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LEAP '92: CONFERENCE SUMMARY

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ABSTRACT

We present a summary of the many new results in antiproton ($\bar{p}$) physics presented at the LEAP '92 conference, in the areas of meson spectroscopy, $\overline{N}N$ scattering, annihilation and spin observables, strangeness and charm production, $\overline{N}$ annihilation in nuclei, atomic physics with very low energy $\bar{p}$'s, the exploration of fundamental symmetries and interactions with $\bar{p}$'s (CP, T, CPT, gravitation), and the prospects for new $\bar{p}$ facilities at ultra-low energies or energies above the LEAR regime (≥ 2 GeV/c).

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1. INTRODUCTION

A wealth of new and stimulating experimental results in $\bar{p}$ physics, mostly obtained at the LEAR facility at CERN, was presented at the LEAP '92 conference. I will not proceed in a linear fashion to summarize each contribution. Rather, from the broad array of topics discussed, I will attempt to identify a few dominant themes. In addition to summarizing the essential new experimental results, I will try to provide some theoretical context whenever possible, emphasizing the "lessons" learned, and the open questions and future prospects.

In Section 2, I discuss the uses of antiprotons to test fundamental symmetries and interactions, in particular CP, T and CPT conservation and antigravity. Atomic physics aspects of $\bar{p}$ interactions are the subject of Section 3, including experiments with antihydrogen and the helium trap, as well as studies of low energy $\bar{p}$ collisions and energy loss. Section 4 is devoted to the most central theme of the conference, namely meson spectroscopy investigations with antinucleons. We summarize the recent evidence in $\overline{N}N$ annihilation for the existence of mesonic resonances which lie outside the established SU(3) nonets of quark–antiquark ($Q\overline{Q}$) states, and comment on possible theoretical interpretations of these data. In Section 5, the new data on $\overline{N}N$ scattering, annihilation and spin observables are reviewed, and the theoretical models for the description of this data are assessed. Recent results on two–body annihilation reactions, such as $\bar{p}p \to \pi^+\pi^-$, K^+K^-, $\bar{\Lambda}\Lambda$, etc., are summarized in Section 6. The interactions of antinucleons with nuclear targets form the subject of Section 7. New data in this area include the production of multiple strangeness in $\bar{p}Xe$ annhilation, studies of neutron radii and $\bar{p}$–induced fission, and annihilation at higher energies (5–9 GeV/c). Finally, in Section 8, some possibilities for future $\bar{p}$ facilities are mentioned.

2. TESTS OF FUNDAMENTAL SYMMETRIES AND INTERACTIONS

In this section, we discuss some of the preliminary results on CP and T violation obtained by the CP LEAR collaboration (talks by Schopper, Jon–And), precision measurements of the $\bar{p}$ mass as a test of CPT symmetry (Thibault, Gabrielse), possibilities for symmetry tests with antihydrogen (Hughes), CP violation and antigravity (Chardin), and the strange quark content and time–like form factor of the proton (Gabathuler, Kudryavtsev, Luppi).

The CP LEAR experiment (PS195) was described at this conference by A. Schopper and K. Jon–And. The idea of CP LEAR is to look at the annihilation reactions

$$\bar{p}p \to K^0 K^- \pi^+,\ \overline{K^0} K^+ \pi^- \tag{1}$$

at rest. The production of a K^0 or $\overline{K}^0$ is tagged by the detection of a K^- or K^+, respectively. The physical states K_S and K_L are given by

$$\begin{aligned} |K_S\rangle &= \frac{1}{\sqrt{2}}\left[(1+\epsilon_T-\delta_{CPT})\,|K^0\rangle + (1-\epsilon_T+\delta_{CPT})\,|\overline{K}^0\rangle\right] \\ |K_L\rangle &= \frac{1}{\sqrt{2}}\left[(1+\epsilon_T-\delta_{CPT})\,|K^0\rangle - (1-\epsilon_T+\delta_{CPT})\,|\overline{K}^0\rangle\right] \end{aligned} \tag{2}$$

If T is conserved, $\epsilon_T = 0$, while if CPT is conserved, then $\delta_{CPT} = 0$. T violation is signalled by a difference in the oscillation rates $R(\overline{K}^0 \to K^0)$ and $R(K^0 \to \overline{K}^0)$. Since $CP = +1$ for the $\pi^+\pi^-$ system, the decay $K_L \to \pi^+\pi^-$ is forbidden if CP is conserved. Experimentally, we have $BR(K_L \to \pi^+\pi^-)/BR(K_S \to \pi^+\pi^-) \simeq 2 \times 10^{-3}$, indicating CP violation. Defining

$$\eta_{\pi\pi} = \frac{\langle \pi\pi | H | K_L \rangle}{\langle \pi\pi | H | K_S \rangle} = |\eta_{\pi\pi}| e^{i\phi_{\pi\pi}}, \tag{3}$$

we expect

$$\eta_{\pi\pi} = \begin{cases} \operatorname{Im} \delta_{CPT} \left(\frac{2(m_L - m_S)}{(\gamma_L - \gamma_S)} - i \right) & (\epsilon_T = 0) \\ \operatorname{Re} \epsilon_T \left(\frac{2i(m_L - m_S)}{(\gamma_L - \gamma_S)} + 1 \right) & (\delta_{CPT} = 0) \end{cases} \tag{4}$$

where $m_{L,S}$ and $\gamma_{L,S}$ are the masses and widths of $K_{L,S}$. Since the measured phase $\phi_{\pi\pi}$ is close to 45°, we see from (4) that the measured CP violation corresponds to T violation ($\epsilon_T \neq 0$), with CPT essentially conserved. A direct test of T violation is made by measuring the ratio

$$A_T = \frac{\overline{R}^+ \left(\overline{K}^0 \to \pi^- e^+ \nu_e \right) - R^- \left(K^0 \to \pi^+ e^- \bar{\nu}_e \right)}{\overline{R}^+ \left(\overline{K}^0 \to \pi^- e^+ \nu_e \right) + R^- \left(K^0 \to \pi^+ e^- \bar{\nu}_e \right)} \tag{5}$$

The preliminary value obtained by CP LEAR is

$$A_T = (8.5 \pm 7.6 \pm 18) \times 10^{-3} \tag{6}$$

By the end of 1993, it is anticipated that the statistical error will decrease to $\pm 1 \times 10^{-3}$. Note that if the $\Delta S = \Delta Q$ rule holds, we have

$$A_T \approx 4 \operatorname{Re}(\epsilon_T), \tag{7}$$

with no assumption of CPT invariance. The parameter x, defined by the amplitude ratio

$$x = A(\Delta S = -\Delta Q) / A(\Delta S = \Delta Q) \tag{8}$$

measures the breaking of this rule. The value of x is extracted from the measured asymmetries

$$\begin{aligned} A_\ell &= \left(\overline{R}^+ + \overline{R}^- - R^+ - R^- \right) / \left(\overline{R}^+ + \overline{R}^- + R^+ + R^- \right) \\ A_{\Delta m} &= \left(R^+ + \overline{R}^- - \overline{R}^+ - R^- \right) / \left(R^+ + \overline{R}^- + \overline{R}^+ + R^- \right), \end{aligned} \tag{9}$$

where A_ℓ depends on $\operatorname{Im} x$ and $A_{\Delta m}$ on $\operatorname{Re} x$. The preliminary CP LEAR results are

$$\begin{aligned} \operatorname{Re} x &= 0.11 \pm 0.07 \pm 0.02 \\ \operatorname{Im} x &= -0.022 \pm 0.032 \pm 0.019 \end{aligned} \tag{10}$$

Ultimately, the statistical errors are expected to decrease to ± 0.01 and ± 0.005 for $\operatorname{Re} x$ and $\operatorname{Im} x$, respectively. For comparison, the current values given by the Particle Data Group (PDG) are $\operatorname{Re} x = 0.006 \pm 0.018$ and $\operatorname{Im} x = -0.003 \pm 0.026$.

In addition, CP LEAR has measured the time dependent asymmetries

$$A_{+-}(t)=\frac{R\left(\overline{K}^0\rightarrow\pi^+\pi^-\right)-R\left(K^0\rightarrow\pi^+\pi^-\right)}{R\left(\overline{K}^0\rightarrow\pi^+\pi^-\right)+R\left(K^0\rightarrow\pi^+\pi^-\right)}$$

$$A_{+-0}(t)=\frac{R\left(\overline{K}^0\rightarrow\pi^+\pi^-\pi^0\right)-R\left(K^0\rightarrow\pi^+\pi^-\pi^0\right)}{R\left(\overline{K}^0\rightarrow\pi^+\pi^-\pi^0\right)+R\left(K^0\rightarrow\pi^+\pi^-\pi^0\right)} \tag{11}$$

From these, the CP–violating parameters $|\eta_{+-0}|$, $|\eta_{+-}|$ and ϕ_{+-} can be extracted, with an expected accuracy comparable or better than that given by the PDG.

A possible LEAR upgrade to study CP violation in Λ, $\overline{\Lambda}$ decays, after production in the $\bar{p}p\rightarrow\overline{\Lambda}\Lambda$ reaction, was described by M. Chanel. At the DAØNE facility, under construction at Frascati, the $e^+e^-\rightarrow\phi\rightarrow K_LK_S$ process will be used to investigate CP violation in the $K^0-\overline{K}^0$ system. The idea is to tag K_L production by detecting K_S decay on the other side. This promising effort was discussed in detail by G. Capon.

G. Chardin presented a fascinating exposé of the possible connection between CP violation and antigravity, re–examining the old argument of Good [1] that an energy difference between K^0 and $\overline{K}^0$ in a gravitational field would induce K_S regeneration. Chardin points out that although general relativity incorporates the equivalence principle, it also allows the possibility of repulsive gravitation (antigravity), via the Kerr solution. The existence of antigravity implies CPT violation, i.e., the CPT theorem does not hold in curved space time. A recent review is due to Nieto and Goldman [2].

CPT invariance is a property of local quantum field theories, deduced from Lorentz invariance, the spin–statistics theorem, and the assumption of Hermitian and local couplings of finite order. A consequence of CPT is the equality of particle and antiparticle masses ($\Delta m=m_{\bar{p}}-m_p=0$). The status of measurements of the $\bar{p}$ mass was described at this conference by G. Gabrielse and C. Thibault. The LEAR experiment discussed by Thibault (PS189) involves the use of a radio–frequency mass spectrometer. A preliminary PS189 result of $\Delta m/m=9.2\pm9.5\times10^{-8}$ was cited, representing a one day $\bar{p}$ run. In a one week run, an accuracy of $\pm2\times10^{-8}$ is expected. The beautiful experiments involving $\bar{p}$'s in a Penning trap were described by Gabrielse. The trapping technique offers the possibility of measuring $\Delta m/m$ to extremely high precision, of order 10^{-11}. For comparison, $\Delta m/m<4\times10^{-8}$ for e^+-e^-. Gabrielse *et al.* have estimated the limit $|\frac{\omega_c(p)-\omega_c(\bar{p})}{\omega_c(p)}|\leq4\times10^{-8}$ for the equality of cyclotron frequencies ω_c for p and $\bar{p}$.

The study of antihydrogen ($\overline{H}^0=\bar{p}e^+$) offers fascinating possibilities for precision tests of CPT symmetry, gravitational interactions of antimatter and the weak equivalence principle. The theoretical as well as experimental aspects of $\overline{H}^0$ physics were the focus of the talk by R. Hughes, while the various techniques proposed for $\overline{H}^0$ production were outlined by C. Zimmerman.

CPT symmetry implies that H^0 and $\overline{H}^0$ have the same level structure. High precision tests of this could come from a comparison of transition energies, for instance $2S\rightarrow1S$. Hughes also mentioned tests of the weak equivalence principle with $\overline{H}^0$, for instance the comparison of red shifts of transitions in H^0 and $\overline{H}^0$. Hughes and Holzscheiter [3] have recently discussed a null red–shift experiment. These fundamental symmetry tests await the successful fabrication of $\overline{H}^0$, which presents a difficult challenge.

Although not strictly related to symmetry tests, we include in this section a review of the contributions related to the structure of the proton, namely the questions of the strange quark content (Gabathuler) and the time–like form factor (Kudryavtsev, Luppi) of the proton.

Gabathuler reviewed the experimental evidence relating to the question of $s\bar{s}$ pairs in the proton, which includes both hard processes (deep inelastic lepton scattering, neutrino elastic scattering) and soft processes (πN scattering σ term, baryon magnetic moment, $\bar{p}p$ annihilation processes). In $\bar{p}$ reactions, possible signatures of $s\bar{s}$ content include:

1. OZI rule violations (example: $\pi\phi/\pi\omega$ ratio)
2. anomalies involving specific strange particle annihilation modes (example: backward peak in $\bar{p}p \to K^-K^+$, not produced in optical model fits, $\bar{p}p \to \overline{\Lambda}\Lambda$ singlet fraction)
3. processes involving η, η' production (example: $\pi^0\eta'/\pi^0\eta$ ratio).

Although $\bar{p}$ processes have been touted as a promising probe of $s\bar{s}$ content [4], the situation remains unclear, and other explanations of the "anomalies" have been advanced [5]. For instance, the analysis of η'/η ratios presented by Noble ($\pi^0\eta'/\pi^0\eta$, $\eta'\eta/\eta\eta$, $\omega\eta'/\omega\eta$) yields a pseudoscalar mixing angle $\theta_{\rm PS} = -(17.3 \pm 1.8)^\circ$, consistent with the standard value $\theta_{\rm PS} \simeq -20^\circ$ [6]. This analysis assumes no $s\bar{s}$ content in the p or $\bar{p}$, and the validity of the quark line rule [7].

The electromagnetic form factors of the nucleon in the space–like region are well measured via the reactions $e^-p \to e^-p$ and $e^-d \to e^-d$. Luppi described recent results for time–like form factors, obtained with the $\bar{p}p \to e^-e^+$ reaction by the APPLE (PS170 at LEAR) and E760 (Fermilab) collaborations, and via the process $e^-e^+ \to \bar{n}n$ by the FENICE (Frascati) group. Some of these results have been recently published [8]. The data are consistent with the equality of electric and magnetic form factors ($G_E = G_M$). The FENICE data show that $|G^n_M| = |G^n_E| \approx 0.42 \pm 0.06$ at $\sqrt{s} = 2$ GeV, so $|G^n| > |G^p|$. The E760 data at higher momentum transfer ($8.9 \le Q^2 \le 13$ GeV^2) display a flat behavior of $|G^p_M|Q^4/\mu_p$, i.e., $|G^p_M| \sim 1/Q^4$. Near threshold, the proton factor, deduced from $\bar{p}p \to e^-e^+$, appears to show a sharp rise. Kudryavtsev questioned this conclusion, presenting an analysis in which the form factor is rather smooth near threshold. In this analysis, the extraction of $|G|$ is influenced by the ratio $x = \Gamma(^3S_1)/\Gamma(^1S_0)$ of widths of the initial $\bar{p}p$ atomic states; an estimate $x \approx 0.4$ was given, leading to $|G^p_{E,M}| \approx 0.39$ at threshold, rather than the value 0.53 (if $x = 1$ is assumed). This issue led to a lively discussion, with Dalkarov presenting an alternate viewpoint involving an $\overline{N}N$ quasinuclear state near threshold.

3. ATOMIC PHYSICS ASPECTS OF $\bar{p}$ INTERACTIONS

Several topics in atomic physics, as related to $\bar{p}$'s, were discussed at this conference. As mentioned in the last section, antihydrogen ($\overline{H}^0$) is an atomic system of considerable interest in terms of tests of fundamental symmetries. Zimmerman discussed a number of techniques for $\overline{H}^0$ production, and reviewed some of the talks presented at the Antihydrogen Workshop [9]. Several mechanisms could be used to produce $\overline{H}^0$:

$$\bar{p} + e^+ \to \overline{H}^0 + \gamma \tag{12a}$$

$$\bar{p} + e^+ + e^+ \to \overline{H}^0 + e^+ \tag{12b}$$

$$\bar{p} + (e^+e^-) \to \overline{H}^0 + e^- \tag{12c}$$

$$\bar{p} + (e^+e^-)^* \to \overline{H}^{0*} + e^- \tag{12d}$$

$$\bar{p} + Z \to \overline{H}^0 + e^- + Z \tag{12e}$$

The radiative capture reaction (12a) is the simplest two body process, but its rate is rather slow. The rate for the three-body reaction (12b) varies as $n_e^2 T^{-9/2}$ where n_e is the positron density and T is the temperature; for low T or large n_e, it dominates radiative capture, which behaves as $n_e T^{-1/2}$. The rates for (12c,d), which involve the ground state (e^+e^-) of positronium or an excited state $(e^+e^-)^*$ are favorable ($\sigma_{e^+e^-} \geq 10^5 \sigma_\gamma$), but experimentation with (e^+e^-) is difficult. The idea of laser-induced formation (12d) is to use an excited state $(e^+e^-)^*$ with $n > 0$ and thereby increase the cross section, since $\sigma_{(e^+e^-)^*} \sim n^4 \sigma_{e^+e^-}$. The production process (12e) on a nucleus Z can be thought of as follows: in passing by the nucleus, the $\bar{p}$ sees a pulse of virtual photons with a frequency distribution given by the Fourier transform of the time dependent Coulomb potential. One of these photons can convert to an e^+e^- pair, with the e^+ being captured to form $\overline{H}^0$.

As emphasized by Zimmerman, a number of practical difficulties remain to be dealt with before $\overline{H}^0$ can be successfully produced. $\overline{H}^0$ may be created in a trap, and once produced, it remains in a static magnetic trap. Various cooling techniques for $\overline{H}^0$ were mentioned, including evaporative cooling (out of reach), "mix-cooling" of $\overline{H}^0$ in H^0-gas (inefficient), optical cooling (suitable for reaching 10 mK energies) and adiabatic cooling (may reach the μK regime).

Uggerhøj reported on results from LEAR experiment PS194, relating to the measurement of stopping powers and single ionization cross sections for $\bar{p}$'s at low energy. Lodi Rizzini described related phenomena studied by the OBELIX collaboration. The problem of stopping power is an old one. A difference in stopping power for positive and negative particles (the Barkas effect [10]), is well known, but has only recently been demonstrated with $\bar{p}$'s vs. p stopping in H_2. The $\bar{p}$ stopping power is seen to display a sharp rise at low energies ($\leq$ 1 keV), and in the 10–120 keV range, it is systematically lower than that of the proton. There is also the phenomenon of inner-shell ionization for relatively charged particles, now being investigated with $\bar{p}$'s. It appears that the study of atomic collisions with antiprotons is a fertile field!

Widmann reported on the results of LEAR experiments involving $\bar{p}$ trapping in helium. It was discovered earlier at KEK [11] that when $\bar{p}$'s are brought to rest in liquid helium, about 3% of them survive for several μsec before annihilating, a much longer time than one would naively expect. This metastability arises because the stopping $\bar{p}$, in its final atomic encounter, replaces an electron in a nearby atom. The captured $\bar{p}$ populates a state with principal quantum number $n \approx (M^*/m_e)^{1/2}$, where M^* is the $\bar{p}$ reduced mass ($n \approx 38$ for $\bar{p} + {}^4\mathrm{He}$). This orbit has maximum overlap with the wave function of the displaced e^-, and the binding energies for $\bar{p}$ and e^- are nearly the same. In this region, the energy level spacing is about 2 eV, much smaller than the e^- ionization energy. Thus fast Auger transitions liberating the remaining e^- are energetically forbidden, and de-excitation of the system can only occur via rather slow radiative transitions, whose rate varies as n^{-3}. The degeneracy of different ℓ levels is lifted by the $\bar{p} - e^-$ interaction, and the coupling to surrounding atoms is weak because of the Pauli principle (unlike the $\bar{p}p$ atom, which has no electron). Thus Stark mixing in the $\bar{p}\mathrm{He}^+$ atom is suppressed. The physics of this intriguing system was explored theoretically in early papers by Russell [12] and more recently by Yamazaki and Ohtsuki [13]. In the LEAR experiments [14], $\bar{p}$ annihilation in ^{4}He gas (3 atm), ^{3}He gas (10 atm) and ^{4}He liquid was studied. The average annihilation time for $\bar{p}$ in ^{3}He is $15 \pm 2\%$ shorter than in ^{4}He, in accordance with the $(M^*)^2$ dependence expected theoretically [13]. Somewhat surprisingly, the spectrum shape and fraction of the metastable component is almost the same in ^{4}He gas and liquid, contradicting the notion of collisional de-excitation. Also, the time spectrum was found to be sensitive to small admixtures of foreign gases, raising the question of whether the metastability is altered by collisions with impurity atoms after formation.

4. MESON SPECTROSCOPY WITH ANTINUCLEONS

We now turn to one of the main themes of the conference, namely the use of antinucleons for studies of meson spectroscopy. Through the annihilation process, the $\overline{N}N$ system provides a rich source of mesons. The main features of annihilation at low energies can be accounted for via a sequential process $\overline{N}N \to M_1M_2$ (or possibly $M_1M_2M_3$), followed by the strong decay of the mesons M, typically into two or three pions. The quasi-two-body modes M_1M_2 stand out prominently in Dalitz plots of the invariant mass distributions of such two and three meson sub-systems. The two-body modes $\overline{N}N \to \pi X$, $\eta X \ldots$ are of particular interest in the search for new meson states X, where X denotes an object which lies outside the SU(3) nonets of quark-antiquark ($Q\overline{Q}$) states, for instance four quark states ($Q^2\overline{Q}^2$), hybrids ($Q\overline{Q}g$), glueballs (gg, ggg) and baryon-antibaryon ($\overline{B}B$) or meson-meson quasinuclear states ("quasi-molecules"). We will discuss the new data suggesting the existence of new states X.

$\overline{N}N$ annihilation is but one method, albeit a very fertile one, of producing new mesons X. Other reactions and decays which have been exploited extensively include

$$J/\psi \to \gamma X \to \gamma M_1 M_2 \tag{13a}$$
$$\pi^- p \to nX \to nM_1M_2 \to n + \gamma's \tag{13b}$$
$$\pi^+ p \to p_f \pi_s^+ X \to p_f \pi_s^+ \bar{p}p \tag{13c}$$
$$\pi^+ p \to \Delta^{++} X \to \Delta^{++}\pi^0\pi^0 \tag{13d}$$

Table 1: Some candidates for non-$Q\overline{Q}$ mesons

Mass (MeV)	$J^{\pi C}(I^G)$	Decay Channels	Experiment
1405	$1^{-+}(1^-)$	$\pi\eta$	GAMS; not seen by VES, $\bar{p}p$
1400–1500	two $0^{-+}(0^+)$, one $1^{++}(0^+)$	$K_S K^{\pm}\pi^{\mp}$, $\eta\pi^+\pi^-$	J/ψ decay, $\bar{p}p$
1480	$1^{--}(1^+)$	$\pi\phi$ (no $\pi\omega$ seen)	LEPTON -F; not in $\bar{p}p$
$\sim$ 1515	$0^{++}(0^+)$	$\eta\eta, \eta\eta'$	CB (no $\eta\eta'$ seen), GAMS
$\sim$ 1515	$2^{++}(0^+)$	$\pi^+\pi^-$, $\pi^0\pi^0$, $\eta\eta$, $\rho^0\rho^0$	ASTERIX, CB OBELIX, E760 (not in GAMS)
1650	$2^{++}(0^+)$	$\omega\omega$	GAMS, VES
1710	$0^{++}(0^+)$	$K\overline{K}$, $\pi\pi$, $\eta\eta$	J/ψ decay, not seen in $\bar{p}p$
1740	$0^{++}(0^+)$ or $2^{++}(0^+)$	$\eta\eta$ (no $\pi^0\pi^0, \eta\eta'$)	GAMS
1910	$2^{++}(0^+)$	$\omega\omega$, $\eta\eta'$ (no $\pi\pi$, $\eta\eta$, $K_S K_S$)	GAMS, VES

$$pp \to p_f p_s X \to p_f p_s \overline{K}K \tag{13e}$$
$$\gamma\gamma \to X \to M_1 M_2 \tag{13f}$$
$$K^- p \to \Lambda X \to \Lambda\overline{K}K \tag{13g}$$

A number of these reactions were discussed in detail in an excellent exposé given by Dunwoodie, which dealt with some of the general issues (partial wave analyses, etc.) in meson spectroscopy. Perepelitsa presented some new data from the WA56 collaboration on pion-induced reactions such as (13c), which give some indication of a narrow state ($\Gamma \simeq 20$ MeV) at 2.02 GeV decaying into the $\bar{p}p$ channel, but not seen in $\pi^+\pi^-$, $2\pi^+2\pi^-$ or K^+K^- decay modes. Shades of narrow baryonium! Peters provided an overview of exotic meson production, focusing on unusual decay patterns and production mechanisms. He discussed a number of candidates for exotic states X. Some of these are listed in Table 1. There are seen to be a number of scalar (0^{++}) and tensor (2^{++}) meson candidates which do not fit in SU(3) nonets. The problem is that these states are seen in some experiments and not in others, or they are detected in two different experiments, but show up in different decay modes (as an example, the 0^{++} near 1515 MeV is seen by GAMS in both $\eta\eta$ and $\eta\eta'$ modes, but only in $\eta\eta$ by Crystal Barrel (CB)). The only candidate for a state with $J^{\pi C}$ exotic quantum numbers (requiring a non-$Q\overline{Q}$ configuration) is the 1^{-+}

at 1405 MeV, seen only by GAMS [15]. This object has been avidly searched for in $\bar{p}p$ annihilation, in its $\pi\eta$ decay mode, but not yet seen. In general, there does not seem to be a good overlap between the candidates seen in different production channels for instance J/ψ decay, GAMS ($\pi^- p \to Xn$), $\gamma\gamma$ and $\bar{p}p$. The existence of a set of resonances which essentially couple only to the $\overline{N}N$ channel would be disturbing (unless one believes in baryonium!). It does seem necessary to try to integrate the results from $\overline{N}N$ annihilation with the rest of the field. At the moment, most of the states shown in Table 1 must be regarded as unconfirmed, and a unified theoretical description is certainly not in hand, although some interpretations have been suggested for specific states (glueballs, $Q^2\overline{Q}^2$ states, quasi–nuclear states, etc.). Note that the candidates of Table 1 have conventional hadronic decay widths, typically of order $\Gamma \simeq 100 - 200$ MeV, so this outburst of new states is not to be viewed as the rebirth of "narrow baryonium"!

4.1 Charmonium Spectroscopy with $\bar{p}p$

The formation of charmonium ($c\bar{c}$) states in $\bar{p}p$ annihilation has been studied in the E760 experiment at Fermilab [16]. The latest $c\bar{c}$ results were reported at this conference by Ceccucci, and data on the $\bar{p}p \to 3\pi^0$, $2\pi^0\eta$, $2\eta\pi^0$, 3η, $3\pi^0\eta$ and $4\pi^0\eta$ channels in the same energy range were presented by Hasan.

Charmonium spectroscopy provides a subtle interplay between perturbative and non–perturbative aspects of QCD. The $c\bar{c}$ and $b\bar{b}$ systems are unique in that the non–relativistic potential model yields a quantitative description of the non–perturbative part, and generates wave functions which enable one to perform realistic calculations of photon, lepton and hadronic decay branches. The new E760 data provide further tests of the $c\bar{c}$ potential, which consists of a scalar confinement potential (kr) and a Coulomb term ($-\frac{4}{3}\alpha_s/r$), plus spin–orbit, tensor and spin–spin contributions. As shown by Godfrey and Isgur [17], such a potential model is in fact successful for all mesons, even those with light quarks, such as the pseudoscalars.

From the $\bar{p}p$ initial state, one gains access to all $J^{\pi C}$ quantum numbers for a $Q\overline{Q}$ system, not just 1^{--} as for an e^+e^- collision in lowest order. Thus one can populate directly the $^1\mathrm{P}_1$, $^3\mathrm{D}_2$ or $^1\mathrm{D}_2$ $c\bar{c}$ states. For instance, the mass difference

$$\Delta M = M_{\mathrm{AV}}\left(^3\mathrm{P}_J\right) - M\left(^1\mathrm{P}_1\right) \tag{14}$$
$$M_{\mathrm{AV}}\left(^3\mathrm{P}_J\right) = \frac{1}{9}\left(M\left(^3\mathrm{P}_0\right) + 3M\left(^3\mathrm{P}_1\right) + 5M\left(^3\mathrm{P}_2\right)\right)$$

is of special interest, since it is sensitive to the presence of a vector component in the confinement potential. The widths of $c\bar{c}$ states are also of interest: the $\chi_1(^3\mathrm{P}_1)$ state is narrow ($\Gamma < 1.3$ MeV), since it must decay by three gluon emission, while η_c, χ_0 and χ_2 decay by two gluon emission and are consequently much broader. Precise width measurements would enable us to test QCD radiative corrections of higher order in the strong coupling constant α_s, i.e. the hadronic width Γ^h is of the form

$$\Gamma^h\left(c\bar{c}\right) = C\alpha_s^2|R_S\left(0\right)|^2\left(1 + \epsilon\alpha_s\right) \tag{15}$$

where C and ϵ are calculable constants and $R_S(0)$ is the radial-wave function at $r = 0$ for an s–state.

The masses and widths of the $\chi_1(^3P_1)$ and $\chi_2(^3P_2)$ states, as measured [16] by E760, are

$$M = \begin{cases} 3510.53 \pm 0.04 \pm 0.12 \quad \text{MeV} \quad (\chi_1) \\ 3556.15 \pm 0.07 \pm 0.12 \quad \text{MeV} \quad (\chi_2) \end{cases} \tag{16a}$$

$$\Gamma = \begin{cases} 0.88 \pm 0.11 \pm 0.08 \quad \text{MeV} \quad (\chi_1) \\ 1.98 \pm 0.17 \pm 0.07 \quad \text{MeV} \quad (\chi_2) \end{cases} \tag{16b}$$

We note the high precision of the results, due to the fact that the beam momentum spread is considerably smaller than the intrinsic width of $\chi_{1,2}$.

E760 has collected 16 pb^{-1} of data in the vicinity of the center of gravity of the χ_J states, looking for the $^1P_1$ state in the reactions

$$\bar{p}p \to h_c\left(^1P_1\right) \to \eta_c\gamma \to 3\gamma \tag{17a}$$
$$\to (J/\psi)\,\pi^0 \to e^+e^-\pi^0 \tag{17b}$$
$$\to (J/\psi)\,2\pi \to e^+e^-2\pi \tag{17c}$$

The analysis of this data is in progress, but there is evidence from reaction (17b) for the appearance of the $h_c(^1P_1)$ slightly below the average mass of the χ_J states, with a preliminary value of mass cited by Ceccucci of

$$M\left(^1P_1\right) \simeq 3526.2 \pm 0.15 \pm 0.2 \text{ MeV} \tag{18}$$

This corresponds to $\Delta M \approx -1$ MeV, at the edge of the range of predictions (-2 to -30 MeV) discussed by A. Martin at the SuperLEAR Workshop [18]. The width is found to be $\Gamma(^1P_1) \leq 1.1$ MeV. Since $(J/\psi)2\pi$ events (reaction 17c) were not seen, this sets a limit

$$BR\left(^1P_1 \to (J/\psi)\,2\pi\right)/BR\left(^1P_1 \to (J/\psi)\,\pi^0\right) \leq 0.18 \tag{19}$$

with 90% CL.

E760 has also collected data on $\bar{p}p \to \gamma\gamma$ in the $c\bar{c}$ region. From the analysis, they obtain

$$\begin{aligned} BR(\chi_2 \to \gamma\gamma) &= (1.73 \pm 0.54) \times 10^{-4} \\ BR(\eta_c \to \gamma\gamma) &= (3.3 \pm 1.4) \times 10^{-4} \end{aligned} \tag{20}$$

The latter value is very preliminary. E760 proposes to continue its studies with higher $\bar{p}$ flux ($\sim 5 \times 10^{31}$ $\text{cm}^{-2}\text{sec}^{-1}$) and increased acceptance, in order to measure the mass and width of the η_c and χ_0, confirm the h_c, and search for the η_c', $^1D_2$, and $^3D_2$.

4.2 Crystal Barrel (CB) Results

The evidence for new mesonic states, as observed by the Crystal Barrel experiment (PS197 at LEAR), was reviewed by I. Augustin. The reactions under study involve all neutral mesonic final states which ultimately decay to photons ($\leq 10\gamma$):

$$\bar{p}p \to 3\pi^0,\ 2\pi^0\eta,\ 2\pi^0\eta',\ \pi^0\eta\eta,\ \pi^0\eta\eta',\ 3\eta \tag{21}$$

Resonant structures were seen in the $3\pi^0$ [19], $2\pi^0\eta$ and $\pi^0\eta\eta$ channels; the following states were necessary to fit the data (M, Γ in MeV):

$$0^{++}(1^-):\ M = 982 \pm 2, \quad \Gamma = 54 \pm 10 \tag{22a}$$
$$0^{++}(0^+):\ M = 1430 \pm 25, \quad \Gamma = 250 \pm 50 \tag{22b}$$
$$0^{++}(0^+):\ M = 1560 \pm 25, \quad \Gamma = 245 \pm 50 \tag{22c}$$
$$2^{++}(0^+):\ M = 1515, \quad \Gamma = 120 \tag{22d}$$

The first two states (22a,b) correspond closely to the $a_0(980)$ and $f_0(1400)$ states given by the Particle Data Group. The $2^{++}(0^+)$ state was seen in the $\pi^+\pi^-\pi^0$ channel by the ASTERIX collaboration [20], and dubbed AX(1565). In earlier $\bar{p}d$ experiments at Brookhaven [21], evidence for a structure near the AX was seen in the $\bar{p}n \to 2\pi^-\pi^+$ channel. This $2^{++}(0^+)$ state cannot be identified with the $f_2'(1525)$, i.e. the $s\bar{s}$ partner of the $f_2(1270)$, since it is not observed to decay into the $K\bar{K}$ channel [21], and it lies too low in mass to correspond to a radial excitation of the $f_2(1270)$.

The $f_2(1515)$ is seen strongly in the $\pi^0\pi^0$ and $\pi^+\pi^-$ channel, but only weakly in $\eta\eta$. A state at essentially the same mass, and with the same decay pattern, was also seen by E760, as reported by Hasan. Although E760 has not yet given a spin assignment, it is likely that they are seeing the same object as CB. The preliminary decay ratio [22] is

$$\frac{BR(f_2(1515) \to \eta\eta)}{BR(f_2(1515) \to \pi^0\pi^0)} \simeq \begin{cases} 0.1 & \text{(PS197)} \\ 0.05 & \text{(E760)} \end{cases} \tag{23}$$

The scalar resonance $f_0(1560)$, on the other hand, decays strongly into $\eta\eta$ but not into $\pi^0\pi^0$ or $\eta\eta'$. CB obtains

$$\frac{BR(f_0(1560) \to \eta\eta')}{BR(f_0(1560) \to \eta\eta)} \leq 0.23\,(6\gamma)\,,\ 0.29\,(10\gamma) \tag{24}$$

The $\pi^0\pi^0$, $K\bar{K}$ and $\rho\rho$ decays are still under investigation. The scalar meson $G(1590)$ seen by the GAMS collaboration has a strikingly different decay pattern, with $\eta\eta'/\eta\eta \simeq 3$ and $4\pi^0/\eta\eta \simeq 0.8$. It is not clear what to make of this.

The CB collaboration is also actively pursuing the $1^{-+}(1^-)$ $\pi^0\eta$ resonance claimed by GAMS [15]. So far only the $a_0(980)$ has been extracted from the $\pi^0\eta$ mass plot, but the question of an exotic resonance in this channel is still open.

4.3. Results from OBELIX

The new results in meson spectroscopy from the OBELIX experiment at LEAR were presented by A. Lanaro. These dealt with a preliminary analysis of 2.3×10^6 $\bar{n}p$ annihilations in flight (220 MeV/c), focusing on the reactions

$$\bar{n}p \rightarrow 2\pi^+\pi^- \qquad (25a)$$
$$\bar{n}p \rightarrow 3\pi^+2\pi^- \qquad (25b)$$

A spin–parity analysis of the data on (25a) reveals the presence of a $2^{++}(0^+)$ resonance in the $\pi^+\pi^-$ system, with $M = 1502 \pm 9$ MeV and $\Gamma = 145 \pm 16$ MeV. This object, produced dominantly from the $\bar{n}p$ P–wave, is consistent with the $2^{++}(0^+)$ meson seen by ASTERIX, Crystal Barrel and E760.

The situation for the 5π channel (25b) is much less clear. Old bubble chamber results on $\bar{p}d$ [23] and $\bar{p}p$ [24] annihilation suggested the existence of a $0^{++}(0^+)$ state with $M = 1410$ MeV, $\Gamma = 90$ MeV [23] or $M = 1435$ MeV [24] and possibly a $2^{++}(0^+)$ state with $M \simeq 1500$ MeV [24], both decaying in the $\rho^0\rho^0$ channel. The analysis of the Brookhaven $\bar{p}d$ data by Bridges *et al.* [25] led to a $2^{++}(0^+)$ assignment for a resonance with $M = 1480$ MeV, $\Gamma = 120$ MeV, decaying into $\rho^0\rho^0$. A re–analysis of the Brookhaven data by Gasperi [26] strongly favors a $0^{++}(0^+)$ assignment rather than $2^{++}(0^+)$, and with a considerably different mass and width ($M = 1390$ MeV, $\Gamma = 310$ MeV).

A first analysis of the OBELIX data on 3π and 5π was published by Adamo *et al.* [27]. Lanaro presented the results of a more complete partial wave analysis. For (25b), it was assumed that the reaction proceeds through a quasi–two–body intermediate state $X^0\pi^+$, followed by $X^0 \rightarrow \rho^0\rho^0$, $\sigma\sigma \rightarrow 4\pi$, where σ represents the $\pi\pi$ s–wave interaction. The spin assignments 0^{++} and 2^{++} were tested for X^0, with 0^{++} being strongly preferred; they obtain $M = 1345$ MeV, $\Gamma \simeq 400$ MeV for $X^0(0^{++})$. A strong interference between the $\rho^0\rho^0$ and $\sigma\sigma$ decays is seen, and is purported to explain the distributions of the $2\pi^+$, $2\pi^-$ and $3\pi^-$ combinations without the need to introduce the Bose–Einstein correlations explicitly. At higher $\bar{n}$ momenta (large initial P–wave contribution), another structure is seen in the 4π spectrum; the angular distribution for its decay into $2\rho^0$ favors a $2^{++}(0^+)$ assignment.

The situation in the 5π channel remains somewhat unclear. One might wonder about the significance of a very broad ($\Gamma \approx 400$ MeV) state, described as a Breit–Wigner resonance, decaying below threshold into $\rho^0\rho^0$. The question of the $2^{++}(0^+)$ strength in the 4π channel is a critical one. Even if the $0^{++}(0^+)$ strength dominates, the decay $AX(1525) \rightarrow \rho^0\rho^0$ must still contribute at some level, and the possibility of *both* 0^{++} and 2^{++} resonances should be included in the analysis. If we argue that the $AX(1525)$ has $\pi\pi$ as the dominant decay mode, we run into several problems, since this $2^{++}(0^+)$ state should then be seen in $\pi\pi$ phase shift analyses and also in the $\gamma\gamma \rightarrow \pi\pi$ process, and it shows up in neither. The decays $AX(1525) \rightarrow \eta\eta$, $\eta\eta'$ are shown to be small by Crystal Barrel and E760, and the $\omega\omega$ mode must be small because of phase space restrictions. Thus $AX(1525) \rightarrow \rho\rho$ is likely to be the largest decay mode. For instance, the quasinuclear model [28] of the $AX(1525)$ predicts a value of about 2–3 for the $\rho\rho/\pi\pi$ ratio. According to Adamo *et al.* [27], if one attributes the entire strength of the peak in the 4π mass spectrum to the $AX(1525)$, a $\rho\rho/\pi\pi$ ratio of 7.6 ± 1.6 is obtained for its decay, larger than one would expect in any reasonable theoretical model. This again suggests that both 0^{++} and 2^{++} strength must be present in the 4π peak.

The data on $\gamma\gamma \to \rho\rho$ could shed some light on the $\overline{N}N \to 5\pi$ puzzle, assuming the same resonances are involved (a big assumption!), since there is also a strong peak near the $\rho\rho$ threshold. Unfortunately, the situation is also murky in the $\gamma\gamma$ case. Various partial wave analyses have found either 0^{++} dominance of $\gamma\gamma \to \rho^0\rho^0$ [29], both 0^{++} and 2^{++} contributions [30], or 2^{++} dominance [31].

4.4. Annihilation Modes with ϕ Mesons

The preliminary results from the JETSET collaboration (PS202) on the reaction $\bar{p}p \to \phi\phi$ were reported by M. Macri. The total cross section, measured in the energy range $2.18 \le \sqrt{s} \le 2.43$ GeV, is of order 1.2 - 1.7 μb. Note that the $\bar{p}p \to \phi\phi$ process is *not* double–Zweig–suppressed; if this were the case, we would expect a cross section of order $\tan^4(\theta - \theta_0)$. $\sigma(\bar{p}p \to \omega\omega) \approx 10$ nb, two orders of magnitude less than observed. Recently, Lu *et al.* [32] have estimated a $\bar{p}p \to \phi\phi$ cross section of 2 μb arising from second order processes involving a $\overline{K}K$ or $\rho\rho$ intermediate state (the dominant term is $\overline{K}K$), in agreement with the data. The JETSET collaboration paid particular attention to the region near the $\overline{\Lambda}\Lambda$ threshold at $\sqrt{s} = 2231.2$ MeV, where a structure may have been seen in the $\bar{p}p \to K_S K_S$ channel. The error bars on the preliminary JETSET data are still too large to draw any conclusion on the existence of resonances in the $\phi\phi$ system. Note that the allowed quantum numbers are

$$\begin{aligned} \phi\phi\,(\ell = 0) &: \quad 0^{++}(0^+), 2^{++}(0^+) \\ \phi\phi\,(\ell = 1) &: \quad 0^{-+}(0^+), 1^{-+}(0^+), 2^{-+}(0^+) \end{aligned} \tag{26}$$

In addition to the non–exotic quantum numbers 0^{++}, 2^{++}, 0^{-+} and 2^{-+}, which couple to the $^{13}\mathrm{P}_0$, $^{13}\mathrm{P}_2 - {}^{13}\mathrm{F}_2$, $^{11}\mathrm{S}_0$ and $^{11}\mathrm{D}_2$ states of $\bar{p}p$, respectively, $\phi\phi$ can also have the $J^{\pi C}$–exotic quantum numbers $1^{-+}(0^+)$. The exotic $\phi\phi$ configuration could be produced in the reaction

$$\bar{p}p\,({}^{33}\mathrm{P}_1) \to \left(\pi^0 + (\phi\phi)_{1^{-+}}\right)_{\ell=0} \tag{27}$$

The reaction (27) is certainly worthy of study.

In the quark model, the reaction mechanism for $\bar{p}p \to \phi\phi$ can be envisaged as the annihilation of three non–strange $Q\overline{Q}$ pairs, with the subsequent creation of two $s\bar{s}$ pairs. The intermediate state may be dominated by 0^{++} and 2^{++} glueballs. The possibility of a "gluon–rich" intermediate state provides much of the motivation for the study of the $\bar{p}p \to \phi\phi$ process. The reaction can also proceed via second order hadron exchange processes, for instance $\bar{p}p \to \overline{K}K \to \phi\phi$, as calculated by Lu *et al.* [32], or $\bar{p}p \to \overline{\Lambda}\Lambda$ $(K, K^*$ exchange) followed by $\overline{\Lambda}\Lambda \to \phi\phi$ (Λ exchange). The $\phi\phi$ final state could then reflect the presence of quasinuclear resonances or bound states in the $\overline{\Lambda}\Lambda$ system. Note, however, that a $^{13}\mathrm{S}_1 - {}^{13}\mathrm{D}_1$ $\overline{\Lambda}\Lambda$ state, proposed in [33] to explain a structure seen near threshold in the $\bar{p}p \to \overline{\Lambda}\Lambda$ reaction (see Section 6), does not couple to the $\phi\phi$ channel.

The results on final states with strangeness ($K\bar{K}\pi$, $K\bar{K}\pi\pi$, etc.) from Crystal Barrel and ASTERIX were reviewed by K. Braune. The ASTERIX data [34] in H_2 gas include the channels

$$\bar{p}p \rightarrow \pi^0\phi,\ \eta\phi,\ \pi^+\pi^-\phi,\ \pi^+\pi^-\pi^0\phi \tag{28}$$

with the $\phi \rightarrow K^+K^-$ mode detected. Crystal Barrel studied the $\pi^0\phi$ and $\eta\phi$ modes in LH_2, with $\phi \rightarrow K_LK_S$, $K_S \rightarrow 2\pi^0$ detected. In the most naive model, ϕ production from a non-strange initial state occurs only through the $u\bar{u}$, $d\bar{d}$ components of the ϕ. This yields the estimate

$$\frac{BR(\bar{p}p \rightarrow \phi M)}{BR(\bar{p}p \rightarrow \omega M)} \approx \tan^2(\theta - \theta_0) \approx (3-5) \times 10^{-3} \tag{29}$$

for a non-strange meson M, taking a deviation from ideal mixing of $\theta - \theta_0 \approx 3 - 4^\circ$. The measured ratios, except for $\phi\eta/\phi\omega$, are larger than (29), typically by a factor of 2–5, and in the case of $\phi\pi/\omega\pi$, by more than an order of magnitude. This apparent violation of the OZI rule is intriguing, and could have many causes, for instance $s\bar{s}$ content in the proton (4) or a resonance in the $\pi\phi$ system (5), among others. The fact that

$$BR\left(K^*\overline{K}^0\right)_{C=-1} : BR\left(\overline{K}^*K^0\right)_{C=-1} : BR\left(\pi^0\phi\right) \approx 1:1:1 \tag{30}$$

was interpreted by Braune as the effect of resonant final state interactions in the $K\bar{K}\pi$ system, rather than violation of the OZI rule. The most dramatic ratio is

$$\frac{BR\left(\pi^0\phi\right)/BR\left(\pi^0\omega\right)}{BR(\eta\phi)/BR(\eta\omega)} \approx 18.3 \pm 3.5 \tag{31}$$

to be compared to the value of unity expected on the basis of Eq. (29).

It has been suggested [5] that the observed enhancement in the $\bar{p}p \rightarrow \pi^0\phi$ channel may be connected with the $C(1480)$, a state with the quantum numbers of the $\rho\,[1^{--}(1^+)]$ seen by the Lepton–F collaboration [35] at $M = 1480 \pm 40$ MeV with $\Gamma = 130 \pm 60$ MeV, decaying predominantly into $\pi\phi$. This state has been looked for in the $\pi^+\pi^-\phi$ channel by ASTERIX and in $\pi^0\pi^0\phi$ by Crystal Barrel, but not seen. The limit quoted by ASTERIX is

$$BR\left(\bar{p}p \rightarrow \pi^\pm C^\mp(1480)\right) \leq 3 \times 10^{-5} \tag{32}$$

Note that for the production of the $C(1480)$ in $\pi^-p \rightarrow \pi^0\phi n$, we have [35]

$$\begin{aligned} \sigma\left(\pi^-p \rightarrow Cn\right) &\approx 40\text{nb} \\ \sigma\left(\pi^-p \rightarrow Cn\right)/\sigma_{\text{tot}} &\approx 10^{-6} \\ BR\left(C \rightarrow \pi^+\pi^-\right) \cdot BR\left(C \rightarrow \pi^0\phi\right) &\approx 10^{-3} \end{aligned} \tag{33}$$

From Eq. (33), it would appear that the limit (32) does not yet rule out the $C(1480)$. For instance, in Ref. (5), it is pointed out that, in the quark rearrangement model, the process

$$\bar{p}p\left({}^{31}S_0\right) \rightarrow \left(\pi + \left(Q^2\overline{Q}^2\right)_{1^{--}}\right)_{\ell=1} \tag{34}$$

is forbidden. Thus if the $C(1480)$ is a four quark state (with a large $s\bar{s}Q\overline{Q}$ component to produce a dominant $\pi\phi$ decay [36,37]), its production from the $\bar{p}p$ s–wave is suppressed;

the transition from the p-wave would be much larger, suggesting that the production of the $C(1480)$ in $\bar{p}d$ annihilation is more promising. Other aspects of ϕ production and the OZI rule are discussed in [38].

4.5. Theoretical Aspects

Theoretical talks were very sparse at this conference, but nonetheless stimulating. An overview on exotic hadrons, focusing on their decay modes, was given by G. Karl, while T. Gutsche provided quark model estimates of the branching ratios for $Q\overline{Q}g$ hybrid meson production in $\overline{N}N$ annihilation.

Karl made some general remarks which are worthy of emphasis. For instance, a theoretical calculation which offers only a mass spectrum, and no estimates of production and decay branching ratios, is very model dependent and of little use. When an experimental candidate for a non-$Q\overline{Q}$ resonance lines up approximately with a particular state in his favorite theoretical spectrum, the theorist is tempted to claim success. He ignores the fact that his model predicts a number of other states which are not seen. Thus the 0^{++} and 2^{++} states detected by ASTERIX, CB and OBELIX are often loosely referred to as "four quark states", without any strong justification. No calculation of the production ($\bar{p}p \to M + (Q^2\overline{Q}^2)$) or decay ($Q^2\overline{Q}^2 \to M_1M_2$) properties of these putative states has been presented, so such identifications are premature. This remains an important theoretical task. Karl also mentioned some features of gluonium decay: a lowest 0^{++} state is expected in many models based on QCD (Bag and flux tube models, lattice calculations, sum rules). If this object is an SU(3) singlet, and we assume that η, η' contain only $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ components, with any mixing angle, we obtain

$$\begin{aligned} BR\,(0^{++} \to \pi^0\pi^0) &= BR\,(0^{++} \to \eta\eta) = BR\,(0^{++} \to \eta'\eta') \\ BR\,(0^{++} \to \eta\eta') &= 0 \end{aligned} \tag{35}$$

We suppose that phase space factors have been removed. The observed 0^{++} candidates do not exhibit this pattern. For example, the $G(1590)$ has $BR(\pi^0\pi^0)/BR(\eta\eta) < 1/3$, and the 0^{++} seen by CB at 1515 MeV (see Table 1) also decays strongly into $\eta\eta$, but not $\pi^0\pi^0$. Deviations from Eq. (35) can arise if η and η' contain a non-$Q\overline{Q}$ component (say $|R\rangle = |gg\rangle$). With

$$\begin{aligned} |\eta\rangle &= \cos\theta|\eta_8\rangle - \sin\theta|\alpha_1\rangle \\ |\eta'\rangle &= \sin\theta|\eta_8\rangle + \cos\theta|\alpha_1\rangle \\ |\alpha_1\rangle &= \cos\alpha|\eta_1\rangle + \sin\alpha|R\rangle \end{aligned} \tag{36}$$

one can reproduce the radiative widths for $\eta, \eta' \to \gamma\gamma$ by the choice $\theta \approx -20°$, $\alpha \approx \pm 24°$, indicating some gluonic content in the pseudoscalar mesons. The relevance of these considerations to the new states seen in $\overline{N}N$ annihilation remains unclear.

Karl also discussed the possibility that some states may be interpreted as mesonic molecules, as suggested by Weinstein and Isgur [39], Barnes, Tornqvist and others. In this case, decays also offer an important diagnostic, for instance the rates for $f_0, a_0 \to \gamma\gamma$ are much slower if f_0 and a_0 are $\overline{K}K$ molecules rather than $Q\overline{Q}$ states. In the related quasinuclear picture [28], detailed predictions have been presented for the production ($\bar{p}p \to MX$) and decay ($X \to M_1 M_2$) of $\overline{N}N$ bound states X. The principal binding mechanism for such states is the coherent $I = 0$ tensor potential arising from meson exchange. This yields a band of natural parity states $[0^{++}(0^+), 1^{--}(0^-), 2^{++}(0^+)\ldots]$. The case for identifying the $2^{++}(0^+)$ member of this band with the state at 1515–1565 MeV observed by ASTERIX, CB, OBELIX and E760 (see Table 1) is given in [28]: the observed production rates for $\bar{p}p(L = 0,1) \to \pi X$ are consistent with the quasinuclear picture, but the results for decays are less clear. The model predicts the hierarchy of decays

$$BR\left(2^{++} \to \rho\rho\right) > BR\left(2^{++} \to \pi\pi\right) > BR\left(2^{++} \to \eta\eta\right) > BR\left(2^{++} \to \eta\eta'\right) \tag{37}$$

The trend $\pi\pi > \eta\eta > \eta\eta'$ is seen in the data, but the detailed prediction (28) $BR(2^{++} \to \eta\eta)/BR(2^{++} \to \pi^0\pi^0) \simeq 0.4$ considerably exceeds the experimental value of Eq. (23). Several speakers (Noble, Peters) concluded from this discrepancy that the quasinuclear model is ruled out, but this conclusion is premature. For instance, in [28], a spectroscopic factor of 1/2 for the π as a $Q\overline{Q}$ state was assumed. If this somewhat ad hoc assumption is relaxed, the $\eta\eta/\pi^0\pi^0$ ratio drops to 0.1, in agreement with Eq. (23); this ratio also depends on the radii assumed for the π and η wave functions. Another crucial question, discussed earlier, is the value of $BR(2^{++} \to \rho\rho)$. The OBELIX analysis has not yet established the amount of 2^{++} seen in the 4π channel, so it is not possible to draw a firm conclusion.

Gutsche presented quantitative quark model predictions for the production of $Q\overline{Q}g$ hybrid mesons in the reaction

$$\overline{N}N \to M + (Q\overline{Q}g) \tag{38}$$

In [40], the possibility was considered of identifying the $E(1420)$ meson $(0^{-+}(0^+))$, seen in $\bar{p}p \to \pi^+\pi^- E$ by Duch *et al.* [41], as a $Q\overline{Q}g$ hybrid. The calculated branching ratio was found to be much too small, however. In the Bag Model, the lowest lying $Q\overline{Q}g$ states are of the structure

$$\left[(Q\overline{Q})_{^3S_1} \otimes TE\left(1^+\right)\right]_{0^{-+},1^{-+},2^{-+}} \left[(Q\overline{Q})_{^1S_0} \otimes TE\left(1^+\right)\right]_{1^{--}} \tag{39}$$

where TE stands for a transverse electric normal mode of the gluon field. These states are predicted to lie in the mass region 1.2–2 GeV, so some of them may be accessible in $\bar{p}p$ annihilation at rest. Of particular interest are the exotic hybrids $\hat{\rho}(I = 1)$ and $\hat{\omega}(I = 0)$ with $J^{\pi C} = 1^{-+}$. For these, Gutsche estimated

$$\begin{aligned} BR\left(\bar{p}p(L=0) \to \pi^0\hat{\rho}^0\left(1^{-+}\right)\right) &\simeq (2-9)\times 10^{-4} \\ BR\left(\bar{p}p(L=0) \to \pi^0\hat{\omega}\left(1^{-+}\right)\right) &\simeq (0.7-3.4)\times 10^{-4} \end{aligned} \tag{40}$$

at rest, assuming $M(\hat{\rho}^0) \approx 1.4$ GeV as in the GAMS experiment [15]. Note that $\bar{p}p(L = 1) \to \pi^0\hat{\rho}^0(1^{-+})$ is forbidden. Another promising possibility is afforded by the P–wave annihilation

$$BR\left(\bar{p}p(L=1) \to \pi^0\hat{\rho}^0\left(0^{-+}\right)\right) \approx (1-4)\times 10^{-2} \tag{41}$$

for $M(0^{-+}) \simeq 1.3$ GeV. Most other processes involving $(Q\overline{Q}g)$ production are predicted to have very small branching ratios.

The decays of hybrids are predicted to satisfy approximate selection rules [42,43]

$$\begin{aligned}(Q\overline{Q})_{\ell=0} \otimes g(TE) \rightarrow & \left[(Q\overline{Q})_s + (Q\overline{Q})_p\right]_{\ell=0} \\ \not\rightarrow & \left[(Q\overline{Q})_s + (Q\overline{Q})_s\right]_{\ell=1} \\ \not\rightarrow & \left[(Q\overline{Q})_s + (Q\overline{Q})_p\right]_{\ell=2}\end{aligned} \quad (42)$$

This makes them difficult to detect, since the simplest decay modes, for instance $\hat{\rho}^0(1^{-+}) \rightarrow \pi^0\eta$, are suppressed. The study of decay chains like $\hat{\rho}^0(1^{-+}) \rightarrow \pi^\pm b_1^\mp \rightarrow \pi^\pm\pi^\mp\omega$ or $\hat{\rho}(1^{-+}) \rightarrow \pi a_1 \rightarrow \pi\pi\rho$ are promising. The predicted $Q\overline{Q}g$ rates depend strongly on the initial atomic state ($L = 0, 1$), and this may afford an important signature.

5. $\overline{N}N$ SCATTERING, ANNIHILATION AND SPIN OBSERVABLES

Experimental and theoretical overviews of the $\overline{N}N$ annihilation process were given by A. Rotondi and W. Weise, respectively. Some recent review articles [38, 44-46] are also useful in obtaining a general picture. The global properties of annihilation can be understood in terms of simple geometrical and statistical models. Beyond the statistical picture, or the two–meson doorway state approach, the data exhibit *dynamical selection rules*, i.e. the suppression of certain channels allowed by $J^{\pi C}(I^G)$ conservation. Several examples are

$$\frac{BR\left(\bar{p}p\left({}^3S_1\right) \rightarrow \pi^\pm\rho^\mp\right)}{BR\left(\bar{p}p\left({}^1S_0\right) \rightarrow \pi^\pm\rho^\mp\right)} \approx 40 \quad (43a)$$

$$\frac{BR\left(\bar{p}p\left({}^3S_1\right) \rightarrow \pi^+\pi^-\eta\right)}{BR\left(\bar{p}p\left({}^1S_0\right) \rightarrow \pi^+\pi^-\eta\right)} \approx 1/2 \quad (43b)$$

These ratios show a large deviation from the statistical factor of 3.

There has long existed a pious hope that dynamical selection rules would provide a signature of the quark–gluon structure of the transition operator, i.e. whether the dominant annihilation topology is planar or non–planar and whether the spin–flavor–color–orbital character of the effective $Q\overline{Q}$ operator is ${}^3S_1$, ${}^3P_0$ or some mixture. This hope remains largely unrealized, since the task of isolating the quark aspects is enormously complicated by the initial and final state interactions. At the low energies and momentum transfers studied at LEAR, it is difficult to distinguish between quark–gluon and hadron exchange pictures. After all, one has low energy theorems, and quark–gluon degrees of freedom can be largely subsumed in effective Lagrangians.

In spite of all these difficulties, there have been some successful phenomenological analyses of $\overline{N}N$ annihilation in the quark model. One tries various combinations of planar and non–planar (rearrangement) topologies, with ${}^3S_1$ or ${}^3P_0$ vertices. A combination of two and three meson planar topologies, with $^3P_0$ vertices, gives a reasonable account of the data (38).

The recent OBELIX results on $\bar{p}p$ and $\bar{n}p$ annihilation at very low energy were presented by F. Iazzi. For momenta below 150 MeV/c or so, the elastic $\bar{n}p$ cross section exceeds the annihilation, in contrast to a typical ratio of 1/2 for $p > 300$ MeV/c. This is a typical signature of a strong attraction in the real part of the $\bar{n}p$ potential, of somewhat longer range than the imaginary part. This strong attraction is an inescapable prediction of meson exchange models. There is also an observed difference of $\bar{p}p$ and $\bar{n}p$ total cross sections at very low energy with $\sigma_{\rm tot}(\bar{p}p) > \sigma_{\rm tot}(\bar{n}p)$. This is explainable in terms of the coherent tensor potential which operates for isospin $I = 0$; the tensor effects are also important in understanding the "$\pi\rho$ puzzle" of Eq. (43a) and the $S = 1$ dominance in $\bar{p}p \rightarrow \overline{\Lambda}\Lambda$ reaction (see later).

The CPLEAR collaboration has studied Bose–Einstein correlations of pions produced in $\bar{p}p$ annihilation at rest; the results were shown by K. Sarigiannis. The correlation function was found to be consistent with two pion sources, a smaller one ascribed to direct pions and a larger one arising from the interference between direct and resonance decay pions.

An excellent review of spin phenomena in $\overline{N}N$ elastic scattering, charge exchange ($\bar{p}p \rightarrow \bar{n}n$), hyperon production ($\bar{p}p \rightarrow \overline{\Lambda}\Lambda$) and annihilation processes was given by C. Leluc. New results from the POLCEX experiment (PS199) on the analyzing power A_{on} and the polarization transfer D_{nn} in $\bar{p}p \rightarrow \bar{n}n$ were put forth by A. Martin. Some earlier results on A_{on} have already been published [47]. These new results were not well reproduced by previous optical model analyses, for instance those of the Paris group [48,49]. M. Pignone described a new fit using the Paris model which accommodates the POLCEX data. As before, the local potential thus obtained has an imaginary part which is strongly dependent on energy E, spin S and isospin I, but with quite different parameters than earlier models. The absorption is much stronger for $S = 0$ than for $S = 1$, and grows rapidly with E. The strong E dependence is expected, since the underlying annihilation potential is certainly non-local, and also the density of final mesonic states increases with E. However, on the basis of microscopic models, there is no understanding of a very strong S dependence, since the number of mesonic channels is comparable for $S = 0$ and $S = 1$. The phenomenological optical potentials in use require many free parameters to produce a very modest fit to the data (χ^2/pt. ~ 6), and perhaps they should be regarded simply as numerical recipes. Although quark models can now reproduce the magnitude and energy dependence of $\overline{N}N$ elastic and total annihilation cross sections, they have yet to be confronted with spin observables.

6. TWO–BODY FINAL STATES IN $\overline{N}N$ INTERACTIONS

Recent results on two–body annihilation modes $\bar{p}p \to M_1 M_2$ were presented by D. Bugg and A. Noble. The data on $\bar{p}p \to \pi^-\pi^+$ and K^-K^+ from PS172, taken at 20 beam momenta from 360 to 1550 MeV/c, were subjected to an amplitude analysis [50], which indicates 1^- and 3^- resonances at about 2050 MeV and 0^+, 2^+, 4^+ states near 2300 MeV. The resonant amplitudes appear to be phase–locked, i.e. the 4^+ follows the 3^- by 90° in phase, etc. Both differential cross section and analyzing power A_{0n} were measured. In terms of helicity amplitudes F_{++} and F_{+-}, we have

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{1}{2}\left(|F_{++}|^2 + |F_{+-}|^2\right) \\ A_{0n}\frac{d\sigma}{d\Omega} &= \mathrm{Im}\left(F_{++}F^*_{+-}\right) \end{aligned} \tag{44}$$

The $\bar{p}p \to \pi^+\pi^-$ data show the remarkable feature that $A_{0n} \simeq 1$ over a large range of $\cos\theta$ and energy. This implies that $|F_{++}| \approx |F_{+-}|$ and that F_{++} and F_{+-} are 90° out of phase. The dips in $d\sigma/d\Omega$ are spaced by $t \approx 1\ (\mathrm{GeV/c})^2$. The nature of these resonant structures is not understood, in particular their relation to the 0^+ and 2^+ states seen below the $\overline{N}N$ threshold in the $\eta\eta$ and $\pi\pi$ channels.

The data obtained by Crystal Barrel on two–body branching ratios was shown by A. Noble. The new LEAR data is much more precise than the old bubble chamber results, and provides crucial input for testing dynamical models of the annihilation process. Some of the measured branching ratios are given in Table 2. One application of these results is the determination of the pseudoscalar mixing angle θ_{PS}. Assuming the validity of the quark line rule and the absence of strangeness in the proton, we have (7)

$$\frac{BR(\bar{p}p \to \eta X)}{BR(\bar{p}p \to \eta' X)} = \tan^2(\theta_{\mathrm{PS}} - \theta_0) \tag{45}$$

with $\theta_0 = 35.3°$. The CB result is $\theta_{\mathrm{PS}} = -(17.3 \pm 1.8)°$, consistent with other determinations. One can also use the two–body branching ratios to test quark models. For instance, assuming the dominance of annihilation over rearrangement graphs [5], one obtains the prediction

$$\frac{BR(\bar{p}p \to \eta\omega)/BR(\bar{p}p \to \eta\rho)}{BR(\bar{p}p \to \pi^0\rho^0)/BR(\bar{p}p \to \pi^0\omega)} = 1 \tag{46}$$

to be compared with the CB value of 1.2 ± 0.3. There are a large number of such tests of annihilation dynamics [38].

The status of the studies of the two–body strangeness exchange reaction $\bar{p}p \to \overline{\Lambda}\Lambda$, $\overline{\Lambda}\Sigma^0 + \Lambda\overline{\Sigma}^0$, $\overline{\Sigma}^-\Sigma^+$ by the PS185 collaboration at LEAR was reported by H. Fischer and N. Hamann. A number of results have emerged from this experiment. For instance, the ratio

$$\sigma\left(\overline{\Lambda}\Sigma^0 + \Lambda\overline{\Sigma}^0\right)/\sigma\left(\overline{\Lambda}\Lambda\right) = 0.29 \pm 0.02 \tag{47a}$$

$$\sigma\left(\overline{\Sigma}^-\Sigma^+\right)/\sigma\left(\overline{\Lambda}\Lambda\right) = 0.15 \pm 0.02^{+0.06}_{-0.03} \tag{47b}$$

Table 2: Two–body branching ratios from Crystal Barrel for $\bar{p}p$ annihilation at rest. The errors are statistical, systematic, and due to uncertainties in decay branching ratios, respectively.

CHANNEL	BRANCHING RATIO
$\pi^0\pi^0$	$6.93 \pm 0.22 \pm 0.37 \times 10^{-4}$
$\pi^0\eta$	$2.12 \pm 0.08 \pm 0.09 \pm 0.02 \times 10^{-4}$
$\pi^0\eta'$	$1.23 \pm 0.11 \pm 0.05 \pm 0.06 \times 10^{-4}$
$\eta\eta$	$1.64 \pm 0.07 \pm 0.07 \pm 0.02 \times 10^{-4}$
$\eta\eta'$	$2.16 \pm 0.21 \pm 0.09 \pm 0.11 \times 10^{-4}$
$\pi^0\omega$	$5.73 \pm 0.22 \pm 0.24 \pm 0.34 \times 10^{-3}$
$\eta\omega$	$1.51 \pm 0.06 \pm 0.06 \pm 0.09 \times 10^{-2}$
$\eta'\omega$	$0.78 \pm 0.05 \pm 0.03 \pm 0.06 \times 10^{-2}$
$\omega\omega$	$3.32 \pm 0.14 \pm 0.14 \pm 0.28 \times 10^{-2}$

compare well with quark model estimates of 0.24 – 0.26 [51-53] for (47a). The cross sections are taken at the same available c.m. energy $\epsilon = \sqrt{s} - 2m_\Lambda$ or $\sqrt{s} - m_\Lambda - m_{\Sigma^0}$, in the final state.

Even very close to threshold, the angular distributions for $\bar{p}p \to \bar{Y}Y'$ are foward peaked, indicating a strong P–wave component in the final state. This "precocious P–wave" also appears in $\bar{p}p$ elastic scattering, and signals the presence of very strong attraction in the real part of the baryon–antibaryon potential. This is expected, since $I = 0$ scalar (σ) and vector (ω) exchange potentials are attractive in all $\bar{B}B$ channels.

Most of the $\bar{p}p \to \overline{\Lambda}\Lambda$ cross section near threshold is described by the smooth function

$$\sigma\left(\bar{p}p \to \overline{\Lambda}\Lambda\right) \approx a_0\epsilon^{1/2} + a_1\epsilon^{3/2} \tag{48}$$

where $a_0 = 1.5$ μb, $a_1 = 0.3$ μb, and ϵ is in units of MeV. The $\epsilon^{3/2}$ term represents the P–wave contribution, which is already comparable to the S–wave part at $\epsilon \approx 6$ MeV. Very close to threshold ($\epsilon \approx 1$ MeV), there is an intriguing bump which rises above the smooth background of Eq. (48). This could signal the presence of a resonance near the $\overline{\Lambda}\Lambda$ threshold (33). A new high precision measurement is called for, also including the channel $\bar{p}p \to \overline{K}^* K^*$ if possible.

The PS185 experiment has also yielded a large set of data on spin observables for the $\bar{p}p \to \overline{\Lambda}\Lambda$ reaction. This is possible because the $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \bar{p}\pi^+$ weak decays are self–analyzing, i.e., the distribution of protons is of the form

$$I\left(\theta_p\right) = I_0\left(1 + \alpha_\Lambda P_\Lambda \cos\theta_p\right) \tag{49}$$

where $\alpha_\Lambda = 0.642$ is the decay asymmetry parameter and P_Λ is the polarization of the Λ. Strong polarization of the Λ is seen even at small ϵ. The spin correlation coefficients C_{ij} have been measured at several beam momenta; from these, one can construct the spin singlet fraction

$$F_0 = \frac{1}{4}\left(1 - \langle\vec{\sigma}_\Lambda \cdot \vec{\sigma}_{\overline{\Lambda}}\rangle\right) = \frac{1}{4}\left(1 + C_{xx} - C_{yy} + C_{zz}\right) \tag{50}$$

The new PS185 data establish that F_0 is indeed *very* close to zero (i.e. $\overline{\Lambda}\Lambda$ is produced only in the $S = 1$ state) in the range 1.546– 1.911 GeV/c. This has led to a variety of theoretical speculations on the origin of the $S = 1$ dominance, in both meson exchange [52,54] and quark models [52,53,55]. Haidenbauer *et al.* [56] have suggested that one might be able to distinguish between meson–exchange and quark–gluon mechanisms for the $\bar{p}p \to \overline{\Lambda}\Lambda$ transition by measuring the depolarization parameter D_{nn}. Clearly the coherent $I = 0$ tensor transition potential (K, K^* exchange) must play a key rôle, since it allows the $\Delta L = 2$ transitions $^3D_1 \to {}^3S_1$, $^3F_2 \to {}^3P_2$, which are kinematically favored because of the large momentum transfer. This kinematical effect could explain $S = 1$ dominance by itself. A detailed phenomenological analysis has been given by Tabakin *et al.* [57].

7. ANTINUCLEON INTERACTIONS WITH NUCLEI

A number of diverse contributions were presented in the area of $\bar{p}$ and $\bar{n}$ interactions with nuclei, including an overview by T. Bressani, a summary of OBELIX results by M. Bussa, a study of multi–strange final states by A. Dolgolenko, a signature of a neutron halo in ^{232}Th by J. Jastrzebski, results on $\bar{p}$–induced nuclear fission by T. von Egidy, and investigations of $\bar{p}$ annihilation in nuclei in the multi–GeV region by S. Ahmad. We now summarize some of the essential aspects of these talks.

The latest results from PS177 at LEAR have established a precise value for the lifetime of the hypernucleus $^{238}_{\Lambda}$U, namely [58]

$$\tau\left({}^{238}_{\Lambda}\mathrm{U}\right) = (1.25 \pm 0.15) \times 10^{-10}\ \mathrm{sec}, \tag{51}$$

about a factor of two less than the free space lifetime of a Λ, $\tau_\Lambda = (2.63 \pm 0.02) \times 10^{-10}$ sec. Since the $\Lambda \to N\pi$ decay is strongly Pauli–blocked in a heavy nucleus, the decay of $^{238}_{\Lambda}$U is dominated by the non–mesonic $\Lambda N \to NN$ process.

The relative yields of various products of $\overline{N}$–nucleus annihilation are in general well explained by IntraNuclear Cascade (INC) calculations, as formulated by Iljinov *et al.* [59] and Cugnon and Vandermeulen [60], among others. However, the INC fails to reproduce high energy $\overline{N}$–nucleus data, as reported by Andreev *et al.* [61] and S. Ahmad (5–9 GeV/c region). In the high energy experiments, the inclusive neutral strange particle production, the charged particle multiplicity, and the rapidity distributions of Λ, $\overline{\Lambda}$ and K_S are measured. The idea of $\overline{N}$–nucleus annihilation is to probe the high temperature (T), low density (ρ) region of the nuclear matter phase diagram, as a complement to relativistic heavy ion experiments. In the first step, and $\overline{N}$ annihilates on a quasi–free nucleon, emitting pions and meson resonances. These annihilation products interact with the rest of the nucleus by scattering or absorption, leading to the transfer of some fraction of the annihilation energy into nuclear excitation. Low energy (< 2 GeV/c) $\overline{N}$ interactions are not very effective at heating nuclei, since annihilations take place mainly on the nuclear surface. For $\overline{N}$ momenta of 6–8 GeV/c incident on nuclei with $A \sim 100$, one can anticipate that conditions with $T \sim 170$ MeV, $\rho \sim (1.4 - 1.8)\rho_0$ might be achieved (ρ_0 = nuclear matter density $\sim 1/6\ \mathrm{fm}^{-3}$). For momenta in excess of 10 GeV/c, the hadronization length of the annihilation products is lengthened by the Lorentz boost and becomes comparable to the size of the nucleus. The energy deposition is then expected to decrease.

At 4 GeV/c, the $\bar{p} + Ta$ data of Miyano *et al.* [62], which included the measurement of inclusive K_S, Λ and $\overline{\Lambda}$ production, is well explained by the INC calculations of Gibbs *et al.* [63]. At the higher momentum of 9 GeV/c, Ahmad reported that the measured number of high multiplicity events is larger than predicted by the same INC code. This may be an indication of some interesting new physics.

Another topic addressed by Bressani was two–body Pontecorvo annihilations [64], such as $\bar{p}d \to \pi^- p$, $\pi^0 n$, $K^0 \Lambda$, $K^+ \Sigma^-$. These processes necessarily involve two–nucleon participation, and they have been optimistically discussed as a way of probing quark degrees of freedom. In the statistical model [60], mesonic model [65] and quark model [66], the $\bar{p}d \to p\pi^-$ branching ratio is predicted to be (4.7, 2.7, 2) $\times 10^{-5}$, respectively. The recent LEAR measurements yield

$$BR\left(\bar{p}d \to \pi^- p\right) = \begin{cases} (1.4 \pm 0.7) \times 10^{-5} & (\,[67]\,) \\ (1.2 \pm 0.2) \times 10^{-5} & \text{OBELIX} \end{cases} \tag{52}$$

The new data have a precision which tests the theoretical models. Note, however, that the theoretical uncertainty exceeds the experimental error bars in Eq. (52).

Dolgolenko reported results of the DIANA collaboration on the production of multi-strange final states in low energy $\bar{p}$ annihilations in a Xe bubble chamber. A separated $\bar{p}$ beam at a momentum of about 1 GeV/c was obtained from the 10 GeV/c proton synchrotron at ITEP in Moscow. The $\bar{p}$'s entering the Xe chamber may annihilate in flight or at rest after energy dissipation due to ionization in Xe. Of order 5×10^5 $\bar{p}$Xe annihilation events were analyzed, looking for reactions involving double strangeness production:

$$\bar{p}Xe \to K^+ K^+ X \tag{53a}$$
$$\bar{p}Xe \to K^+ K^0 \Lambda X \tag{53b}$$
$$\bar{p}Xe \to K^+ K^+ H X \qquad (\text{with } H \to \Sigma^- p) \tag{53c}$$

No events of type (53c), involving the $S = -2$ H dibaryon, were seen, whereas 8 and 6 events, respectively, were recorded for reactions (53a,b), corresponding to branching ratios of order 10^{-5}. An attempt to calculate the double strangeness production as a sum of various first, second and third order processes yielded a rate considerably smaller than this, indicating that the mechanism of multi–strange production is not so easily understood.

Dolgolenko also reported on the inclusive production of ω mesons in $\bar{p}Xe$ annihilations. The yield (8.5% at rest, 6% in flight) is substantially smaller than that in $\bar{p}p$ annihilation at rest (28%), reflecting the influence of ω absorption in the nucleus. A cascade calculation with $\sigma_{\omega N} \approx \sigma_{\pi N}$ yields a rate of 8%, in agreement with the data.

In the realm of what might be called "classical nuclear physics", there were contributions by Jastrzebski on neutron halos and von Egidy on $\bar{p}$–induced fission. The neutron halo analysis of experiment PS203 is based on a simple idea: if a $\bar{p}$ annihilates on a neutron in the nuclear periphery, the nucleus produced has $(Z_t, N_t - 1)$, whereas $\bar{p}p$ annihilation leads to $(Z_t - 1, N_t)$. If the $(N_t - 1)$ and $(Z_t - 1)$ products are both radioactive, their yields $N(\bar{p}n)$ and $N(\bar{p}p)$ can be determined by radiochemical methods. This enables one to extract a "halo factor"

$$f = \frac{N\left(\bar{p}n\right)}{N\left(\bar{p}p\right)} \frac{\operatorname{Im} a_p}{\operatorname{Im} a_n} \frac{Z_t}{N_t} \tag{54}$$

where a_p, a_n are $\bar{p}p$ and $\bar{p}n$ scattering lengths. For a ^{232}Th target, the activities of ^{231}Th and ^{231}Ac were measured, yielding a ratio of neutron and proton densities

$$f \simeq \frac{\rho_n(R)}{\rho_p(R)} \simeq 6.8 \pm 1.9 \tag{55}$$

where $R \simeq 12$ fm is the typical radius at which $\overline{N}$ annihilation occurs. Thus a neutron halo in ^{232}Th seems to be clearly identified. Theoretical calculations employing single particle wave functions, fit to the correct binding energies, are in agreement with Eq. (55).

Recent results on antiproton–induced fission were described by von Egidy. Earlier, the PS177 collaboration had measured fission fragments and probabilities, and identified Λ hypernuclei by delayed fission. The current measurements included energy and mass of both fission fragments, the folding angle of the fragments, the momentum of the fissioning nucleus, and particle emission before and after scission. Three fission modes were found: a) asymmetric fission at low excitation energy ($E^* < 20$ MeV), b) symmetric fission for higher excitation, and c) fission before thermalization for $E^* > 500$ MeV. In contrast to heavy ion–induced fission (which involves large spins), $\bar{p}$–fission becomes faster with increasing E^* (the $\bar{p}$ produces hot nuclei with low spin and essentially no compression). Detailed comparisons with cascade calculations were made, enabling one to study a number of dynamical effects such as multifragmentation, coalescence, trawling, evaporation, thermalization, etc.

A number of aspects of charm production in nuclei by $\bar{p}$ annihilation were addressed by D. Kharzeev. These included the study of the propagation of heavy quark systems ($c\bar{c}$) in nuclear matter (with a view toward extracting the J/ψ–nucleon cross section) and the production of charmed nuclei and four–quark ($c\bar{c}Q\overline{Q}$) states with $\bar{p}$'s.

8. PRESENT AND FUTURE $\bar{p}$ FACILITIES

There were a number of talks related to the capabilities of present facilities, and the advances to be expected at future ones. D. Lazarus and S. Hsueh reviewed the $\bar{p}$ physics programs at Brookhaven and Fermilab, respectively. A LEAR upgrading for CP studies was discussed by M. Chanel, and another option for ultra–low energies by S. Baird. The broad physics program which could be addressed at KAON was described by E. Vogt, while the physics accessible at a tau–charm factory was summarized by E. Gonzalez. The design of the proposed SuperLEAR machine was outlined by D. Möhl, and the physics case for SuperLEAR was developed in considerable detail by D. Hertzog, W. Oelert and M. Poulet. R. Eisenstein provided a comparison of the SuperLEAR capability with that of existing or planned antiproton sources. I refer the reader to the proceedings of the SuperLEAR Workshop [18] for further details.

9. FINAL REMARKS

The LEAP '92 conference was characterized by a wealth of new experimental data, dominantly from LEAR, and very lively theoretical discussions as to their interpretation. The field of $\bar{p}$ physics is lively and robust, with advances occurring on a variety of fronts, ranging from studies of fundamental symmetries to meson spectroscopy to the microscopic dynamics of the $\overline{N}N$ annihilation process itself. We look forward to further advances, for instance the discovery of $J^{\pi C}$ exotic mesons among the $\overline{N}N$ annihilation products.

Finally, I would like to thank Carlo Guaraldo for organizing a most stimulating conference in the flawless setting of Courmayeur.

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