PHYSICS POSSIBILITIES WITH LEAR,
A LOW-ENERGY ANTIPROTON FACILITY AT CERN

U. Gastaldi\textsuperscript{(*)} and K. Kilian\textsuperscript{(**)}

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\textsuperscript{*}) CERN Visitor from the Institut für Physik, Mainz, Germany.
\textsuperscript{**}) CERN Visitor from the Max-Planck-Institut für Kernphysik, Heidelberg, Germany.
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U. Gastaldi*) 
Institut für Physik, Mainz, Germany 

K. Kilian*) 
Max-Planck-Institut für Kernphysik, Heidelberg, Germany 

ABSTRACT 

A summary is given of the conceptual design characteristics of LEAR (Low-Energy Antiproton Ring), the facility planned at CERN to perform physics at low energy with cooled antiprotons. With respect to present ā p beams, the LEAR facility will increase low-momentum beam intensities by factors of $10^5$ to $10^6$, eliminate beam contaminations, and increase the beam density. Storage-ring operations feasible in later developments may include use of a gas-jet target, injection of $H^-$ ions in order to produce ā p atoms in-flight, and ā ā collisions in a minicollider mode. An outline is given of the physics possibilities opened up by the impressive improvements of the extracted beams and by the new experimental approaches made possible by the storage-ring operations. 

*) Visitor at CERN, Geneva, Switzerland.
INTRODUCTION

A new facility for performing experiments with antiprotons at low energy is planned at CERN.

The core of the facility will be a small storage ring with acceleration capability, called LEAR (Low-Energy Antiproton Ring). LEAR will be installed in the PS South Hall (Fig. 1) and used

a) to feed high-intensity (> $10^6 \bar{p}$/s), high-duty cycle ($\sim$ 100%) low-energy (0.1 to 2 GeV/c) extracted beams (stretcher-ring operation);

b) to perform experiments that use directly the circulating internal beam (stretcher-ring operations with $10^9$ to $5 \times 10^{11}$ stored $\bar{p}$).

LEAR will receive antiprotons from the Antiproton Accumulator (AA)\(^1\), the intense source of antiprotons at present under construction\(^2\) for the $\bar{p}$-SPS programme. Antiprotons will be transferred to LEAR from the AA through the PS used as a decelerator (antiprotons collected, cooled in phase space, and stacked in the AA at 3.5 GeV/c will be injected in the LEAR at $\sim$ 0.6 GeV/c).

![Diagram of the site layout](image)

**Fig. 1 Over-all site layout**

The construction of the facility will be carried out in successive stages. A detailed project proposal for the first stage (stretcher-ring operation) will be worked out and will take into account the constraints
connected with the use of LEAR in the later stages of development (storage-ring operations). These stages include the use of an internal gas-jet target, injection of $H^-$ ions in order to produce $\bar{p}p$ atoms in flight, and $\bar{p}p$ collisions in a minicollider mode. Implementation of ISR-type vacuum and $\bar{p}$ cooling, that are necessary for the later stages of development, will also improve, by orders of magnitude, the quality of the extracted beam in the low-momentum region.

The LEAR facility will meet the increasing demand for good quality low-momentum antiproton beams produced by the focusing of interest on NN physics at low energies. Present-day experiments use antiprotons collected by tuning the beam transport line at the required low momentum. The production cross-section for $p < 1$ GeV/c is orders of magnitude below the maximum — which is met at $p \sim 3.5$ GeV/c with 26 GeV/c protons on the $\bar{p}$ production target (see Fig. 2 taken from CERN/PSCC/79-17)³.

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Fig. 2 Momentum spectrum of antiprotons produced at 0° with 23 GeV/c protons on a lead target. The number of $\bar{p}$ per interacting proton is normalized to 1 msr solid angle and ±1% momentum bite. Below 4 GeV/c the curve is estimated by "kinematic reflection". The crosses are preliminary values obtained on the CERN $k_{25}$ beam.
The scheme of the new facility foresees, instead, the collection of antiprotons in the AA always at the maximum of the production cross-section*) and subsequent transfer to the required low momentum via deceleration (in the PS). Before deceleration, antiprotons will be compressed in phase space by application in the AA of stochastic cooling techniques recently tested with success at ICE\(^9\). The resulting high density of the initial beam will allow deceleration, without relevant losses, down to all required low momenta.\(^5\) This combination of cooling (in AA) and deceleration will improve the present working conditions with extracted beams (beam intensity and density, momentum definition, pion contamination) by several orders of magnitude. Further improvements will result from applying additional cooling in LEAR. Moreover, new experimental possibilities will be opened up by making direct use of the antiproton beam stored in LEAR.

Schemes for a low-energy antiproton facility\(^6\) and indications for the physics programme to be performed there\(^7-9\) were presented at the 1977 CERN Workshop on Intermediate Energy Physics\(^10\). Work of two study groups set up at CERN in 1978 to investigate physics possibilities and machine aspects resulted in an assessment of the physics case\(^11\) and in the first conceptual design of LEAR\(^12\). The increasing interest in low-energy antiproton physics motivated the organization of a dedicated workshop, which was held in March 1979 in Karlsruhe\(^13\), and preceded by meetings at CERN of study groups dealing with the physics and machine aspects. Physics interest, detection capabilities, and technical aspects of the LEAR facility were discussed extensively\(^13,14\). A second conceptual design taking into account the result of the discussions at the Karlsruhe Workshop was worked out by the authors of Ref. 12 and included in the report\(^3\) to the CERN PSCC by the conveners of the study groups. The principle of constructing the LEAR facility was approved in June 1979. The date for the start of LEAR operations in the stretcher mode will be fixed after the approval of the detailed project proposal. The end of 1982 seems a reasonable estimate.

In the following sections we present an outline of the LEAR facility and of the physics programme.

THE LOW-ENERGY ANTIPOTON RING (LEAR) FACILITY

Figure 3 shows a design layout of LEAR located in the west side of the PS South Hall.

Antiprotons collected, cooled in phase space, and stacked in the AA at 3.5 GeV/c\(^15\) will be ejected from the AA in batches, decelerated in the PS down to a fixed momentum of about 0.6 GeV/c (\(\beta \approx 0.5\)), and then injected into LEAR. Each batch must contain more than \(10^9 \bar{p}\), the lower limit for safe operation of the PS instrumentation.

Antiprotons will be transported to LEAR through the building of the old 50 MeV linac. A return loop has been envisaged\(^16\) to connect the \(\bar{p}\) transport beam line to the old linac in order to allow \(p^+\) and \(H^-\) injections into LEAR completely decoupled from PS operations.

The average amount of antiprotons available for LEAR physics will be \(\geq 10^6 \text{ s}^{-1}\) (note that the AA will be able to stack a maximum average of \(7 \times 10^6 \bar{p} \text{ s}^{-1}\)).

*) This is the standard mode of operation of the AA.
This together with the lower limit of $10^9 \bar{p}$ per injection imposes a $\bar{p}$ beam lifetime $\geq 10^5$ s for operations with good duty cycle.

LEAR will consist of four laminated magnets and a focusing structure with two quadrupole doublets in each straight section. Design characteristics and lattice parameters for the stretcher ring operation are listed in Table I, which is taken from Chapter III of Ref. 3, "The proposed facility".

An imaginary transition energy has been chosen to maximize the efficiency of stochastic cooling\(^1\). The return yoke of the bending magnets will be inside the ring to allow easy extraction of neutrals ($\bar{p}$
Table I. Stretcher ring lattice with $\rho = 3.6$ m bends

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum range</td>
<td>$0.1 - 2$ GeV/c</td>
</tr>
<tr>
<td>Circumference</td>
<td>62.8 m</td>
</tr>
<tr>
<td>Length of straight sections</td>
<td>10 m</td>
</tr>
<tr>
<td>Free length (regular lattice)</td>
<td>6 m</td>
</tr>
<tr>
<td>Number of straight sections</td>
<td>4</td>
</tr>
<tr>
<td>Working point</td>
<td>$Q_H = 2.67$</td>
</tr>
<tr>
<td></td>
<td>$Q_V = 1.25$</td>
</tr>
<tr>
<td></td>
<td>$\gamma_t^2 = -(4.5)^2$</td>
</tr>
<tr>
<td>Maxima of lattice functions</td>
<td>$\beta_H = 6.8$ m</td>
</tr>
<tr>
<td></td>
<td>$\beta_V = 17.8$ m</td>
</tr>
<tr>
<td></td>
<td>$\alpha_p = 2.5$ m</td>
</tr>
<tr>
<td>Maxima in bends</td>
<td>$\beta_H = 4.5$ m</td>
</tr>
<tr>
<td></td>
<td>$\beta_V = 17.5$ m</td>
</tr>
<tr>
<td></td>
<td>$\alpha_p = 0.55$ m</td>
</tr>
<tr>
<td>Aperture of vacuum chamber</td>
<td>$a_H = \pm 70$ mm</td>
</tr>
<tr>
<td></td>
<td>$a_V = \pm 32$ mm</td>
</tr>
<tr>
<td>Beam apertures</td>
<td>$a_{H3} = \pm 45$ mm</td>
</tr>
<tr>
<td></td>
<td>$a_{H5} = \pm 45$ mm</td>
</tr>
<tr>
<td></td>
<td>$a_{V} = \pm 27$ mm</td>
</tr>
<tr>
<td>Maximum acceptances</td>
<td>$E_H = 250 , \mu \text{m mrad}$</td>
</tr>
<tr>
<td></td>
<td>$E_V = 35 , \mu \text{m mrad}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta p/p = \pm 1.8%$</td>
</tr>
<tr>
<td>Momentum</td>
<td>2 GeV/c</td>
</tr>
<tr>
<td>Bending field</td>
<td>18.4 kG</td>
</tr>
<tr>
<td>Integrated quadrupole gradient</td>
<td>610 (G/cm)m</td>
</tr>
<tr>
<td></td>
<td>31 (G/cm)m</td>
</tr>
</tbody>
</table>

Atoms and $\bar{\text{H}}$ produced in the straight sections. The orientation of the ring and the circulation sense of antiprotons will be such as to permit installation in the experimental hall of a long $\bar{\text{pp}}$ atom beam line prolonging one straight section of the ring. A 20 kV RF system will decelerate or accelerate the beam stored in LEAR from the fixed transfer momentum of about 0.6 GeV/c to the desired working momentum. The bunch length will be $\sim 40$ m working on the first harmonic. ISR-type vacuum elements have been envisaged since the beginning with a view to operation at very low momentum ($\beta \geq 0.1$), $\text{H}^{-}$ storage in LEAR, and operation with a low-density polarized jet target.

LEAR will be usable in various modes corresponding initially to stages of completion, and alternating later on as required by the experimental programme. The modes are:
1) **Stretcher-ring operation**
   la) above 0.3 GeV/c,
   lb) down to 0.1 GeV/c.

In this mode a slow extraction system\(^{18}\) located in straight section LSS2 (Fig. 4) should allow the feeding of an extracted beam with an average intensity up to \(1.7 \times 10^6 \, \bar{p} \, \text{s}^{-1}\) and a spill time of about one thousand seconds. Splitting of the beam will allow simultaneous feeding of two experiments, and branching with a bending magnet will afford the possibility of having more experiments on the floor in standby position.

![Fig. 4 PS South Hall](image)

2) **Storage-ring operations**
   2a) **Jet target operation:** An atomic H or D jet beam (eventually polarized) would cross the stored \(\bar{p}\) beam in a straight section\(^{19}\). The experimental apparatus would be installed around the interaction region in the space not occupied by the jet-target installation. An apparatus located behind the bending magnet downstream from the jet target could exploit the monochromatic \(\bar{n}\) beam of antineutrons forward-produced by charge exchange on protons in the jet\(^{20}\).

   2b) **Overlapping \(\bar{p}\) and \(H^-\) beams:** An \(H^-\) beam (from the old linac equipped with an \(H^-\) source\(^{21}\)) would be stored in LEAR together with the \(\bar{p}\) beam. Both beams (circulating in the same direction) would be held by the same RF system. Protonium atoms (\(pp\) Coulomb bound states) formed in flight\(^{22}\) in the straight sections of LEAR would emerge straight out of the bends and i) feed experiments on \(pp\) atoms located at the end of a long \(pp\) atom beam-line prolongating LSS2 (Fig. 4), ii) feed conventional \(\bar{p}\) beam lines (after stripping of \(pp\) atoms with foils inside dipole magnets).
2c) **pp minicollider:** pp frontal collisions with c.m. energies up to 4.4 GeV/c$^2$ would be obtainable by injecting protons into LEAR with a second injection located in LSS4. The experimental apparatus would be located around the interaction region in LSS3 (Fig. 4).

Operation (1a) will be feasible with good duty cycle without additional cooling in LEAR and with vacuum at the $10^{-18}$ Torr level. ISR-type vacuum ($\approx 10^{-16}$ Torr) will be necessary for all other operations, especially (1b), (2a), and (2b).

Electron cooling$^{23}$ is necessary for operating efficiently in the mode (2a)$^{19}$ and would boost the performances of all operation modes including (2c) if relativistic electron cooling should prove to work at LEAR energies$^{24}$ and should become available.

Electromagnetic stripping limits the upper velocity of $\bar{p}p$ atoms obtainable in mode (2b) to $\beta \leq 0.6$. Gas, $H^-$ intrabeam, and $\bar{p} H^-$ beam-beam stripping, limit the lifetime of the $H^-$ beam, and beam-beam and intrabeam stripping limit the maximum $H^-$ beam intensity compatible with refilling with fresh $H^-$. A luminosity of $10^{24} \Delta \nu / c s^{-1} cm^{-2}$ is estimated with $10^9$ $H^-$ and $10^8 \bar{p}$ stored in LEAR ($\Delta \nu$ is the $\bar{p}$ velocity in the $H^-$ c.m. system). This luminosity seems to be obtainable with an $H^-$ refilling frequency below 0.1 Hz.

The luminosity estimated for operation (2c) is $\approx 10^{29} s^{-1} cm^{-2}$ with $6 \times 10^{11}$ $\bar{p}$ and $6 \times 10^{11}$ $p^+$ stored in the ring, and a bunch length of 5 m (60 kV RF system).

**PHYSICS POSSIBILITIES AT LEAR**

Figure 5 shows the momentum range that can be explored with LEAR used in the beam-stretcher mode and in the jet-target operation. The

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**Fig. 5** Momentum range of LEAR together with some relevant resonances and thresholds. In the hatched region below 200 MeV/c no excitation functions are known. In the lower part, thresholds of experimental importance are indicated.
momentum range of the extracted beam can be lowered to zero by deceleration in a degrader, with negligible losses if degradation starts below 300 MeV/c. Work at the \( \bar{p}p \) threshold could also be done using the \( \bar{p}p \) atoms produced in flight in the \( \bar{p}H \) overlapping beam mode. The maximum invariant mass accessible is 2400 MeV/c\(^2\) in the stretcher-ring and jet-target operations; it would be possible to raise it to 4400 MeV/c\(^2\) in the \( \bar{p}p \) minicollider mode.

The external beam intensity in the stretcher-ring operation will be \( \sim 10^6 \bar{p} \text{ s}^{-1} \), and it will stay constant independently of momentum over all the momentum range covered by LEAR. This is due to the combined action of cooling and deceleration and to the big acceptance of the LEAR ring, and can be understood immediately from inspection of Fig. 2. Gains exceeding a factor of \( 10^3 \) will be obtainable in the low-energy region, as indicated and explained in Table II.

**Table II. Gains possible with LEAR versus the present situation**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Parameter</th>
<th>Gain</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>All modes</td>
<td>Beam purity</td>
<td>( \infty )</td>
<td>a)</td>
</tr>
<tr>
<td></td>
<td>Duty cycle</td>
<td>( \approx 10 )</td>
<td>b)</td>
</tr>
<tr>
<td></td>
<td>Emittance</td>
<td>( &gt; 10 )</td>
<td>c)</td>
</tr>
<tr>
<td>Extracted beam operation: stop expts.</td>
<td>Stop rate in gas targets</td>
<td>( 10^4 )</td>
<td>d)</td>
</tr>
<tr>
<td></td>
<td>Stop rate in dense targets</td>
<td>( &gt; 10^4 )</td>
<td>e)</td>
</tr>
<tr>
<td></td>
<td>Reduction in stop volume for dense targets</td>
<td>( &gt; 10^6 )</td>
<td>f)</td>
</tr>
<tr>
<td>Extracted beam operation: scattering expts.</td>
<td>Beam intensity below 500 MeV/c</td>
<td>( &gt; 10^3 )</td>
<td>g)</td>
</tr>
</tbody>
</table>

\( \pi^-/\bar{p} \)\(_{\text{LEAR}} = 0 \) because no pions from the AA. \( \pi^-/p \)\(_{\text{present \bar{p} beams}} \approx 10-100. \)

b) Present PS duty cycle \( \approx 0.1; \) LEAR duty cycle \( \sim 1. \)

c) Present low-energy \( \bar{p} \) beams have emittance \( \varepsilon \approx 150 \pi \text{ mm mrad}; \) AA beam decelerated to 300 MeV/c will have emittance \( \varepsilon < 15 \pi \text{ mm mrad}. \)

d) Factor of \( \sim 1000 \) beam intensity. Factor of \( \sim 1000 \) shrinkage of range curve width owing to lower beam momentum and momentum spread.

e) Factor of \( \sim 1000 \) beam intensity.

f) Factor of \( \sim 1000 \) range curve width. Factor of \( > 10 \) beam cross-section.

g) Almost no data as yet available in the literature because \( \Delta p \approx \langle p \rangle \) with present beams. In contrast to this, LEAR acts as a monochromator.

Table III indicates gains of some new approaches that would be possible with the storage-ring operations in LEAR.
Table III. Gains possible with \( \bar{p} \) beams stored in LEAR

<table>
<thead>
<tr>
<th>Mode</th>
<th>Parameter</th>
<th>Gain</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet-target operation</td>
<td>Energy resolution</td>
<td>Optimal use of ( \bar{p} &gt; 10^2 )</td>
<td>a)</td>
</tr>
<tr>
<td>Polarized jet-target operation</td>
<td>Energy resolution</td>
<td>( &gt; 10^2 ) polarization</td>
<td>a)</td>
</tr>
<tr>
<td>( \bar{p}^- ) storage ring</td>
<td>Energy resolution for ( \bar{p}p ) atom X-ray detection</td>
<td>( &gt; 10^3 )</td>
<td>b)</td>
</tr>
<tr>
<td></td>
<td>Population of high-J baryonium below NN threshold</td>
<td>( &gt; 20 )</td>
<td>c)</td>
</tr>
<tr>
<td></td>
<td>domimant P-wave annihilation</td>
<td></td>
<td>c)</td>
</tr>
<tr>
<td></td>
<td>( \bar{p}p ) atom-induced spectroscopy feasible with sensitivity</td>
<td>( \frac{\Delta E}{E} \approx \frac{\Delta p}{p_{\text{LEAR}}} )</td>
<td>d)</td>
</tr>
<tr>
<td>( \bar{p}p ) minicollider</td>
<td>Energy resolution</td>
<td></td>
<td>e)</td>
</tr>
<tr>
<td></td>
<td>Direct access to ( 0^{-+}(\eta_c) ) and ( 0^{++}, 1^{++}, 2^{++}(\chi) ) charmonium states</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Energy resolution is limited only by \( \Delta p/p \) of the circulating beam. With \( 10^8 \) stored articles, \( \Delta p/p < 10^{-5} \) can be obtained with \( e^- \) cooling, while standard spectrometers provide \( \Delta p/p \approx 10^{-3} \).

b) i) By using the Doppler shift of the forward-emitted X-rays by \( \bar{p}p \) atoms formed in flight, ii) by using differential absorbers, and iii) by tuning the Doppler shift by varying the storage energy in LEAR, the accuracy for energy measurements is independent of the X-ray energy and is determined by \( (\Delta p/p)_{\text{LEAR}} \).

c) Atomic cascade develops in vacuum.

d) Resonant frequency can be obtained by varying the velocity of the \( \bar{p}p \) atom and employing monochromatic high-power commercial lasers. Static properties of \( \bar{p} \) (\( \mu, m \)) and strong interaction perturbations to atomic levels can be determined with \( (\Delta p/p)_{\text{LEAR}} \) accuracy.

e) \( \Delta E/E \approx 10^{-3} \) without cooling in LEAR. It could become \( < 10^{-4} \) with relativistic electron cooling.
The physics programme of the low-energy antiproton facility highlights the study of antinucleon-nucleon interactions. Topics of great interest are antiproton annihilation reactions, baryonium spectroscopy, NN resonances and quasi-nuclear NN bound states, and protonium spectroscopy.

Annihilation reactions explore the interior of the nucleon and can therefore provide deep insight into the internal structure of the proton and the neutron. In spite of a great amount of work performed at high and intermediate energies\(^\text{25,26}\) and at rest, the available experimental information is very limited and the dynamics of annihilation reactions is still unknown. The low-energy region that will become fully accessible with LEAR (at present almost no data exist in flight for \(p_{\text{lab}} < 0.3\ \text{GeV/c}\) looks the most promising and natural one for the study of annihilation. Indeed, while at high energy annihilation is just a small fraction of NN interactions, at low energy it becomes the dominant component. By lowering the energy, the annihilation cross-sections approach the unitary limit in each partial wave, while phase space for non-annihilation events shrinks; channels such as pion production and charge exchange can be switched off by going below their threshold, high partial waves in the entrance channel are damped, and the identification of the final state becomes easier. At rest, \(\bar{p}p\) annihilation occurs from discrete states of \(\bar{p}p\) atoms, that form when stopping antiprotons in a hydrogen target. There it is conceivable in some cases to have complete information on the initial state (angular momentum, even spin perhaps) by choosing adequate conditions of the target and by detecting the X-ray emitted in the atomic transition that populates the initial state of an annihilation reaction. This would permit the study of the dependence of annihilation on angular momentum (S-, P-wave annihilation) and maybe also on total spin, and could contribute strongly to the understanding of the annihilation mechanism.

Baryonium spectroscopy is at present considered as being one of the most attractive topics. Several different theoretical approaches lead to the expectation of states strongly coupled to the baryon-antibaryon system and weakly coupled to ordinary mesonic decay channels\(^\text{27,28}\). Baryonium states below the threshold of the relevant \(BB\) channel should be narrow because the coupling to meson channels is dynamically suppressed, and the allowed decay into \(BB\) is inhibited by energy conservation. Baryonium states just above the \(BB\) threshold could be narrow, because phase space keeps the allowed \(BB\) decay small. The experimental signature of a baryonium state, which must be highly elastic and weakly coupled to meson channels at all energies, is therefore expected to be much clearer and more striking at low energy near the \(\bar{p}n\) and \(\bar{p}p\) threshold and at higher energies around the \(\Lambda\Lambda\) and \(\bar{\Xi}\Xi\) thresholds. Indeed most of the baryonium candidates so far observed\(^\text{29}\) cluster in these regions. However, the experimental situation is in continuous evolution because most of the existing baryonium candidates suffer from poor statistics, and for all candidates the experimental information is not enough to assign quantum numbers. All theoretical approaches have in common the expectation of \(qqq\) states which escape the classification of known hadrons among \(qq\) states (mesons) and \(qqq\) states (baryons). Confirmation of baryonium
states of this $qqqq$ nature would open up a new domain for spectroscopy. Understanding the origin of the rules which inhibit the mesonic decays would help to piece together a picture of the dynamics of light quarks in ordinary nucleons. Baryonium spectra could be used to test ideas in order to provide basic foundations for a theory of strong interactions and to show dynamically evidence of colour.

Nuclear physics approaches also lead to the expectation of a variety of resonances and quasi-nuclear bound states in the vicinity of the $NN$ threshold. These states are seen here as 3-quark 3-antiquark states organized in a $NN$ system, where nucleon and antinucleon maintain their identity (like $n$ and $p$ in a deuteron). They are bound by medium- and long-range nuclear forces in a volume with dimensions of the order of 1 fm. These forces are originated by strongly attractive $NN$ potentials that are derived, in one-boson exchange (OBE) models, from $NN$ potentials by $G$-parity transformation of the different boson exchange contributions. The contribution of annihilation (which is not present in the $NN$ case) is not known. The influence of annihilation on the structure and even on the existence of the $NN$ states, and the relation between quasi-nuclear $NN$ states and baryonium ($qqqq$), are subjects that are now being debated and are as yet experimentally unsettled. The observation of $NN$ states and the determination of their quantum numbers could provide deep insight into the nature of OBE potentials (nature and origin of the hard core and of the spin-orbit forces and tensor forces in nuclear physics). Establishing relations between quasi-nuclear states and baryonium states will require bridging the gap between particle and nuclear physics with a deeper understanding of subnuclear processes.

Protonium spectroscopy is of interest for two reasons. One is that the X-rays emitted in certain transitions to the low-lying levels of the $\bar{p}p$ atom can be used to tag initial (atomic) states from which annihilation or transitions to baryonium/quasi-nuclear bound states may occur. The second reason is that measurements of shifts and widths induced by strong interactions on the low-lying $(L, S)$ states of the $\bar{p}p$ atom ($^1S_\text{e}, ^3S_\text{e}, \ldots$) can monitor the existence of resonances and bound states in the corresponding $(L, S)$ channel in the region quite near to the threshold. This region is the hardest to approach experimentally (low beam rates and poor resolution above threshold, high $\gamma$ background below threshold). Shifts and widening of the Coulomb levels are directly connected with the strong $\bar{p}p$ interactions. Precision measurements, typical of atomic physics, look possible owing to the long lifetime of the antiproton, so that $\bar{p}p$ atoms could be used as a testing ground for strong interaction theories (a working theory must predict shift, total width, and decay and annihilation branching ratios of the $(L, S)$ levels of protonium).

Other fields of interest at low energy are $\bar{p}$ interactions with nuclei: $\bar{p}A$ exotic atoms and $\bar{p}A$ annihilation.

Charmonium spectroscopy is the most attractive topic in the high-energy region accessible with LEAR used as a minicollider. The whole charmonium family can be explored with $\bar{p}p$ collisions in LEAR used as a $\bar{p}p$ collider. Antiproton-proton reactions can form directly all members of the charmonium family (in particular the $0^+ (\eta_c)$ and the $0^{++}, 1^{++}, 2^{++}(\chi)$ states not directly accessible with $e^+e^-$ machines). The mass and width of these states can then be measured with a resolution given by the
momentum dispersion of the beams in LEAR. With e⁺e⁻ machines, these states can be reached only via γ transitions from ψ states, with an energy resolution limited by the γ detectors.

A general overview of the physics possibilities opened up by LEAR in the various energy regions and operation modes was given in topical summary talks at the Karlsruhe Workshop and reviewed in Ref. 3. Table II indicates the big improvements possible with LEAR in terms of beam intensity, purity, quality and duty cycle. These gains could solve all present experimental uncertainties connected with low statistics and high background. In the following we shall restrict ourselves to enumerating some points where specific experimental approaches offer additional improvements and qualitatively new physics possibilities.

Experiments at threshold
Use of gaseous targets possible because of the extremely narrow range curve width (0.5 mg cm⁻² H₂ → < 10 cm H₂ gas NTP). Stark mixing drastically reduced → high population of low n atomic states → emission of detectable Lyman (ν 10 keV), Balmer (ν 2 keV), ..., X-ray transitions. Use of these atomic transitions to measure strong interaction perturbations (ΔE, Γ) of atomic levels and to monitor initial states of subsequent annihilation or transition to quasinuclear bound states (x, γ/π coincidences).

̅p̅H⁻ parallel beam approach → beams of ̅p̅p atoms. Atomic cascade in high vacuum → dominance of P-wave annihilation. High-resolution X-ray spectroscopy with differential absorbers and tunable Doppler shift. Induced spectroscopy to study hyperfine splittings conceivable.

Experiments above threshold
a) External transmission target
Access to completely unexplored region below 300 MeV/c incident momentum. Possibility of studying pure S-wave interaction at very low energy and onset of higher partial waves with increasing energy. ̅n threshold (98 MeV/c) can be scanned. Monochromatic ̅n beams possible (̅p̅ interactions: only I = 1 states, no Coulomb distortions).

High resolution and high sensitivity for weakly populated narrow states (baryonium!).
Excitation functions for channels with branching ratios down to the 10⁻⁷ level.

b) Internal jet target
Extreme resolution combined with extreme target efficiency. Polarization experiments with pure polarized atomic beam targets (H₂, D₂, ...).

̅p̅p collider experiments
Access to 4.4 GeV/c² invariant mass states also with quantum numbers ≠ 1⁻⁻ (interesting for charmonium family).
Extreme mass resolution (depends on phase-space cooling applicable).

CONCLUSIONS

LEAR is likely to produce important physics results in a very short time after the beginning of operations. Indeed it will be possible to
enter immediately into an unexplored energy region using present-day
detectors and taking maximum advantage of the high quality of the LEAR
beam.

Use of compact sophisticated apparatuses with high detection capa-
bility will become possible, due to the restricted volume of the interac-
tion region even with gas targets.

Development on the detector sector for extracted beam operation can
go in parallel with implementation of storage-ring operations, which will
permit the most efficient use of the available antiprotons together with
the maximum energy resolution.

The resolution $\Delta E/E$ of experiments in the jet, $\bar{p}H^-$ parallel beams
and $\bar{p}p$ minicollider mode is determined essentially by the momentum dis-
persion $\Delta p/p$ of the stored beam. Implementation of strong phase-space
cooling would permit the measurement of strong interaction effects with
high accuracy ($\Delta p/p \approx 10^{-5}$ with electron cooling) in all interesting
energy regions in an energy domain ranging from protonium to charmonium.

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