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ANTINUCLEON ANNIHILATIONS AT LOW ENERGIES AT LEAR

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ABSTRACT

This report is limited to a skeletal summary of the topics covered in the lecture. The arguments discussed were: physics interest of $N\bar{N}$ annihilations; S and P-wave $p\bar{p}$ annihilation at rest: new experimental techniques established with the ASTERIX detector at LEAR and physics prospects; $\bar{p}$ annihilation in nuclei: experimental findings of the Streamer chamber detector at LEAR and physics prospects; brief presentation of LEAR and summary of the physics programme planned starting from the end of 1987 when the antiproton collector (ACOL) will come into operation.

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1. PHYSICS INTEREST OF $N\bar{N}$ ANNIHILATIONS

At low energies annihilation is the dominant reaction between particle and antiparticle and it produces the mediators of the forces acting between them in the elastic channel. $N\bar{N}$ annihilations produce the mediators of the strong force acting both at the nucleon level (mesons) and at the quark level (gluons).

Real $N\bar{N}$ annihilation is the sector in experimental studies of $N\bar{N}$ interactions with the richest phenomenology because of the numerous annihilation channels that are open. The various final states may contain pions, kaons and gammas with several multiplicities. In each exclusive final state with more than two particles are generally present intermediate resonant states. Virtual annihilations play an important role in non-annihilation reactions. Real and virtual annihilation reactions depend in principle on the angular momentum, the isospin, the energy and the spin of the initial $N\bar{N}$ state and on whether the target nucleon is free or bound into a nucleus. The dynamics of $N\bar{N}$ interactions will be understood when theory will have been able to make quantitative predictions on different exclusive final states and on their intermediate resonances for several initial states and when these predictions will have been checked experimentally for different initial states or compositions of initial states. $N\bar{N}$ interactions can be linked to NN interactions by G parity transformations if the $N\bar{N}$ annihilation effects are independently known. Experimental and theoretical work in the $N\bar{N}$ sector can therefore also shed light onto short range NN forces, that are at present poorly understood.

From a particle physics point of view $N\bar{N}$ annihilation is an advantageous instrument with unique features to study interactions between quarks and gluons. Indeed $N\bar{N}$ annihilation is a copious source of light mesons and mesonic resonances and it is a natural source of exotic mesonic resonances (like glueballs (gg, ggg), hybrids ($q\bar{q}g$) and multiquark ($qq\bar{q}\bar{q}$, $qqq\bar{q}\bar{q}\bar{q}$) structures), if they exist as it is expected in the framework of the Quantum Chromo Dynamic theory of strong interactions. These objects can be produced with the constituent quarks and antiquarks of the original $N\bar{N}$ pair that did not annihilate in the interaction and the gluons produced by the pairs of constituent quarks and antiquarks that did annihilate in the

interaction. The determination of the existence of glueballs and hybrids is of fundamental importance as it would prove the basic point in QCD that gluons couple directly also to gluons. To this purpose the main physical advantages offered by $N\bar{N}$ annihilations at low energies are

- a) high interaction rates
- b) several possible initial states with different quantum numbers, that give access in formation experiments to many resonant final states with the same quantum numbers as the initial state and that can give access in production experiments to states with exotic quantum numbers.
- c) extremely well defined energy of the initial state that permits in formation experiments to find and measure accurately narrow resonances (that cannot have exotic quantum numbers)
- d) possibility of observing in production experiments also broad structures (that can have exotic quantum numbers) with differential measurements by comparing with the same detector identical decay channels (e.g. $\pi^+\pi^-$ and K^+K^-) of possible resonant states present in exclusive final states of the same type (e.g. final states with three pions and final states with a K^+K^- pair plus one pion) produced from different $N\bar{N}$ initial states, differing by angular momentum, isospin or spin¹⁻³⁾. Reviews covering topics mentioned in this section are indicated in ref. 3 and 4.

2. S AND P-WAVE $p\bar{p}$ ANNIHILATIONS AT REST

The second part of this lecture focused on the possibility of changing the angular momentum of the initial state of $p\bar{p}$ annihilations at rest without changing the total energy, the spin and isospin composition. This possibility⁵⁻⁷⁾ had been one of the leading motivations⁸⁾ for LEAR. It has been established as an operational experimental technique by the ASTERIX experiment, that has also produced clear evidence of dynamical effects appearing in exclusive final states when the angular momentum distribution of the initial states is changed^{9,4,10)}.

The low momentum and small energy dispersion of the LEAR beam permits to stop efficiently antiprotons also into gas H_2 targets. Lowering the beam momentum the distribution of annihilation vertices concentrates around the target centre. Nearly all antiprotons annihilate at rest after having formed a $p\bar{p}$ atom.

The atomic cascade of protonium ($p\bar{p}$ atom) depends on the target density because of the combined effects of annihilation in S and P atomic levels and of collisions of protonium with the surrounding molecules¹¹⁾. At normal temperature and pressure more than 10% of the $p\bar{p}$ atoms populate the 2P level¹²⁾. 2P levels decay by radiative transitions (with emission of a K_α X-ray) to the 1S ground state with less than 2% probability and annihilate with more than 98% probability. By using as central detector a cylindrical X-ray Drift Chamber¹³⁾, XDC, (that has low mass, low energy threshold, large acceptance and granularity and can therefore also detect in coincidence two or more X-rays emitted by the same $p\bar{p}$ atom), the ASTERIX experiment is able to select P-wave annihilation events where an L X-ray populating the 2P level is measured in coincidence with the particles present in the final state. The XDC detects M, L and K $p\bar{p}$ X-rays to the $n=3$, $n=2$ and $n=1$ states. L X-rays ($1.7 \div 3.2$ KeV) are detected with typically 50% overall efficiency and the X-ray background in the L X-ray energy region is less than 10% of the L X-ray signal. The background is mainly constituted by X-rays produced by internal brehmsstrahlung¹⁴⁾. Consequently events with an X-ray in the L energy region undergo in more than 90% of the cases annihilation in P-wave in one of the 2P sublevels. The S-wave contamination of events with an X-ray in the L energy region is due mainly to events with an internal brehmsstrahlung X-ray simulating a L X-ray and the $p\bar{p}$ annihilation occurring in S-wave from any nS state. The fraction of annihilation in S-wave from all the nS levels is not yet determined exactly, however the comparison of bubble chamber data and ASTERIX preliminary data^{10,15)} indicate that this fraction is in the region 20 to 50% of all annihilations, and that correspondingly the fraction of $p\bar{p}$ P-wave annihilation at rest in H_2 gas is in the region 50 to 80%. Taking into account also the possibility of 2P-1S radiative transitions, the contamination of the P-wave annihilations data sample selected with the L X-ray coincidences is then less than 7%.

Preliminary ASTERIX data in several exclusive final states (e.g. $p\bar{p} \rightarrow \pi^+\pi^-$, K^+K^- , $K_S^0 K_S^0$, $\pi^+\pi^-\pi^0$) show experimentally that the branching ratios (BR) and ratios between branching ratios (RBR) for final states and intermediate resonant states change markedly when changing the fraction of initial states in S- and P-wave. We can also compare $p\bar{p}$ annihilations in liquid H_2 (Bubble Chamber data - dominant S-wave annihilation), $p\bar{p}$ annihilations in H_2 gas at NTP and $p\bar{p}$ annihilations with L X-ray in coincidence (dominant P-wave annihilation). This comparison in particular shows that resonant intermediate states hardly visible in bubble chamber data are present and dominant in P-wave annihilation.

A brief description has been given of the ASTERIX experimental set up^{6,7,16)} (fig. 1) and of the projection chamber of new geometry (Spiral Projection Chamber¹⁷⁾ SPC/XDC) that we used as central detector¹⁸⁾. ASTERIX has been a step in the realization of an experimental programme that was proposed in 1978⁵⁾ to study the dependence of $p\bar{p}$ annihilations at rest on angular momentum. This programme required LEAR, plus a new type of large acceptance X-ray detector, plus a detector of annihilation products as complete and performant as possible. In ACOL time the research line of ASTERIX will be continued and extended by two experiments that plan to use an X-ray Drift Chamber¹³⁾ to measure $p\bar{p}$ X-rays and plan to improve substantially on the detection capability of the final state. One detector, OBELIX³⁾ (fig. 2) is based on the Open Axial Field spectrometer¹⁹⁾. It will have good charged particles detection efficiency and momentum resolution and identification ($\Delta p/p \leq 2\%$, full $K^\pm$ identification from ~ 50 MeV/c up to 1 GeV/c), it will have high granularity and angular resolution for γ detection and will have trigger capabilities on angular momentum of the initial state and strangeness in the final state. The other detector, Crystal Barrel²⁰⁾ (fig. 3), will have high efficiency and energy resolution for γ 's and good charged particle momentum resolution. To study S-wave dominant $p\bar{p}$ annihilations the Crystal Barrel plans to use a liquid H_2 target and to remove the XDC. OBELIX will use only one detector configuration in order to factorize away detector and software efficiencies, acceptances and biases and will study at the same time S and P-wave annihilations to factorize detection and operation instabilities¹⁾.

3. $\bar{p}$ ANNIHILATIONS IN NUCLEI

This topic is covered extensively in a recent review of Piragino²¹⁾. The main results of the measurements made at LEAR by the Streamer Chamber Collaboration²²⁾ are:

- a) the principal mechanism of $\bar{p}$ absorption is the annihilation on quasi free nucleons of the nuclear surface.
- b) non elastic reactions different from $\bar{p}$ annihilation are suppressed.
- c) nuclei appear, in terms of the optical model, as black to antiprotons.
- d) annihilations of antiprotons penetrating inside the nucleus have been observed and can be selected requiring high multiplicity of annihilation particles and nuclear fragments in the final state.

Fig. 1: ASTERIX detector. (XDC) X-ray Drift Chamber and SPC (C_1, C_2, Q_1, Q_2, Q_3). Cylindrical MWPCs with cathode read_out, (P_1, P_2) cylindrical MWPCs.

Fig. 3: Crystal Barrel detector: (1) Yoke, (2 & 3) Coils, (4) CsI Barrel, (5) Jet Drift Chamber, (6) PWC, (7) LH₂ target.

OBELIX

Fig. 2: OBELIX detector, (1) Open Axial Field Magnet, (2) Spiral Projection Chamber, and XDC, (3) Time-Of-Flight, (4) High Density Spiral Projection Chamber, (5) AFS Jet Drift Chamber, (6) High Angular Resolution Gamma Detector.

An extensive programme on $\bar{p}$ annihilations into nuclei is planned by the OBELIX collaboration. This programme includes:

- a) survey of $\bar{p}$ annihilations in ^2H , ^3He , ^4He , N, Ne, Ar, Kr, Xe at rest and at a few momenta up to the highest LEAR energy.
- b) search for effects that could witness quark-gluon aspects of nuclear matter and the existence of highly excited or exotic states of nuclear matter. To this purposes dedicated triggers will be employed to search and measure i) pionless annihilation, ii) single pion annihilation and iii) strange particle production.

4. THE LEAR FACILITY

The reader is referred to the papers given at the last LEAR Workshop²³⁾ by R. Billinge, E. Jones, P. Lefèvre, D. Simon and D. Möhl who presented in turn the CERN Antiproton Complex, the new Antiproton Collector (ACOL) now under construction, the LEAR ring, the LEAR experimental areas and the LEAR machine developments necessary to accommodate new physics options. Fig. 4 shows schematically the LEAR facility with the experimental area in the 1986 configuration before the shutdown for ACOL.

LEAR delivered beams of antiprotons with no contamination at momenta between 105 and 1600 MeV/c with intensities going from up to $10^5 \bar{p} \text{ sec}^{-1}$ at 105 MeV/c to up to $10^6 \bar{p} \text{ sec}^{-1}$ at 600 MeV/c. The beam spill is continuous and lasts from 15min. to 5 hrs. Beam intensities are stable in the central momentum region and vary during one spill within typically a factor of 2 at low momenta. Up to three users can work simultaneously in parallel by the action of two beam splitters that divide the beam in the vertical plane. Table 1 summarizes 1986 LEAR operation for physics.

5. THE LEAR PHYSICS PROGRAMME IN THE ACOL TIME

A large number of intentions have been expressed since the third LEAR workshop and are documented in the proceedings²³⁾. The experiments at LEAR in the ACOL time approved so far by the CERN Research Board are listed in table 2. An overview is given in ref. 24. The topics besides those already mentioned in this lecture ($N\bar{N}$ annihilation dynamics, spectroscopy of light mesons and exotics, $\bar{p}$ nuclei) include: precise measurements of the $\bar{p}$ inertial mass, measurement of the $\bar{p}$ gravitational mass, measurements of CP violation parameters, spin physics.

Fig. 4: CERN PS South Area

(1986)

LEAR AND EXPERIMENTAL AREAS

● SPLITTER MAGNETS

Table 1: Distribution of spills during 1986 with slow ejection
(typically 1 hr long spills)

		S U D					C E N T R E					N O R D					
		1		2			1		2			1				2	
USERS		Piragino	Smith	Davies	Garreta	V. Egidy	Dalpiaz	Tauscher	Bugg/Bradamante	Walcher	Bressani	Simons	Gabrielse	Polikanov	Kilian	Uggerhoj	Asterix
		PS 179	PS 183	PS 174	PS 184	PS 186	PS 170	PS 182	PS 172	PS 173	PS 178	PS 175	PS 196	PS 177	PS 185	PS 194	PS 171
Weeks	P (MeV/c)																
20,26,27,28	105	115		117													
18,21,22,25	202	80				78				37		136	15	107		35	156
19	250									18							
18	309									9							
29,30,31,32	352		98				113	53	36		95				44		
19	400									11							
17	420								28								
30	432		37						37								
17	530								14								
13,17,19	612						190		19								
33	800								21								
32	1100								37								
12,34	1300						14		15						14		
16	1360								13								
33	1369						16								16		
33	1407						15								15		
16	1425								17								
33	1426						16								16		
34	1435						18								18		
33	1444						14								14		
34	1453						17								17		
33	1472						15								15		
16	1475								7								
34	1491						12								12		
33	1506						10								10		
11,12	1512								44								
34	1568						12								12		
Total spills		195	135	117		78	462	53	288	75	95	136	15	107	203	35	156

Table 2: Post-ACOL LEAR experiments (November 1986)

Exp	Title	Collaboration	Spokesman
PS189	High-precision measurement of the $p\bar{p}$ mass difference with a RF mass spectrometer	Orsay-CERN	C. Thibault
PS195	Tests of CP violation with K^0 and $\bar{K}^0$ at LEAR	Athens-Basle-CERN Fribourg-Liverpool- Saclay-SIN-Stockholm- Thessaloniki-Zurich	P. Pavlopoulos
PS196	Precision comparison of p & $\bar{p}$ masses in a Penning trap	Fermilab-Mainz- Washington	G. Gabrielse
PS197	The Crystal Barrel: Meson spectroscopy at LEAR with a 4π neutral and charged detector	Berkeley-Irvine-Karlsruhe-London-Mainz-Munich-Pennsylvania State-Strasbourg-Surrey-Vienna-Zurich	H. Koch
PS198	Measurement of spin-dependent observables in the $\bar{p}N$ elastic scattering from 300 to 700 MeV/c	Karlsruhe-Lyon-Saclay-SIN	R. Bertini
PS199	Study of the spin structure of $p\bar{p} \rightarrow n\bar{n}$ channel at LEAR	Cagliari-Geneva-Karlsruhe-Trieste-Turin	F. Bradamante
PS200	Measurement of the gravitational acceleration of the antiproton	Case Western-CERN-Genoa-Houston-Kent State-Los Alamos-NASA-Pisa-Texas A&M	M.V. Hynes
PS201	Study of antinucleon annihilation at LEAR with OBELIX, a large-acceptance and high-resolution detector, based on the Open Axial Field Spectrometer	Brescia-Cagliari-CERN-Dubna-Frascati-Legnaro-Orsay-Padua-Pavia-Trieste-Turin-Udine-Vancouver	U. Gastaldi

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