each trigger can be studied by flagging the trigger in data collected with minimum-bias or low-bias triggers. Since typically the experiments can write 10 events per second or more on cassette, the data-taking time for a high-statistics run is between one week and one month. For triggers with rejection power at the level of 10^3 and efficiencies at the level of 1% for a structure produced in $\bar{p}N$ annihilations at rest, some 10^5 events will be present in the signal. For narrow structures this will enable quantum-number determination via spin-parity analysis and differential-production analysis. For broad structures this will enable their observation by differential analysis.

An ambitious programme requires a community motivated to exploit and improve its instruments. At LEAR there are three main lines of extension represented by: i) upgrading of the detectors that are presently on the floor, ii) extension of the control of the discrete quantum numbers of the initial state, which permits differential measurement, and iii) extension of the accessible energy range.

Operation of LEAR at the lowest reliable momentum is most advantageous for experiments at rest. Extension of the LEAR operation to higher energies is possible in the collider-beam mode, but not competitive, in terms of luminosity and length of the interaction region, with jet target operation at a dedicated $\bar{p}$ ring with energy higher than LEAR.

Soon $p\bar{p}$ collider operation at the CERN SPS will stop for physics runs. LEAR will then be the only user of the $\bar{p}$ source. LEAR operation will be possible at high intensities all the year round, and will be continued on the medium and long term, provided the physics interest is strong enough to justify the operation costs in the context of an acute need for resources for the completion of the LEP 200 upgrading and for the construction of the LHC. The facts reported in the preceding sections demonstrate that the results and the unique possibilities in light-meson spectroscopy at LEAR alone call for a long-term continuation of the work with the new detectors installed on the floor and with the new experimental approaches whose effectiveness has been demonstrated, but not yet systematically exploited. This work should be done not only with the aim of finding exotics but also of really studying their spectroscopy. The issue is a fundamental one on qualitative grounds, namely a clear-cut demonstration of the direct coupling of gluons that would be proved unambiguously by the demonstration of the existence of glueball and/or hybrid states with quantum numbers not accessible to $q\bar{q}$ systems. (This would complement the recent beautiful results on multijet production and angular distributions at LEP and at the $p\bar{p}$ colliders). The issue is also a quantitative one on the long term as calculations of glueball states on fundamental grounds are likely to become precise before those of the spectrum of light $q\bar{q}$ mesons. When a quantitative agreement between an experimental candidate and a computed one will be reached, it will be crucial to have the facility active to be able to check states predicted by the theory and not yet observed. The differential measurements that are possible only at LEAR with high statistics offer the perspective of observing exotics also if they are rather broad. This permits having a long-term strategy of measurements and analysis. The failure of all tentatives of observing protonium K X-rays in liquid targets and of demonstrating the existence of baryonium via inclusive measurements has illustrated negatively the importance of having ambitious long-term experimental strategies, whilst the observations of the AX at LEAR have demonstrated the same thing positively.

Critical attention and more active contributions from theorists working in particle physics would be an asset for the community of LEAR interested in meson spectroscopy. This could be rewarding in view of the unique experimental possibilities in this field.

Every accelerator at a certain stage of its history becomes useful also as a test facility. LEAR is a decelerator. Amusingly, it can offer a superb test facility for LHC detector components facing the interaction vertex. Conversely, the detector technology that has to be developed for the LHC, used at LEAR, will enable glueballs to be shown on line on Saturday mornings guided tours at CERN.

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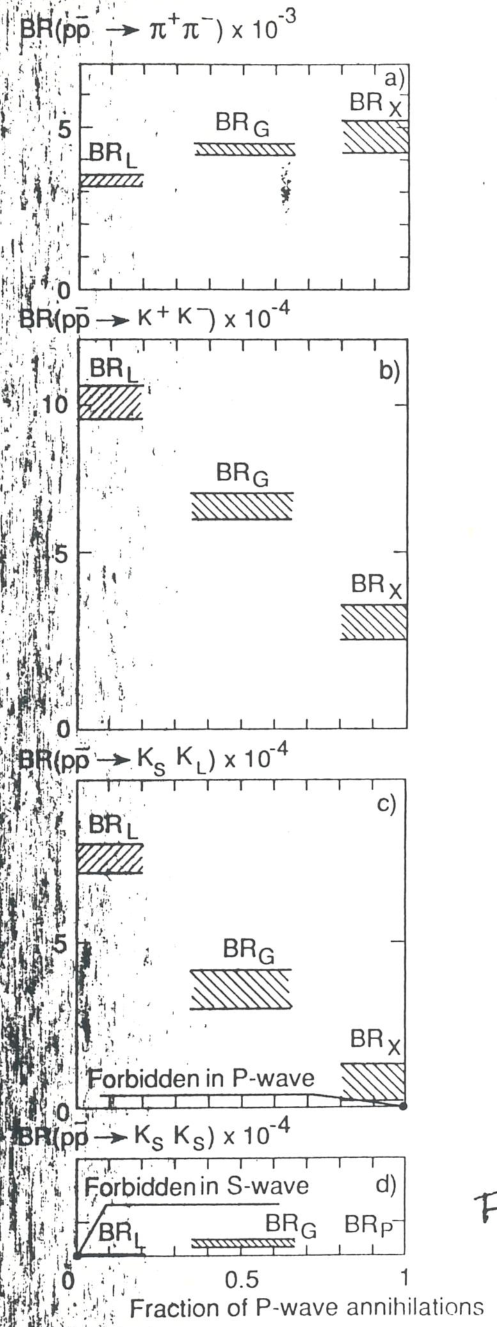
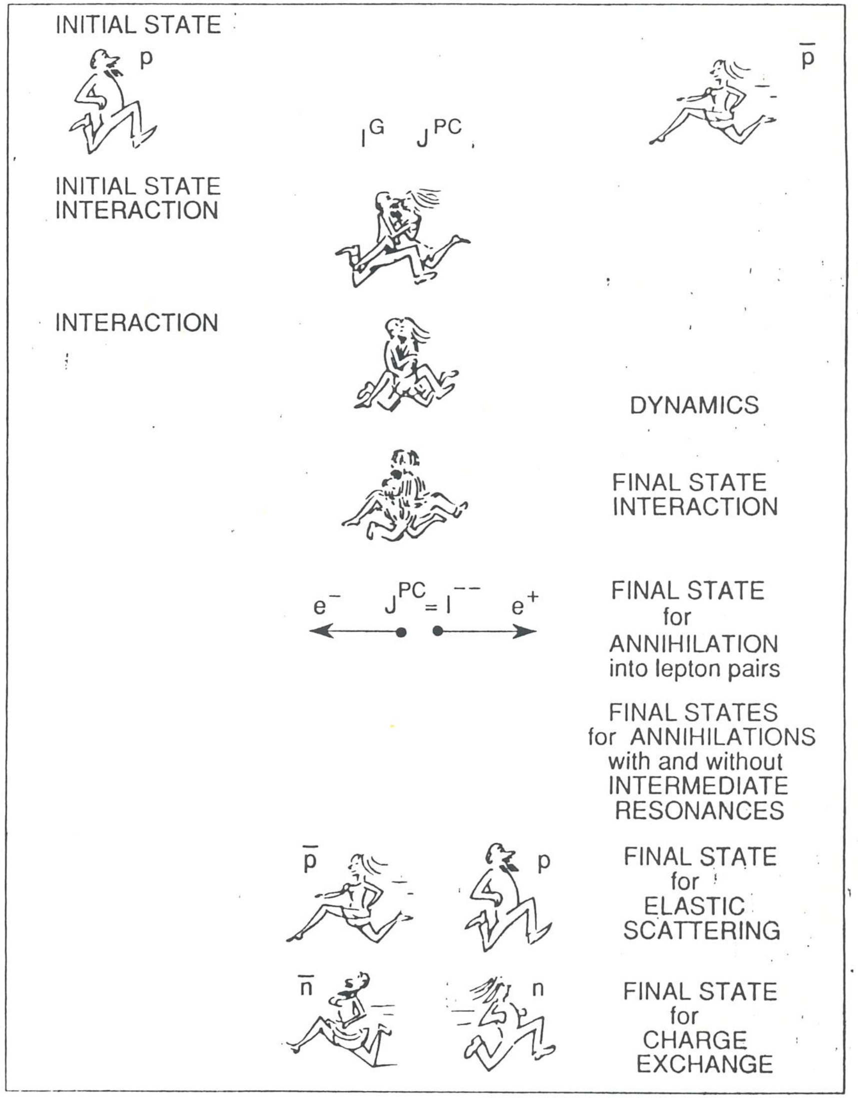


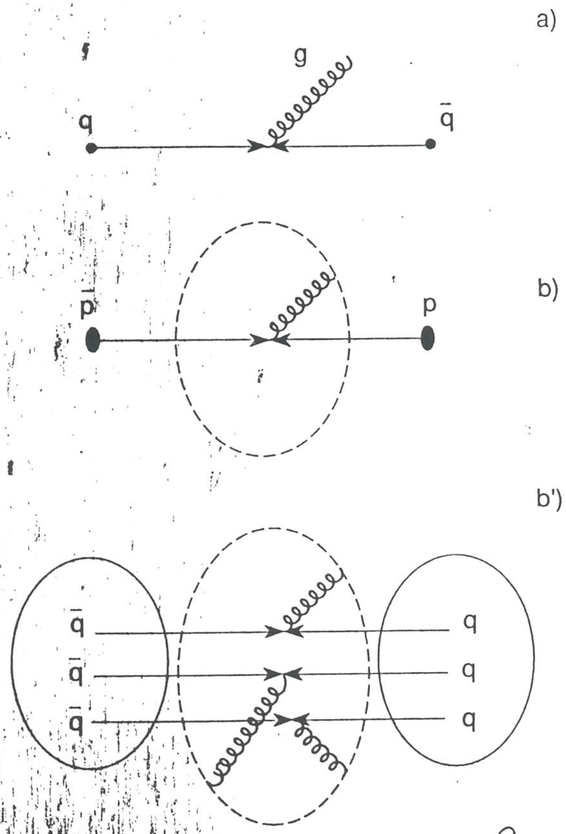
BR(p$\bar{p}$ → $\pi^+\pi^-$) x 10^{-3}
a)
BR$_X$
BR$_G$
BR$_L$
BR(p$\bar{p}$ → K^+K^-) x 10^{-4}
b)
BR(p$\bar{p}$ → $K_S K_L$) x 10^{-4}
c)
Forbidden in P-wave
BR(p$\bar{p}$ → $K_S K_S$) x 10^{-4}
d)
Forbidden in S-wave
BR$_P$
0
0.5
1
Fraction of P-wave annihilations

Fig 1



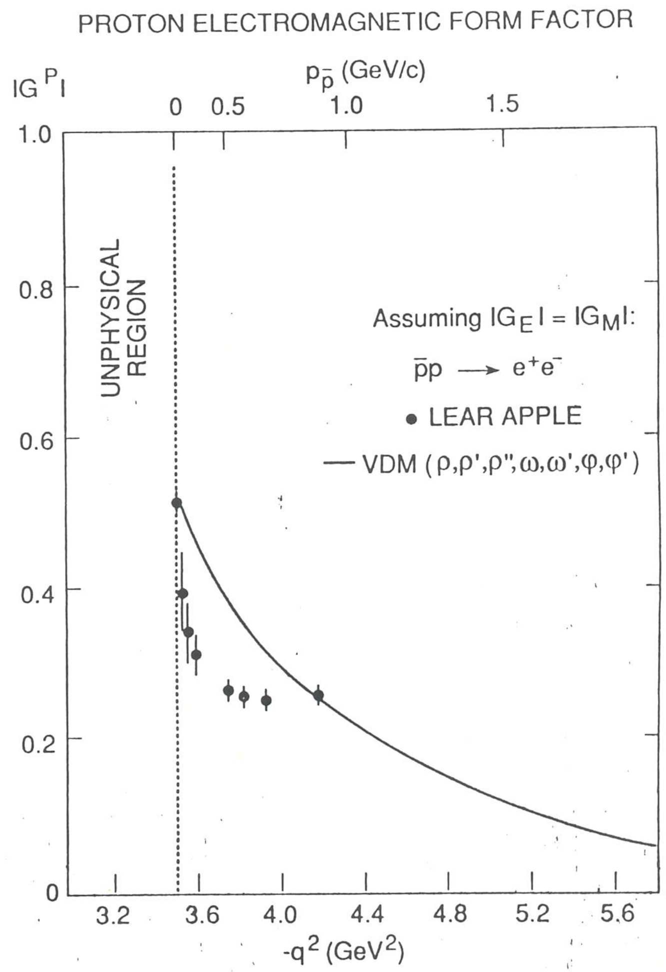
INITIAL STATE
p
$\bar{p}$
I^G J^{PC}
INITIAL STATE
INTERACTION
INTERACTION
DYNAMICS
FINAL STATE
INTERACTION
e^- $J^{PC} = 1^{--}$ e^+
FINAL STATE
for
ANNIHILATION
into lepton pairs
FINAL STATES
for ANNIHILATIONS
with and without
INTERMEDIATE
RESONANCES
$\bar{p}$ p
FINAL STATE
for
ELASTIC
SCATTERING
$\bar{n}$ n
FINAL STATE
for
CHARGE
EXCHANGE

Fig 2



a)
g
q
q̄
b)
p̄
p
b')
q̄
q̄
q̄
q
q
q

Fig 3



PROTON ELECTROMAGNETIC FORM FACTOR
IG P I
$p_{\bar{p}}$ (GeV/c)
0
0.5
1.0
1.5
1.0
0.8
0.6
0.4
0.2
0
UNPHYSICAL REGION
Assuming IG$_E$I = IG$_M$I:
p̄p ⟶ e⁺e⁻
• LEAR APPLE
— VDM (ρ,ρ',ρ'',ω,ω',φ,φ')
3.2
3.6
4.0
4.4
4.8
5.2
5.6
$-q^2$ (GeV^2)

Fig 4

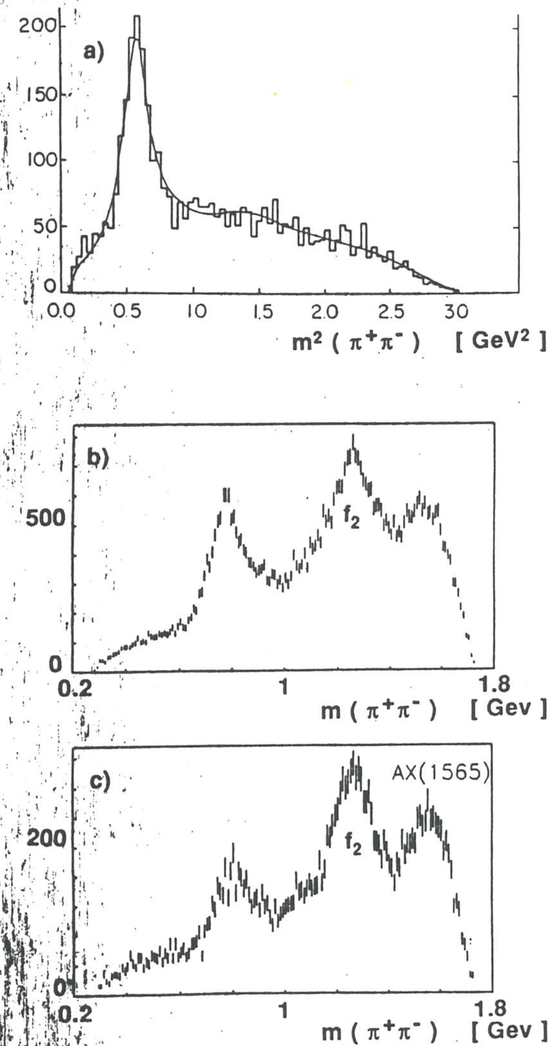

a)
m² (π⁺π⁻) [GeV²]
b)
f₂
m (π⁺π⁻) [Gev]
c)
AX(1565)
f₂
m (π⁺π⁻) [Gev]

Fig 5

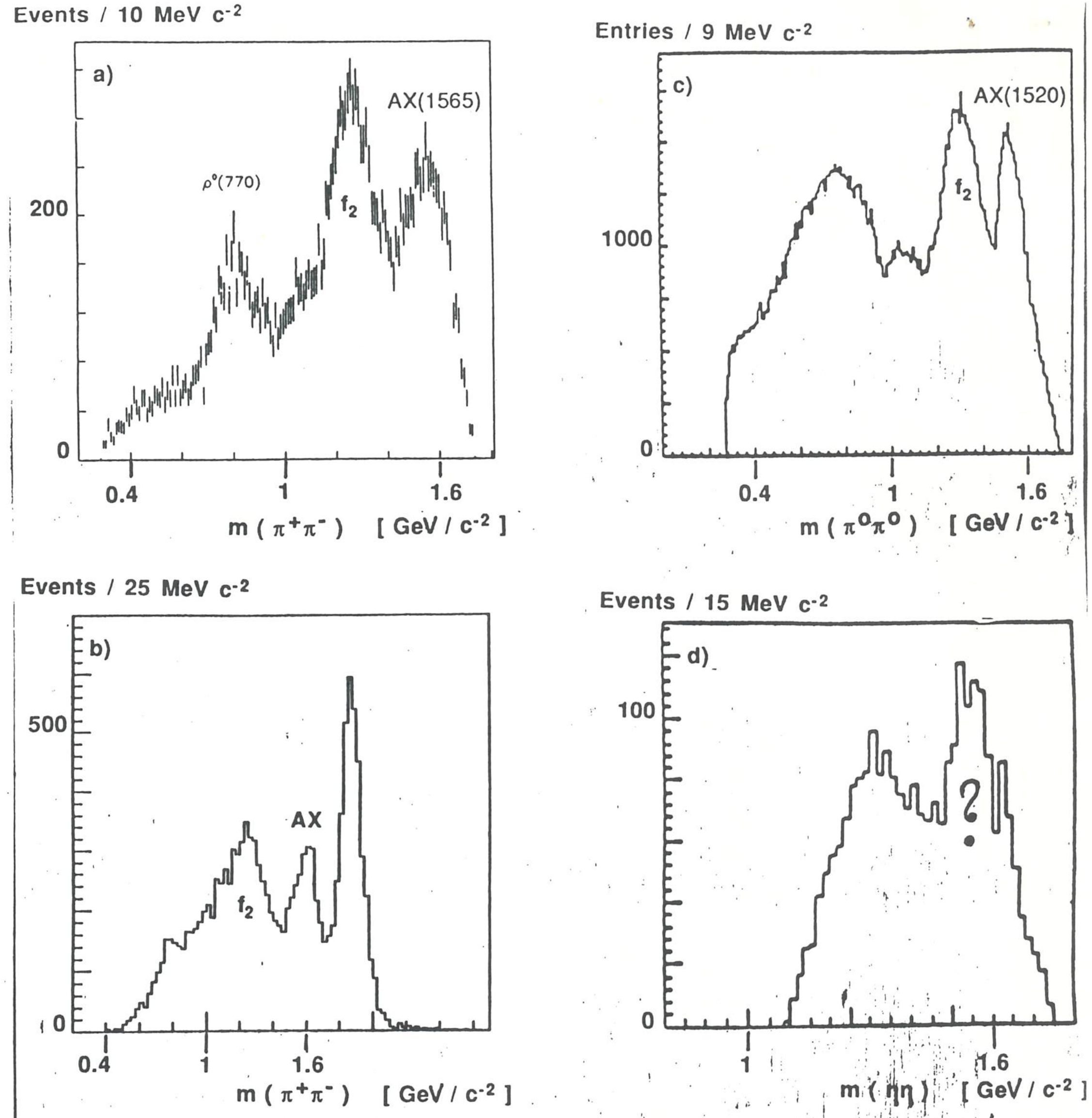

Events / 10 MeV c⁻²
a)
ρ°(770)
f₂
AX(1565)
m (π⁺π⁻) [GeV / c⁻²]
Entries / 9 MeV c⁻²
c)
AX(1520)
f₂
m (π⁰π⁰) [GeV / c⁻²]
Events / 25 MeV c⁻²
b)
f₂
AX
m (π⁺π⁻) [GeV / c⁻²]
Events / 15 MeV c⁻²
d)
?
m (ηη) [GeV / c⁻²]

Fig 6

288.

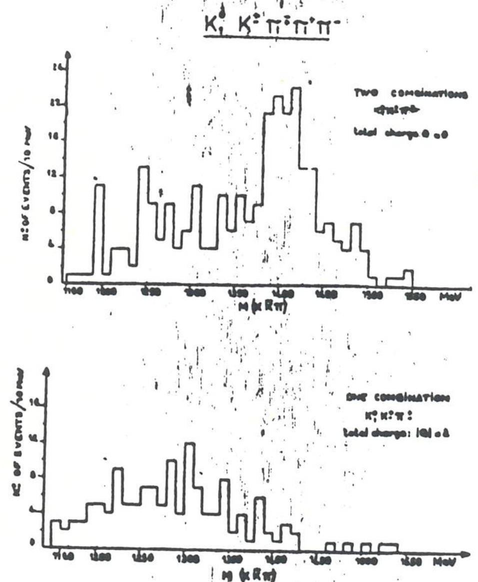


FIG. 1 $(K_1^0 K^{\pm} \pi^{\pm})$ and $(K_1^0 K^{\pm} \pi^{\pm})$ effective mass distribution of the $K_1^0 K^{\pm} \pi^{\pm} \pi^+ \pi^-$ events.

Fig 7

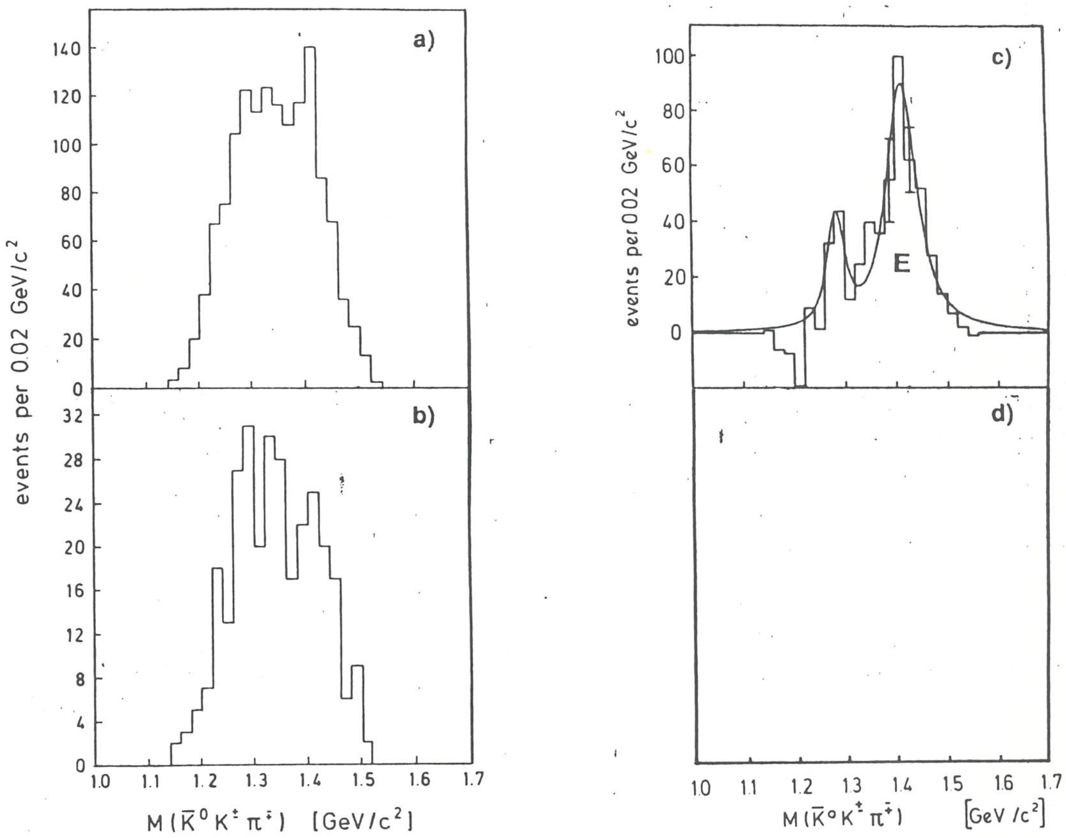


Fig 8

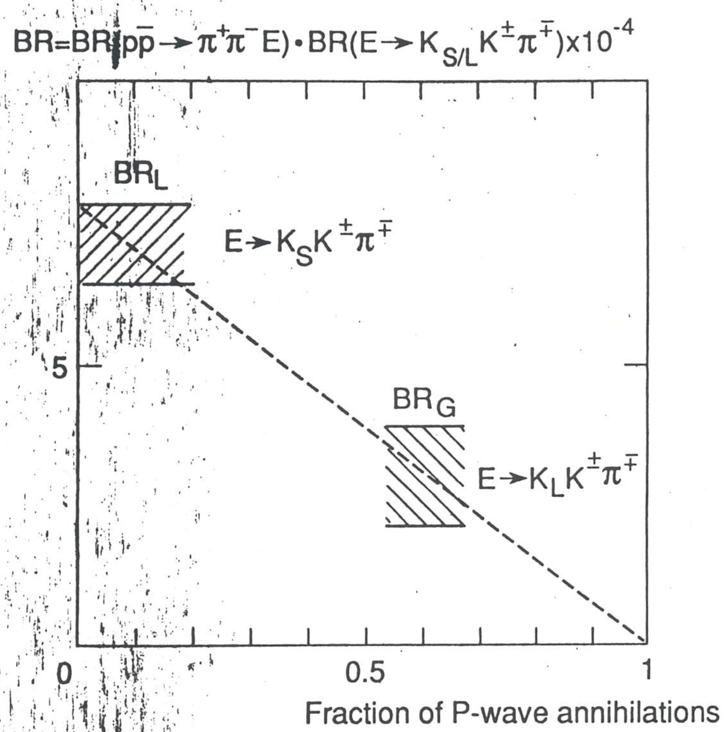
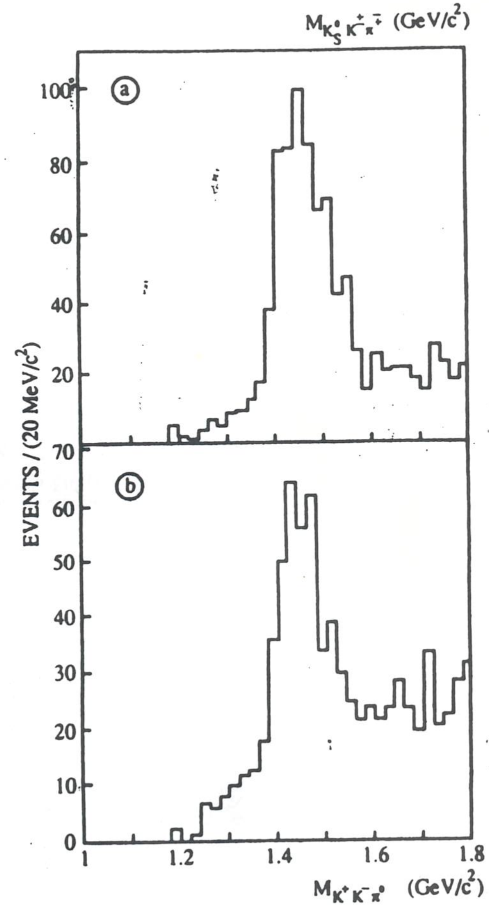


Fig 9



~~Fig.1~~ Mass distributions for the two $J/\psi \to \gamma K \bar{K} \pi$ modes:
(a) $K_S^0 K^\pm \pi^\mp$ channel;
(b) $K^+ K^- \pi^0$ channel.

Fig 10

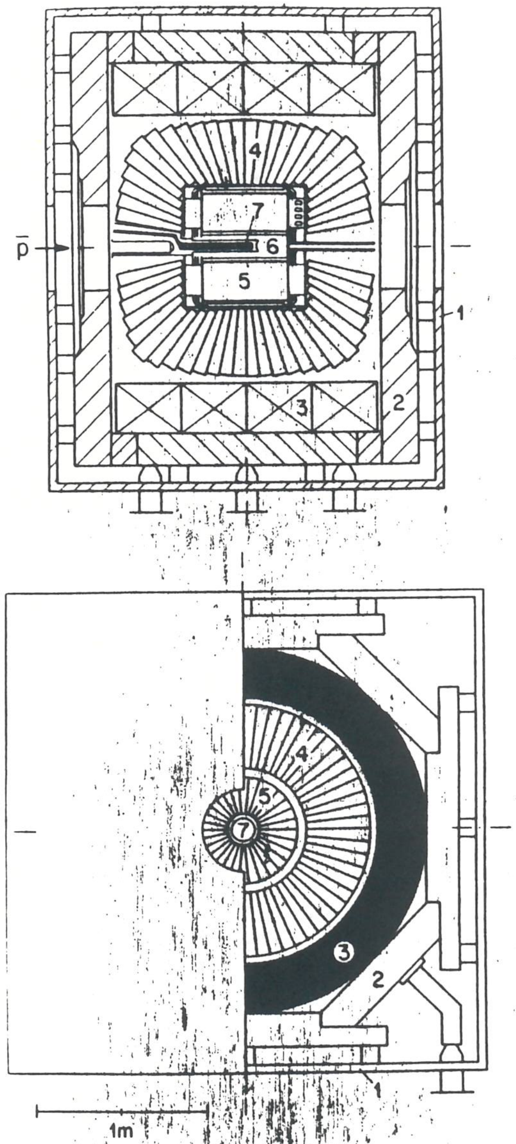


Fig 11

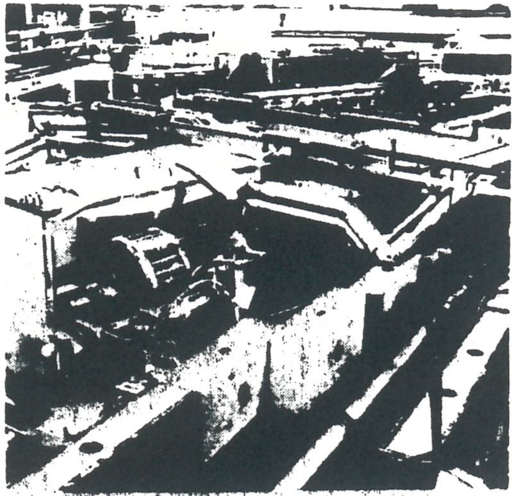
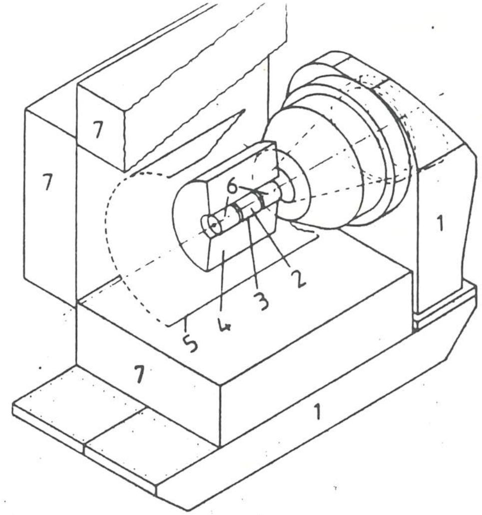


Fig 12



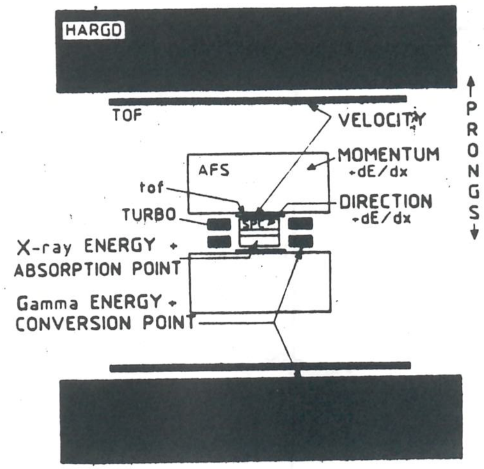


Fig 13

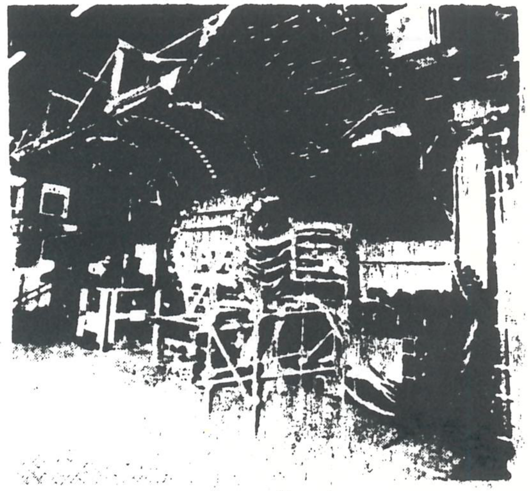


Fig 14a

Fig 14

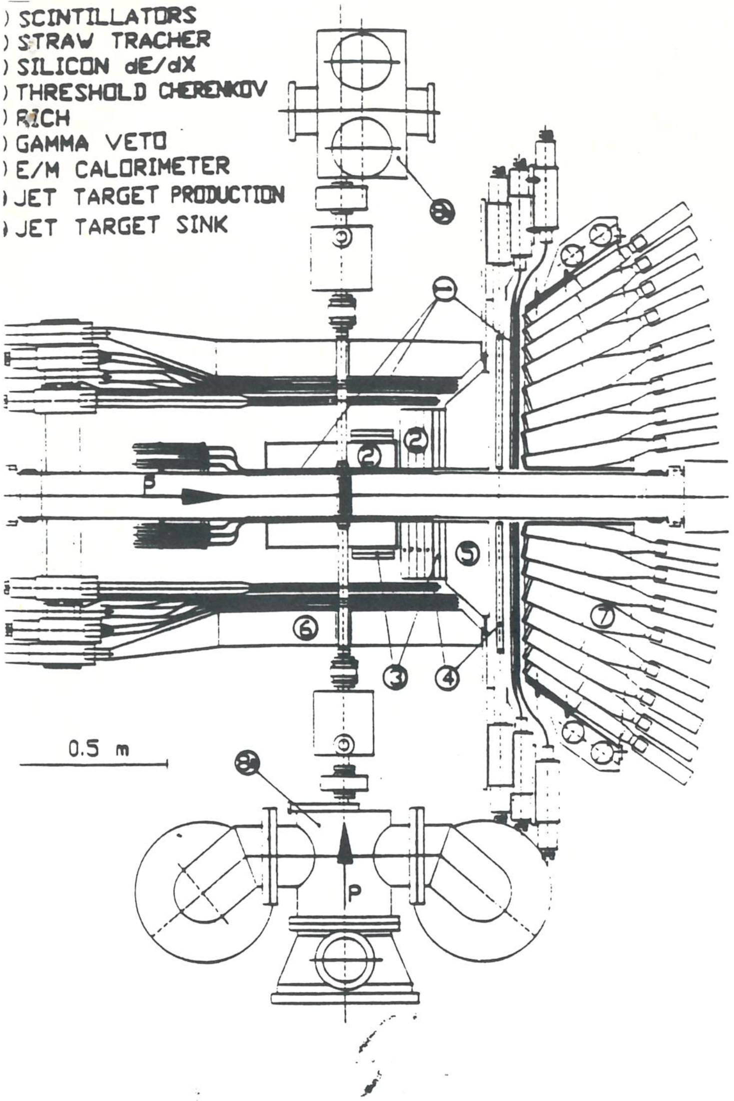

) SCINTILLATORS
) STRAW TRACHER
) SILICON dE/dX
) THRESHOLD CHERENKOV
) RICH
) GAMMA VETO
) E/M CALORIMETER
) JET TARGET PRODUCTION
) JET TARGET SINK
0.5 m
P
P

Fig 15

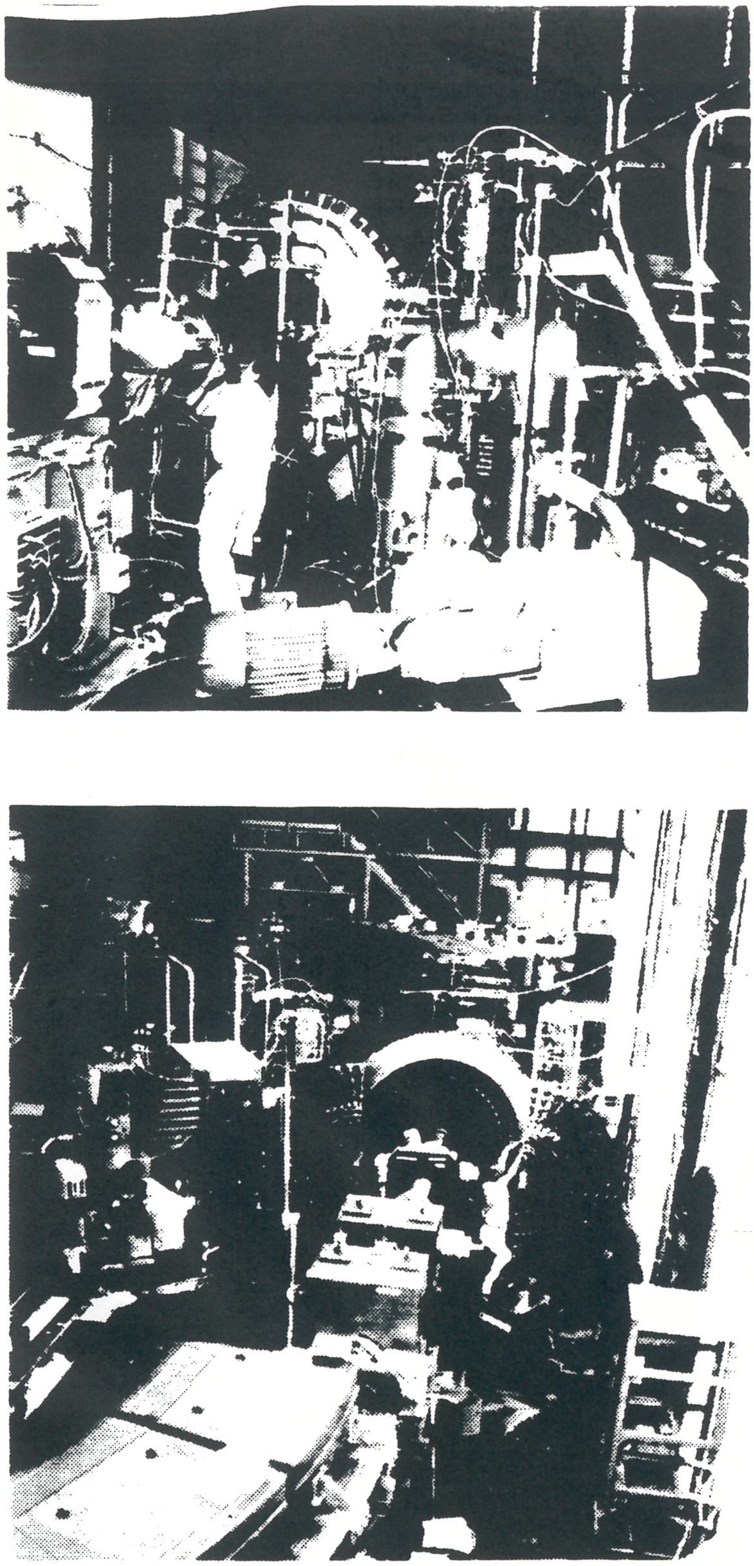


Fig 16