ERRATA

page, line 2 11 says:
\[
\text{ratio } \frac{BR(\bar{p}p \to \pi^0\omega + \pi^0\rho + \pi^0\eta + \pi^0\eta')}{BR(\bar{p}p \to \eta_\omega + \eta\rho + \eta\eta + \eta\eta')} \text{ an upper limit of 0.50 could in addition be}
\]
reads:
\[
\text{ratio } \frac{BR(\bar{p}p \to \eta_\omega + \eta\rho + \eta\eta + \eta\eta')}{BR(\bar{p}p \to \pi^0\omega + \pi^0\rho + \pi^0\eta + \pi^0\eta')} \text{ an upper limit of 0.50 could in addition be}
\]

page, line 18 last should be omitted

page 55 should be replaced with figure on next page

page, line 57 5 says:
\[
\text{UMERTO, ECO } \text{Il nome della rosa}
\]
reads:
\[
\text{UMBERTO, ECO } \text{Il nome della rosa}
\]

Reference 14 says:
reads:

Reference 44 has been omitted. It reads:
SEARCH FOR RARE NEUTRAL TWO-BODY CHANNELS IN THE \( \bar{p}p \) ANNIHILATION AT REST

performed by

measurements of high energy \( \gamma \)-rays
using a modular NaI(Tl)-spectrometer
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Lars Adiels

STOCKHOLM 1986
Adiels, L.: Search for rare neutral two-body channels in the pp annihilation at rest (Royal Institute of Technology, Department of Physics, and Research Institute of Physics, Stockholm 1986).

Abstract

Proton-antiproton annihilation at rest in liquid hydrogen has been studied with a modular NaI(Tl)γ-spectrometer. For the purely neutral two-body channels the following branching ratios, some of them not known before, have been obtained:

\[ \text{BR}(pp \rightarrow \pi^0\omega) = (2.38 \pm 0.65)\%, \text{ BR}(pp \rightarrow \pi^0\eta) = (0.82 \pm 0.10)\%, \]
\[ \text{BR}(pp \rightarrow \pi^0\eta') = (0.0015 \pm 0.0007)\% \text{ and BR}(pp \rightarrow \pi^0\pi^0) = (0.06 \pm 0.04)\%. \]

The upper limit for the branching ratio \( \text{BR}(pp \rightarrow \pi^0\eta') \) was found to be 1.1%. For the ratio \( \text{BR}(pp \rightarrow \pi^0\omega + \pi^0\rho^0 + \pi^0\eta + \pi^0\eta')/\text{BR}(pp \rightarrow \eta\omega + \eta\rho^0 + \eta\eta + \eta\eta') \) an upper limit of 0.50 could in addition be obtained. It was also concluded that a substantial part of the annihilation comes from F-wave processes.

In a search for Baryonium or other exotic states, peaks appeared in the singles gamma spectrum corresponding to four possible states with masses 1210±5, 1638±3, 1694 ± 2 and 1771 ± 1 MeV, respectively, with yields having upper limits of 0.1, 0.3, 0.16 and 0.18 %, respectively. Two of these peaks are consistent with data obtained from pHe annihilation. A considerable effort was made to establish the existence of Baryonium created in pp annihilation but it must be concluded that the yield of such states, if they are narrow, seems to be much lower than anticipated. Possible interpretations of these results are briefly discussed.

A pilot experiment for further studies of the \( \pi^0 \) and the \( \eta \) spectra at LEAR was also performed.

Descriptors: Baryonium, γ-ray spectorscopy, pp annihilation at rest, pHe annihilation at rest, Glueballs.
PREFACE

"I sit beside the fire and think
of people long ago,
and of people who will see a word
that I shall never know."

J. R. R. TOLKIEN The Lord of the rings

This thesis is part of the requirement for a Swedish PhD. It is written entirely in English (with the exception of some quotations) and will be defended in Swedish at the Royal Institute of Technology, Department of Physics. The thesis is based on work which the author have performed in the Basle – Karlsruhe – Stockholm collaboration at CERN during 1978 – 1984. The scientific work have been published in five papers, enclosed in Appendix E. Finally in Appendix F the proposal to the experiment PS182, which followed on the results obtained documented here, is enclosed. The experiment PS182 at LEAR has taken data since 1984 and the analysis is in progress.

Since I joined the group in november 1978 I have worked mainly with the analysis once the experiment was set-up. When the data taking was finished in 1981 I got the opportunity to take care of the on-line software for the experiment PS182 and since 1982 I gradually moved over to the new experiment. I left CERN in mid 1984 to complete my thesis at my home institute in Stockholm, after a very interesting and stimulating delay as responsible for the data-taking of PS182. Before the summary I would like to give my thank to some of all the persons involved in the development of this work.

Acknowledgements

The scientific work on which this thesis is based is a team work and could not have come through without all my colleagues and co-writers in the group. It was also dependent on CERN and its experimental as well as computer facilities. The hospitality of CERN and the very international scientific ambience at CERN has been a great source of inspiration during my stay.

Among all the persons in the group and others closely related at the participating institutes to whom I feel indebted I wish to take the opportunity to give a special thank to prof. I. Bergström for giving me the opportunity to join the group, to A. Kerek and I. Bergström for taking special care of me during their sabbatical at CERN coinciding with my first year there. I would also like to thank L. Tauscher who in reality acted as my supervisor both in physics and in skiing for several years. K. Fransson, who travelled a lot between CERN and Sweden induced inspiring discussions as well as P. Pavlopoulos whose original experiment also to a great extent motivated the effort. Among the other senior physicists I would also like to thank A. Nilsson and R. Guigas who never hesitated to take time from their work to help me progress with my tasks. For several parts of the analyses I have worked in close contact with B. Richter whose time in the group will not be forgotten. From a group of three students S. Carius, H. Danared and H. Johansson unfortunately only S. Carius has continued in the group but his help and discussions have been so much more fruitful. Other students D. Hatsifotiadou, J. Repond, D. Tröster C. Findeisen and R. Buser, some of them joining the group so late that they do not appear in those papers, have been very helpful also in private matters. I would also like to give a special thanks to two of the technicians Å. Engström and K. Agehed with whom I have worked in close contact during the set-up of the experiments. Two visitors in the group M. Cooper and M. Hasinoff have been very helpful to me by virtue of their personal qualities and their new ideas. Among the CERN staff I would in particular like to thank the computer-librarian H. Renshall, M. Sendall and his group (DD/OC) and P. Darrulat who once introduced me to particle physics.

The work would not have been possible without the unlimited support from my wife Marianne and my family who have always supported my work with their hearts and souls.

This manuscript was excellently typed by E. Oppenheimer who has also helped in revising the language together with Marianne, any remaining mistakes are however introduced by me afterwards. The manuscript is produced by our \TeX* setting-system and I would finally, still not being able to mention several persons to whom I owe great thanks to, like to thank N. Elander who helped me acquire the necessary equipment for the \TeX*nology at the institute.

* \TeX is a trademark of the American Mathematical Society
Ever since the Dirac-equation [1] was explored and the positron and antiproton were discovered, the subject of matter-antimatter has fascinated many physicists and even laymen. The study of the matter-antimatter annihilation process has played an important role in elementary particle physics for many years. As a consequence of the increasing understanding of the proton and antiproton structure, the antiproton itself has become an important probe for investigating matter, as for example was manifested in the recent pp-collider project at CERN which led to the discovery of the W- and Z-particles.

Although the proton-antiproton system has been extensively studied, the annihilation process is not understood in detail. In particular, experimental information is poor regarding rare neutral two-body annihilation channels, which are hard to study with bubble chamber techniques. In addition, current well established theories are only able to predict the main features of the annihilation process. In the late 70's several groups found evidence for exotic objects named Baryonium, when investigating the proton-antiproton annihilation process. The masses of these objects were reported to be in the 2 GeV region. The interpretation of these results, some of them suffering from poor statistics, was not very clear. As a result, a large number of papers on both experimental and theoretical aspects of the proton-antiproton annihilation were published. Independently, new calculations based on the major theory for strong interaction, Quantum chromodynamics (QCD), have led to predictions of exotic states in the same energy range. Such exotic particles could for instance be objects composed of two quarks and two antiquarks, Baryonium, or of gluons only, Glueballs.

Comments on the pp annihilation process

The most striking feature of the proton-antiproton interaction is the annihilation process. This means that when a particle and an antiparticle are brought together they disintegrate into lighter particles by strong interaction. These particles ultimately decay to stable leptons and photons. The pp annihilation process was studied extensively in the 1960's. Information about the most frequent annihilation channels based on pp annihilation at rest in a liquid target of H₂ is collected in Table 1, where it should be observed that the bubble chamber technique then available was rarely able to distinguish channels with more than two neutrals in the final state.

"Wheresoever the carcass is, there will the eagles be gathered together"

St. Matthew xxiv.28
Table 1

Branching ratios from pp annihilation at rest in a liquid target

<table>
<thead>
<tr>
<th>Annihilation channel</th>
<th>Resonant channel</th>
<th>Branching ratio BR (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td></td>
<td>3.7</td>
<td>2</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>$\rho^0\pi^0$</td>
<td>2.7</td>
<td>2</td>
</tr>
<tr>
<td>$\pi^+\pi^-2\pi^0$</td>
<td></td>
<td>9.3</td>
<td>3</td>
</tr>
<tr>
<td>$\pi^+\pi^-3\pi^0$</td>
<td></td>
<td>23.3</td>
<td>3</td>
</tr>
<tr>
<td>$\pi^+\pi^-4\pi^0$</td>
<td></td>
<td>2.8</td>
<td>2</td>
</tr>
<tr>
<td>$2\pi^+2\pi^-\pi^0$</td>
<td></td>
<td>3.8</td>
<td>2</td>
</tr>
<tr>
<td>$2\pi^+2\pi^-\pi^0$</td>
<td>$\rho^0\pi^0\pi^-\pi^-$</td>
<td>7.3</td>
<td>2</td>
</tr>
<tr>
<td>$2\pi^+2\pi^-\pi^0$</td>
<td></td>
<td>6.4</td>
<td>2</td>
</tr>
<tr>
<td>$2\pi^+2\pi^-2\pi^0$</td>
<td></td>
<td>16.6</td>
<td>3</td>
</tr>
<tr>
<td>$2\pi^+2\pi^-3\pi^0$</td>
<td></td>
<td>4.2</td>
<td>3</td>
</tr>
<tr>
<td>$3\pi^+3\pi^-\pi^0$</td>
<td></td>
<td>1.3</td>
<td>2</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta$</td>
<td></td>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>$\eta\rho^0$</td>
<td></td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>$\rho^0\rho^0$</td>
<td></td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>$\eta\eta$</td>
<td></td>
<td>0.22</td>
<td>2</td>
</tr>
<tr>
<td>$\eta\eta$</td>
<td></td>
<td>3.2</td>
<td>2</td>
</tr>
<tr>
<td>$\eta^+\eta^-$</td>
<td></td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>$4\eta^+4\eta^-$</td>
<td></td>
<td>6.9</td>
<td>4</td>
</tr>
<tr>
<td>$3\pi^+3\pi^-$</td>
<td></td>
<td>2.1</td>
<td>4</td>
</tr>
<tr>
<td>$K\bar{K}m_0(m \geq 0)$</td>
<td></td>
<td>6.82</td>
<td>2</td>
</tr>
<tr>
<td>$\eta\eta\eta^0$</td>
<td></td>
<td>0.014/0.048</td>
<td>5/6</td>
</tr>
</tbody>
</table>

Compared with the electron-positron system, for which the annihilation is well understood, the annihilation of the proton-antiproton system is much more complicated for many reasons. Experimentally the antiprotons have been very hard to produce, requiring very large and expensive accelerator facilities. In contrast to $e^+e^-$annihilation, where the interaction is entirely electromagnetic, the electromagnetic interaction in the pp case is followed by the strong interaction which in this case is entirely responsible for the annihilation process. No reliable theory is so far available since this annihilation process is nonperturbative and involves composite particles. A strong effort to gain a better understanding of pp annihilation both experimentally and theoretically is in particular motivated by the fact that the annihilation process is a genuine quark phenomenon also in the low energy regime. As pointed out the results in Table 1 were obtained using a liquid $H_2$-target. The results from a gaseous target are quite different (see below). The experiment presented in this thesis deals with pp annihilation at rest in a liquid $H_2$-target where the annihilation products are two neutral objects. The experimental set-up was able to detect decay channels with one $\gamma$ + any neutral particle, and one $\pi^0$ + any neutral particle or one $\eta$ + any neutral particle, in the latter cases by studying the subsequent decay of $\pi^0$ and $\eta$, respectively, into two $\gamma$'s (see Table 2). Thus the experiment covers most of the frequent energetically possible neutral two-body channels, since phase space favours the light $\pi^0$- and $\eta$-mesons.

Annihilation and quarks

As can be seen from Table 1 the most frequent annihilation channels are those in which three or more hadrons are produced. This can be qualitatively understood by the application of the quark concept. The idea of quarks was introduced [7] in the early 60's when it first served as a simple tool to formulate SU3 symmetry in strong interactions. Nowadays the quark concept is so well established that it serves as the starting point of any theory of hadrons and their interactions.

Figure 1

Schematic figure of a) Mesons b) Baryons

From the five well established basic quarks* (u, d, s, c, and b) all known hadronic (i.e. strongly interacting) particles can be built. As is well known they are divided into two groups, baryons and mesons. The baryon consists of three quarks and the meson of a quark and an antiquark, both of them kept together by gluons (see Figure 1). All mesons decay (see Table 2) by strong or weak interaction, but the lightest baryon, the proton, is remarkably stable. To our present knowledge the proton does not decay. The lifetime is larger than $10^{32}$ years and thus very much longer than the age of the universe. The quark content of the proton (antiproton) and the mesons built from only u and d quarks is given in Appendix D.

* Several experiments have been carried out in order to search for a sixth quark predicted by theory long ago. It may have been observed by the UA1 collaboration [5] in the above mentioned pp collider project, but so far no final conclusion has been reported.
As already emphasized (Table 1) most $\bar{p}p$ annihilation channels involve the emission of pions. The charged pion has a mean life of $2.6 \times 10^{-8}$ s while the mean life of the $\pi^0$ is only $0.8 \times 10^{-16}$ s. This means that the charged pions survive distances much longer than the detector dimensions while the $\pi^0$ decays (mostly into 2 photons) in the target, a fact which has consequences for the detector design and data analysis.

Most naturally [9] one can consider a model where the three quarks and antiquarks in the proton and antiproton are rearranged into three mesons (see Figure 2a). The immediate conclusion of this model is that only three-body annihilations can occur. Thus the final state should contain three or more mesons due to further decay of the primary mesons. Furthermore, no strange mesons should appear and especially the production of $\phi(S8)$ must be suppressed. This simple model fits $80-90$% of the total experimental data (cf. Table 1). However, $\approx 7$% of the annihilation channels do contain strange particles and there are at least $10$% two-body annihilations. For the understanding of the annihilation process in finer details a more refined model is needed, in particular to treat channels with more than one neutral particle in the final state. For obvious reasons such channels were hard to study with bubble chamber techniques.

Some possible extensions to allow 2-body annihilation channels within the framework of the simple rearrangement model mentioned above are indicated in Figures 2b and 2c, but most theoretical works tend to avoid this question so far. The experimental information on the yields of two-body annihilation channels is not only rare, but sometimes also contradictory when it exists. For instance for the annihilation channel $\bar{p}p \rightarrow \pi^0\pi^0$ the yield is reported by two different groups to be $(0.014 \pm 0.003)$% and $(0.048 \pm 0.010)$%, respectively (cf. Table 1).

Other annihilation models

Among several theoretical approaches to the understanding of the $\bar{p}p$-system (for a review until 1983 see Green [11] and references therein) the potential concept has been extensively used. The potential used has developed from a simple phenomenological nucleon-nucleon interaction potential to more refined potentials in which the quark nature of the associated particles is taken into account. A potential approach predicts only the appearance of two-body annihilation channels, but as shown in Table 1 many-body channels dominate the experimental data. This deficit of the model can, however, be cured to some extent by the construction of many-body channels from weakly coupled resonant two-body channels.

Baryonium and other exotic states

One striking feature of the nuclear potential models, observed first in 1956 [12,13] and developed by Shapiro [14], is that a nucleon-antinucleon force is necessarily strongly attractive. The corresponding deep potential well should thus contain several bound states as well as states in the continuum (Figure 3). Such states were named Baryonium in analogy with the name positronium ($e^+e^-$). The level energies and widths of Baryo-
nium are, however, difficult to calculate because of the uncertain radial position of the hard core and the interference with the annihilation process itself.

In the energy region 0 - 2 GeV the standard QCD theory is not calculable in a perturbation approach. However, there are some models, using simplifications, approximations or further assumptions to make the theory calculable, which agree reasonably well with the measured meson mass spectrum. Furthermore, qualitative arguments show that all possible mesons in this region are found. With "all possible" we mean $q q$ systems where $q$ is $u$, $d$ or $s$. Other flavours are heavier and thus resulting in objects with masses larger than 2 GeV. However, the question must be raised why there would not be meson-like states of the type $q q q$, or states with only gluons, often named Glueballs. This name is a little bit misleading since spherical Glueballs are not stable in QCD according to Robson [15] and a Glueball has to have a torus shape or more complicated geometry to be stable. Therefore, names like "Gluerings" have been suggested. There are several models predicting such objects. In many experiments such exotic states have been searched for.

**Early experimental evidence of Baryonium**

In 1974 an experiment by A. Caroll et al. [16] claimed the observation of a narrow resonance in the $p p$ and $p d$ total cross section at $1932 \pm 2$ MeV having a width of $\Gamma = 9 \pm 4$ MeV. Similar results were also obtained by Chalupka et al. [17]. As no mesons were known or expected in this energy region these objects were interpreted as being something else than ordinary mesons. The interpretation chosen at this time was a $p p$-state slightly above threshold, i.e. a Baryonium state in the continuum. These measurements stimulated an intensive search also for bound Baryonium states, several experiments claimed evidence for structures in this energy region. The results of some of these experiments are collected in Table 3 together with some results from older experiments on $p p$ annihilation and some results from observations of $e^+ e^-$ collisions. All experiments claimed states below 1850 MeV and were suggested to be candidates for either Baryonium or Glueballs. In Table 4 suggestions are collected for Baryonium states in the continuum. The present thesis is very much related to the search for bound Baryonium states, i.e. narrow objects with a mass less than $2m_p$, and was particularly motivated by the findings of Pavlopoulos [18] et al.

**Theoretical background**

A general review of Baryonium is presented in the theoretical work by Rossi and Veneziano [25]. The general impression from this and other surveys is that Baryonium should exist, though different authors may use the name in slightly different ways. Two basic theoretical approaches have been applied extensively to explain Baryonium states; the nuclear potential model and the concept of four-quark states. Here, some nuclear potential results and one four-quark model, the MIT-bag model, will be briefly commented.

**The nuclear potential model**

The first work by Shapiro mentioned above [14] and later reports [31] cover the essential ideas for the possible existence of bound states and resonances in the $\bar{N}N$-system.
Table 3

Some experiments claiming objects with a mass below the \(2m_p\) threshold of \(pp\) annihilation at rest. All those "states" has been discussed as possibly being Baryonium or Glueballs (but not necessarily by the original authors).

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>&quot;Name&quot;</th>
<th>Reaction</th>
<th>ref</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1394±23</td>
<td>&lt;46</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>18</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>1423±10</td>
<td>45±20</td>
<td>(E(1420)) (\rightarrow \gamma \rightarrow \gamma \gamma)</td>
<td>19</td>
<td>1967</td>
<td></td>
</tr>
<tr>
<td>1425±7</td>
<td>80±10 (\rightarrow \gamma(1600))</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>20</td>
<td>1967</td>
<td></td>
</tr>
<tr>
<td>1640±50</td>
<td>220±100 (\rightarrow \gamma(1690))</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>22</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>1646±11</td>
<td>&lt;24</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>18</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>1653±28</td>
<td>&lt;21</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>18</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>1708±30</td>
<td>156±60 (\rightarrow \gamma(1690))</td>
<td>(e^+e^-\rightarrow \gamma + K^+K^-)</td>
<td>23</td>
<td>1982</td>
<td></td>
</tr>
<tr>
<td>1772±6</td>
<td>(e^+e^-\rightarrow X^0)</td>
<td>(pp\rightarrow p + X^-)</td>
<td>24</td>
<td>1971</td>
<td></td>
</tr>
<tr>
<td>1794±1.4</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>(pp\rightarrow \gamma + X^0)</td>
<td>18</td>
<td>1978</td>
<td></td>
</tr>
</tbody>
</table>

Most later calculations are done after a similar scheme based on boson exchange models. The general features of the one boson exchange potential model can be deduced in a systematic way [32], providing a specific coupling strength for each exchange particle. This model or more elaborate ones, taking also two boson exchange into account, parametrized as the exchange of the hypothetical mesons \(\sigma_0\) and \(\sigma_1\) is fitted to low energy \(NN\) scattering data. In analogy with the transformation of the \(e^-e^-\) system into a \(e^-e^-\) system by charge conjugation the \(NN\) system can be transformed to an \(NN\) system like \(pp\) by a G-parity transformation (cf. Figure 3). It then turns out that the NN force, which is repulsive with the exception of the small attractive well which allows the only bound state \(1D\), changes to a strongly attractive force for a large part of its range, mainly due to the fact that the \(\omega\)-exchange is strongly attractive in the NN case.

The major problem with such an approach is that the hard core NN potential due to \(\omega\)-exchange is difficult to determine experimentally. Its G-parity transform which dominates the NN behaviour is thus sensitive to the least known part of the NN potential. In addition, the levels of possible bound or resonant states are pushed and broadened in an uncontrolled way by annihilation. Furthermore, the whole approach assuming point-like objects must be questioned, since it leads to predictions for effects on such small distances that the quark substructure of the nucleons should be taken into account.

Some of the main features of the nuclear model are compared with the MIT-bag model (to be discussed below) and some other models in Table 5. In Figure 4 one of the potential calculations of level energies is compared to one of the MIT-bag calculations.

The MIT-bag model for quarks and gluons

In the MIT-bag model the quarks and gluons are put in a spherical cavity of radius \(r\). The eigenstates are then found using a proper completely antisymmetric wave function. The masses of the states are obtained by minimizing with respect to \(r\) the quantity

\[
E(r) = E_q + E_v + E_0 + E_g
\]

where \(E_q\) is the quark kinetic energy, \(E_v\) is an energy contribution from the confining pressure, \(E_0\) is an estimate of the effects of zero-point fluctuations of fields in a confining sphere and \(E_g\) is the quark - gluon interaction. The only limitation from colour is that the system is a colour singlet. In the MIT-bag model there is room for multiquark states of the \((q)^n(q)\overline{q}\) type besides the usual \(qq\)-mesons and \(qqq\)-baryons. The most interesting case in this thesis is \(n = m = 2\), and the further discussion will be restricted to this case and \(n = m = 0\), i.e. a state containing only gluons. Following Jaffe [39] the discussion about Baryonium-like states will be divided into two parts depending on the angular momentum and the internal geometrical composition of states.

(i) \(S\)-wave \(qqqq\) states analogous to the usual \(S\)-wave mesons and baryons. An \(S\)-wave state of \(qqqq\) is analogous to the usual \(qq\)-mesons and \(qqq\)-baryons, which are "well"
A comparison of different models (from reference [25]). All models are not discussed in this thesis. Further references to these models and theories are: for the Colour chemistry models [35] and for the Topological bootstrap theory [36], The references in the table (54,55) are given as references [37,38] respectively in this thesis.

Table 5

A comparison among various approaches to baryonium physics.

<table>
<thead>
<tr>
<th>Baryonium properties</th>
<th>OCD required</th>
<th>dual topological picture</th>
<th>Nuclear physics approach</th>
<th>MIT bag model</th>
<th>Colour chemistry model</th>
<th>Topological bootstrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>Hysterunon states rather than mesons (diquarks) and baryon states</td>
<td>No E0 (E = 1 states dominate structure)</td>
<td>Linear EXD approach for ( J^P = 1 )</td>
<td>Two levels of states: ( 1 ) and ( \Lambda ) baryonium</td>
<td>Linear EXD approach for ( J^P = 1 )</td>
<td>Only the odd kind of baryonium states</td>
</tr>
<tr>
<td>Trajectory parameters</td>
<td>Computed via duality from the multiperipheral structure of the创头 channel</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Assignments</td>
<td>No specific assignment attempted</td>
<td>Difficult, but many parameters needed for couplings</td>
<td>Usually ignored for those of ref [44]</td>
<td>No specific assignment attempted</td>
<td>No specific assignment attempted</td>
<td>-</td>
</tr>
<tr>
<td>Isospin G-parity</td>
<td>Suppressed by large centrifugal barrier</td>
<td>Suppressed by the centrifugal barrier</td>
<td>Suppressed by centrifugal barrier</td>
<td>Suppressed by centrifugal barrier</td>
<td>Suppressed by centrifugal barrier</td>
<td>-</td>
</tr>
<tr>
<td>Coupling to mesonic channels (a.s.m.)</td>
<td>Allowed</td>
<td>Allowed</td>
<td>Allowed</td>
<td>Allowed</td>
<td>Allowed</td>
<td>-</td>
</tr>
<tr>
<td>Coupling to NN channels (b.s.m.)</td>
<td>Allowed</td>
<td>Allowed</td>
<td>Allowed</td>
<td>Allowed</td>
<td>Allowed</td>
<td>-</td>
</tr>
<tr>
<td>Coupling to K-mesonic states (dual)</td>
<td>High spin states near threshold</td>
<td>Resonances with ( J^P = 1 )</td>
<td>High spin states near threshold</td>
<td>Baryonium and other states with exotic internal angular configuration</td>
<td>Low angular momentum, lower mass states. Weak candidates states under threshold</td>
<td>-</td>
</tr>
<tr>
<td>Nuclear potential</td>
<td>Linear EXD approach to be compared with results of ref[44]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*It is the angular momentum of the NN system.

**It is the angular momentum of the qqq (diquark) system.

understood within the model. The major contribution to the mass of the states comes in this case from the kinetic energy of the quarks and antiquarks. Thus the model predicts, in first approximation, a ratio \( 2:3:4 \approx 700:1100:1500 \) MeV for the masses of \( q\bar{q} \) (mesons), \( qq \) (baryons) and \( qqq \) ("Baryonium") respectively. This would possibly be an explanation for the absence of exotic states in the low mass region. Jaffe [39] has associated four-quark states of this type with the mesons \( \psi(3000), S(980), P(980) \) and \( a(980) \). Other authors have proposed to associate such states with bumps seen in \( \gamma \) annihilations in the mass region \( 3.6 - 4.4 \) GeV [40]. However, states of this type also have a large width into mesonic channels and are therefore not Baryonium-like states with the definition usually chosen which require Baryonium to have relatively long half-life.

(ii) High \( \ell \) (angular momentum) qq (diquark) - qqq (diquark) states corresponding to elongated bag structures. The coupling to mesonic states is supposed to be suppressed by centrifugal barrier effects. A motion which possesses a non-zero angular momentum is plausible to result in an elongated object. If there are two quarks in one end of this structure and two antiquarks in the other, one can assume that they are kept apart by a centrifugal force and thus the coupling to mesons are reduced since it is not possible to form a colour singlet from qq or qqq. It seems reasonable to

* This work was done when these "mesons" were still "alive". They are not listed in the 1984 version of reference 10.
assume that it is the colour flux lines that keep the system together while the angular momentum provides a centrifugal barrier that prevents the quarks and antiquarks to combine to ordinary mesons. Using the assumption that string-like hadrons are tubes of colour flux lines which terminate on colour charges at the ends K. Johnson [41] found that the first narrow state, with spin 2, has a mass about 1.6 GeV. The bag model also predicts that states of high spin (high mass) should be more narrow. States of this type could be candidates for Baryonium states.

Glueballs

One distinctive feature of the MIT-bag model is that also a state consisting of only gluons must have a mass [42], a prediction which is not a priori true for other models. A naïve MIT-bag model gives a mass of 960 MeV for the lowest glueball state. However, more realistic calculations increase this mass to above 1300 MeV. Some MIT-calculations on masses for glueballs are collected in Figure 5.

assume that it is the colour flux lines that keep the system together while the angular momentum provides a centrifugal barrier that prevents the quarks and antiquarks to combine to ordinary mesons. Using the assumption that string-like hadrons are tubes of colour flux lines which terminate on colour charges at the ends K. Johnson [41] found that the first narrow state, with spin 2, has a mass about 1.6 GeV. The bag model also predicts that states of high spin (high mass) should be more narrow. States of this type could be candidates for Baryonium states.

Quantum chromodynamics (QCD), as all quantized field theories, has to be regularized and renormalized in order to give results which can be compared with experimental data. Generally, this is accomplished with a perturbative expansion, but in QCD there are problems which are not amenable to a perturbative treatment. This problem is not unique to QCD, but the availability of nonperturbative methods of analysis is particularly important, since the calculation of mass spectra hinges on them.

In order to solve these problems, Wilson proposed [47] in 1974 a formulation of QCD to provide a nonperturbative regularization, which has led to the very important result of proving confinement, as well as to estimations of glueball masses. The theory is defined on a hypercubical lattice in Euclidian space-time with a spacing \( a \). Matter fields are only defined at the lattice points, but the gauge dynamical variables are finite group elements \( U_a \) associated with links, from \( x \) to \( x + \mu a \), on the lattice. There is an action \( S \) consisting of \( S_g + S_m \) where \( S_g \) is the gauge field action and \( S_m \) is the action from the matter fields. \( S_g \) is built up from terms depending on colour exchange in each lattice point. In the continuum limit \( a \rightarrow 0 \) this formalism is able to regularize the theory with the proper normalization. Numerical "experiments" show that a lattice spacing of \( \approx 0.11 \text{ fm} \) or less is enough to obtain stable results which is reasonable since the typical scale for hadronic phenomena is 1 fm.

Several authors [45,46] have calculated the mass for glueballs within the framework of lattice theories. However, the technical (computer resource) problems are substantial. The results from different attempts are slowly converging (sometimes with a scale-factor) and some results are given in Figure 5. A comparison with the theoretical estimates of the masses from bag models is also done.

Conclusion

There exists several models predicting new exotic states in the 0–2 GeV region, but they all suffer from lack of experimental data, since they contain parameters which have to be fixed by experiments. From the experimental point of view there are a number of claims that new states have been found. However, some of these claims suffer from poor statistics and others are questioned by new experiments. The work described in this thesis was to a great extent inspired by the fact, that it should be possible to reach four-quark states \((qq-qq)\) as well as Glueballs in the annihilation of \( pp \) at rest and it might be possible that such states \((X^0)\) are populated in the two-body process \( pp \rightarrow \gamma X^0 \), where the energies of the \( \gamma \)-rays should fall in the energy region 0-1 GeV, which can be studied with NaI(Tl)-detectors at a reasonable cost.

Lattice QCD and glueballs

For a long time the use of the bag models was the only method to make reasonable numerical estimates of masses of particles, as it is not known how to make calculations of many observables with basic QCD (see below). However, recently there are new calculations on glueball masses done with a new approach to the QCD problems, namely the use of the lattice gauge concept. These calculations emerged from attempts to solve basic problems with QCD but has also resulted in estimates of glueball masses which gave similar results as the bag model. Unfortunately, the masses of the bosons and mesons are still difficult to calculate.
CHAPTER 2
EXPERIMENTAL SETUP

"It is a capital mistake to theorize before one has data."

Sir ARTHUR CONAN DOYLE, Scandal in Bohemia

Requirements on the experimental equipment

As emphasized in the preceding section the main aim of the work presented in this thesis was to search for Baryonium states and for rare two-body channels where one or both particles decay by gamma-emission. Thus, the main experimental device needed was a gamma detector with good efficiency and resolution. Studies of the pp-system at rest means that the highest available momentum is equal to the proton mass. Thus the detector had to cover a range up to 1 GeV. The device chosen was a big modular NaI(Tl) detector described in detail below and in Paper I.

Furthermore, it is desirable to determine the multiplicity of the pions since the decay of Baryonium could be dominated by one channel and thus a window on the multiplicity spectrum could help to reduce the background. Since the dominant neutral particle is the n° which decays mainly to two γ-rays (cf. Table 2) it is also desirable to have two γ-detectors operating in coincidence mode. The ideal detector is one having 4π solid angle, including a magnetic spectrometer for the charged π and having almost no mass acting as a secondary source of radiation, could not be constructed nor for technical neither for economic reasons. Furthermore, since the experiment had the character of a pilot experiment for further studies, the detector had to be simple and a poor solid angle had to be accepted. This simple equipment offers still some experimental possibilities but also some obvious experimental difficulties.

Below some experimentally important remarks are made before the final set-up is described.

• Neutral decay products

One objective of the experiment was to study poorly known neutral pp annihilation channels. All the neutral particles, to be considered, decay on a time scale which makes it difficult to measure their energy before they have decayed. The final decay products are usually two or several γ-rays which results in a continuous spectrum with an approximately exponential fall towards higher γ-energies. However, both n° and η (and to some extent ω) have interesting decay properties which makes it possible to study monochromatic particles by measuring only one of its decay γ-rays (see below).

• Two-body annihilation channels

Experimentally two-body annihilation channels play a special role, since the system is well determined if one of the two decay particles is detected. This fact permits experiments with much less costly equipment than when simultaneously several particles have to be detected for the reconstruction of a certain event.

• Decay kinematics

In appendix A the kinematics relevant for this thesis is presented in greater detail. One central observation is that one can detect monoenergetic particles decaying into two γ-rays by measuring only one of the decay γ-rays and thus measure neutral two-body channels with one single γ-detector. This is due to the fact that the two decay γ-rays form a uniform distribution, with a maximum (and minimum) value depending only on the velocity of the decaying particle.

• Target

For several reasons we have used a liquid H₂ target:

(i) One obtains different results from annihilation in a gas target and a liquid target. This is due to the fact that annihilation occurs from different initial states. In a gas target the annihilation occurs predominantly from a P-wave, whereas in a liquid target Stark-mixing is shaking the system down to an S-wave state before annihilation takes place. As the n°π° channel is restricted to come from P-wave its branching ratio is dramatically different in a gas and a liquid target.

(ii) The poor quality of the p-sources (before LEAR) and the big momentum spread implies that one must have a big enough stopping power in the target region. This is difficult with a gas target.

(iii) The pp is not in a well defined initial isospin state. However, a neutron target is not feasible and for a heavy nuclide the Fermi motion is distorting the relevant part of the spectrum.

For the Baryonium search (see above) a He target was also used.

The experimental equipment

As emphasized above the purpose of the experiment was to study the proton-antiproton annihilation at rest resulting in γ + any other particle(s), or (n° or η) + any other particle. As is well known (cf. Table 3) the n° and sometimes the η decay into two γ-rays. The fact that studies of these particles in two-body channels can be done by measuring accurately only one photon means that one good NaI(Tl) γ-calorimeter was needed. A second NaI(Tl)-calorimeter was used to study coincidences. However, the coincidence count rate was very low and this detector combination served only as a pilot experiment for later studies at LEAR.

In addition a good p-beam with a beam telescope was needed in order to provide a trigger and separate the antiprotons from other particles in the beam in particular negative pions. The experiment included also multiplicity counters for both γ-rays
and charged particles. Below the experimental set-up is described item by item. The schematic layout can be seen in Figure 7.

The antiproton beam

As a source for p's the electrostatically separated so-called K_{23} beam at the CERN proton synchrotron (PS) was used. The beam elements together with its optical equivalent is shown in Figure 6. The optimum efficiency was found at a beam momentum of 600 MeV/c in an earlier experiment \cite{48} using the same beam line. At this beam momentum the beam was fine-tuned several times a day to optimize the stop rate. A maximum stop rate of \approx 250 p's per machine burst was obtained. The same beam line was used in both the 1979 and the 1980 runs.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{The beam K_{23} and its optical equivalent.}
\end{figure}

The symbols stands for, PT = Production target, Q = Quadrupole magnets, B = Bending magnets, SM = correcting magnets to the Separator S, \Delta P = momentum slits, BS = Beam stopper, \Delta M = mass slits and FT = Target.

The antiprotons are produced by letting the proton beam of the PS hit an internal tungsten target. The particles around a given momentum (in our case 600 MeV/c) are collected with a \Delta p/p of 1 % into a total acceptance of 8.7 msterad. This beam of particles is focussed and bent into an electrostatic separator. After passing the momentum defining slit (\Delta P) the beam is again focussed and passing a mass slit (\Delta m).

Finally, the beam is bent into the experimental area and focussed. However after all this beam manipulation the beam still contains all the long-lived negative particles with the same momentum produced in the production target.

The beam telescope

In order to distinguish between p from K\(^-\), \pi\(^-\) and e\(^-\) with the same momentum, a beam telescope was constructed, which consisted of four scintillation counters (T_0, T_1, T_2, T_3) and one Čerenkov detector (Č). The lay-out is shown in Figures 6 and 7. Between the counter T_2 and the multi-wire proportional chambers (MWPC) (see Figure 7) there were placed carbon plates (6-7 cm) to degrade the beam in order to obtain the maximum of the stopping distribution at the center of the target.

The counter combination T_0 - T_1 T_2 was used in the time-of-flight mode, and the Čerenkov counter discriminated at \beta = 0.67. From this we could define two triggers, one for p and one for \pi\(^-\) as follows

\begin{align*}
T(p) & = (T_0 - (T_1 + T_2)) \text{ time}=p \\
T(\pi^-) & = (T_0 - (T_1 + T_2)) \text{ time}=\pi^-
\end{align*}

(Here Č indicates that the Č is in anti-coincidence mode, \bullet coincidence and - (minus) a delayed coincidence. The index h or t refers to the discriminator level which is set high for p and at just above noise threshold for \pi\(^-\)). The time separation between p and \pi\(^-\) was nominally 21.6 ns. The first trigger was also used as a p stop trigger.

The separation power is shown in Table 6. The counter T_3 placed just in front of the target defined a beam size which was smaller than the target. In order to keep the annihilation process within a reasonably small region, liquid hydrogen (helium) was used which enabled the target to be sufficiently thick to stop p within the target after \approx 15 cm. A target container with a cooling system was provided by the CERN target group \cite{49} for each data-taking period. The target used in 1979 could also be used for helium and thus data for the process pHe \rightarrow \gamma + any other particles (Paper IV) were consequently produced only in the 1979 run. The possibility to tune the beam to both \pi\(^-\) and e\(^-\) was also used for calibration purposes.

The \gamma-ray calorimeters

For the main part of the experiment, two different NaI(Tl)-calorimeters were used. The so-called SECTOR, which was by far superior for E_\gamma \geq 100 MeV, was a modular (54 units) detector in a single housing covering 1/13 of 4\pi. In addition a 12\(^\circ\) x 10\(^\circ\) cylindrical mono-crystalline NaI(Tl) was used for the construction of \pi\(^0\) and \eta energy spectra (Paper V). The \pi\(^0\) and \eta spectra so obtained were merely used for tests for a later experiment at LEAR (see Appendix D) and thus the performance of the 12\(^\circ\) NaI(Tl)-detector was less important.
Table 6

The beam telescope performance.

With a trigger which required only $T_0, T_1$, and $T_2$ in coincidence a ratio of $\approx 1$ for $\pi^-/\rho$ was obtained. Then by using the beam telescope we can gain the factors given below. It should be noted that although the trigger is virtually free from unwanted particles ($\pi^-/\rho \approx 10^{-4}$) after this telescope, secondary particles are also produced in the target.

<table>
<thead>
<tr>
<th>Improvement in the intensity ratio $\pi^-/\rho$</th>
<th>gain factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$ in coincidence</td>
<td>$&gt; 5$</td>
</tr>
<tr>
<td>also $C$ in anti-coincidence</td>
<td>$&gt; 12$</td>
</tr>
<tr>
<td>also time requirement on $T_0 - (T_1 \cdot T_2)$</td>
<td>$&gt; 175$</td>
</tr>
</tbody>
</table>

The SECTOR-detector

The SECTOR-detector was the main component of the experimental set-up and Paper I is devoted to describing its development and performance. It was the prototype of what became known as the Crystal Ball at SLAC [50]. The layout is shown in the following Figure 8 as well as in addition to several relevant figures in Paper I.

The SECTOR-detector* was built from 54 NaI(Tl) modules. All modules were similar in shape but had for geometrical reasons differences in dimension of up to 12%. Each module was a truncated equilateral triangular pyramid ($b \approx 13.5$ cm at the wide base, $h \approx 39$ cm) of polycrystalline NaI(Tl) and was wrapped in white paper and in aluminized mylar for optical separation. Through a hole with a diameter of 50 mm at the outer triangular surface an air light-guide was fitted towards the glass window of the aluminium housing. A photomultiplier tube was connected to each module by a second air light-guide into which light could also be injected from the light pulser (see below)**. The multipliers were magnetically shielded by 1 mm of $\mu$-metal and a housing of $\approx 5$ mm iron. The specifications† were tested individually for each module before packing into the common housing. All modules met the resolution requirement. Nine modules did not fully meet the uniformity requirements and were therefore placed in the outer ring of the assembly (No. 25-54 in Figure 9) where less energy was accepted in each event and thus the performance was less critical. Figure 10 shows the performance of a typical module.

As mentioned all the 54 individually wrapped modules were closely packed in a sealed

* Manufactured by Harshaw Chemical Co., Solon, Ohio, USA.
† The PM's were SRC L50BOI or KTC XP2202B, which are semi-fast, $\phi$ 50 mm, 10 stage tubes
** These two air light-guides were the main reason for the relatively poor light output of the modules, 7% of a 2" x 2" cylindrical NaI(Tl) placed directly on the tube which however, was acceptable for the energy range used.
†† See Paper I for details about the specifications.

A vertical and a horizontal cut through the experiment. The main detector systems are described in detail in following figures.

The symbols are as follows, $T=H_2$ Target
$S=$scintillation counters $T_0-T_5$, $M=$moderator (6-7 cm carbon), $MW=$Multi Wire Proportional Chambers,
$C=$Cerenkov detector
and $FP=$ Front plastic (veto scintillation counters)
Figure 8
THE SECTOR

Schematic picture of the SECTOR-detector set-up. Only the modules are shown. Technical details and specification can be found in Paper I.

Figure 9
Projection of the SECTOR. You stand in target and look on the SECTOR.

single aluminium housing. The stacking was done so that the arrangement cut out a honeycomb from a hollow sphere with an inner radius of 25 cm and an outer radius of ≈ 64 cm. The honeycomb-shaped projection can also be seen as three rings with 6, 18 and 30 modules in each (see Figure 18 in chapter 4).

To discriminate charged particles from neutrals entering the γ-ray detector there was a thick scintillation plastic veto-counter between the target and the detector (see Figure 7). Furthermore, in all places where the mechanics and support allowed it, the part close to the target was covered by four plastic counters to veto charged particles entering from other sources than the main interaction region.

All PM's for the SECTOR itself and surrounding plastic counters were fed with high-voltage (HV) from individual channels. Once the calibration was done this HV was kept constant for each data taking-period, and any drift in the calibration was taken care of in the off-line analysis (see below).

In the 1979 run a negative HV was used. This had the drawback that irrecoverable gain losses occurred (up to several % in one day). Thus the HV voltage was changed to positive for the 1980 data taking, which however had the drawback of causing non-linear response for high energy inputs. The different PM bases are shown in Figure 11.

Each PM was read out individually in two different lines in order to have both a large dynamic range and still keep a good precision in the low energy range where most modules have some energy deposit due to escapes from the module actually hit. Each line fed an 11 bit ADC (LeCroy 2249 W). The ranges were set to ≈ 0–1 GeV for the high channel and 0–100 MeV for the low channel.

The light pulser of the SECTOR

In order to monitor and control the stability of the SECTOR-detector, a light pulser was developed. The construction used is schematically described in Figure 12. The pulser consisted of a light source, a light attenuator, a light diffuser, a distribution system, and a reference module with a radioactive source. The setup was constructed in a modular way so that the main unit, the light diffuser box with a filter wheel containing six filters, and its remotely controllable electronics also served as a holder for the light source tower and electronics. The reference module (a 2" x 2" NaI(Tl) crystal and a 22Na source) were placed in a lead shield in the same thermally shielded box as the SECTOR itself. The light pulse was produced by a xenon flash tube of the type FX 280°. This pulse was shaped so that it resembled the pulse from the NaI(Tl) modules. The intensity

* Manufactured by EGG Electro Optics Division, Salem, Mass., USA.
could be adjusted continuously so that the light output after filter attenuation covered a range corresponding to 20-1000 MeV. But, once set, it was kept constant during the run.

After attenuation the light was diffused in the diffusion box. Then it was distributed by 56 fiber light guides* each one of them with a diameter of 1 mm and a length of 2 m. 54 of these fibers were connected went to their respective modules via a small hole in the second air light guide, one fiber was led to the reference crystal, and finally one fiber led to a special PM serving as a light pulser trigger. The possibility to check the LP against the 1.27 MeV line of $^{22}$Na showed that running the LP continuously with 5 Hz deteriorated the light output from the flash bulb by $\sim 1\%$ per week. A resolution of 2-4 % was obtained for selected flash bulbs. The LP was also used to check the linearity of the electronics and read-out system of the modules up to an energy range corresponding to 1 GeV.

12" NaI(Tl)

The second calorimeter was the same detector as the one used by the collaboration in an earlier experiment [18] on $p\bar{p} \rightarrow \gamma$ + anything. In our work, however, it was only used for the coincidence analysis where the performance was less critical.

* Manufactured by Fiberoptik-Heim AG, CH 8707 Uetikon am See, Zurich, Switzerland.

The cylindrical detector is described in reference [51] and in Figure 13. The NaI(Tl)-crystal ($12" \times 10"$ cylindrical) was surrounded by thick scintillation counters to enable electronic collimation. The $\gamma$-rays were further collimated by a lead collimator ($\phi_{\text{inner}} 12$ cm $\times 12$ cm deep). In front of the crystal there was one thick and one thinner scintillation veto counter to discriminate between charged particles and $\gamma$-rays entering the detector. The collimation had to be weak in order to maintain a large solid angle for the coincidence experiment.

**Multiplicity counters**

With the aim of reducing the background and identifying the decay of a possible exotic state, a set of multiplicity counters covering a solid angle of about 80% was constructed. This set of detectors are in the text below named the TONNE (inner, outer) from the German word for barrel. However in the quantitative analysis the requirement of identifying the final state of a decay channel reduced the statistics too much because of the poor overall efficiency, and thus the information from the TONNE detectors was not of much use in the final analysis. The detectors are shown in Figures 14 and 15.
The light pulser (schematic). Not shown are the motor and the encoder for the diaphragm, and an additional retractable filter between the diaphragm and the filter wheel.

The inner TONNE-detector was constructed to measure the charged particle multiplicity and consisted of 30 scintillator strips, each one 1 m long and 1 cm thick, arranged in a cylindrical shape with a diameter of 30 cm. They were held in position from the outside by an aluminium cylinder. From the inside they were supported by the slightly wedged shape of the slabs and by a black paper cylinder, which also served as protection for an aluminized mylar wrapping applied for the optical separation of each module. Each detector strip was coupled individually to a photomultiplier (PM). The signals were amplified and the threshold was set for optimizing the efficiency of minimum ionizing particles. The signals from all 30 strips were read out by two 16 bit pattern units in CAMAC.

The outer TONNE-detector was constructed to measure the photon multiplicity, and was located outside the inner TONNE on a 0.7 cm thick iron cylinder. It was made of 60 identical modules, each one 0.5 m long and having an angular width of 12 degrees.
The modules were sandwiches of lead and scintillator plastic (see Figure 15 for details). Each module was connected to a PM via a light guide and read out individually via a bit pattern unit in CAMAC. The thresholds were adjusted so that an isotropic count rate was obtained when a small carbon target was irradiated in the center of the TONNE. Two holes were cut out in the $2 \times 3$ central modules on each side of the cylinder in order to avoid any interaction with matter before the $\gamma$-rays reached the NaI(Tl)-detectors (Figure 14 and 7).

Before data could be taken the equipment had to be tested and calibrated. The requirement for the inter-calibration of the modules was that the energy calibration for any module should not vary by more than $\approx 10\%$ from its nominal value. Once this calibration was established it had to be monitored. However it was not corrected on-line. Instead any variation during data-taking was corrected off-line in conjunction with the final calibration (see next chapter). Furthermore, all equipment had to be monitored during the run so that any temporary malfunction of the equipment could be corrected for.

**Calibration**

Before the run there were three possibilities for calibration, a source calibration up to a few MeV, the use of an electron beam or the 129.4 MeV $\gamma$-rays produced from the reaction $\pi^- p \rightarrow n + \gamma$. None of these methods could however be used during data-taking without interrupting it, but a source calibration record was made every morning. Finally, off-line after the run the upper edge of the $\gamma$-spectrum ($E_{\text{max}} = m_p$) and the energy of $\gamma$-rays originating from the reaction

$$ pp \rightarrow \pi^0 + \omega \text{ or } \rho^0 $$

could be used for calibration. For the $12''$ NaI(Tl) crystal the calibration was somewhat easier since it consisted of one big module and hence no inter-calibration had to be done. Furthermore, minimum ionizing particles due to high energy cosmic rays could be used to check the stability of the $12''$ NaI(Tl)system in contrast to the more complicated SECTOR case. This cosmic ray calibration could be performed simultaneously with interruptions done for the source-calibration of the SECTOR. The 2.38 MeV Compton edge of $^{228}$Th was used for inter-calibration and absolute calibration of the SECTOR modules at low energies. The high voltage of the PM's was adjusted so that all modules
had the same gain after feeding the signal through the same amplifier. The same procedure without any adjustment of the high voltage was also applied once early every morning to check the stability. This procedure was performed also in between beam periods to keep record of the stability of the equipment. For the 12" NaI(Tl) detector we used $^{228}$Th ($E_y=2.62$ MeV) for calibration at low energies.

Before the final set-up the beam was tuned for electrons in order to check the energy calibration and the linearity by putting the detector in the target position. This check was limited by the precision in momentum to which the beam could be tuned ($\approx 2\%$). In the 1979 run the non-linearities were negligible (from calibration points in the pp data and from the light pulser (LP) data) and no correction was necessary. In the 1980 set-up a few modules became non-linear above 400 MeV. This deviation was still reflected in the resolution at high energies after correction. The response of the 12" NaI(Tl) detector was well-known from earlier experiments [18], and the detector was therefore not calibrated in the electron beam in this experiment.

The calibration described above was not sufficient for the experiment, where the energy of the $\gamma$-ray was distributed in several modules. Thus the calibration was important in the energy range where the shower properties are dominant. At an energy $\approx 100$ MeV three calibration points can be obtained by tuning the beam for $\pi^-$ (see Figure 18 in chapter 4). These were:

- $\pi^- p \rightarrow n\gamma \hspace{1cm} E_\gamma = 129.4$ [MeV]
- $\pi^- p \rightarrow n\pi^0 \hspace{1cm} E_{\pi^0} = 54.9$ [MeV]
- $E_{\max} = 83.0$ [MeV]

The beam was thus tuned to stopping $\pi^-$ before and after each pp data-taking period, and the $\pi^- p$ data were stored on magnetic tape and used in the final calibration, which was done off-line after each run period. The data were also used for calibration for the on-line data-taking monitoring program.

**Stabilization**

Once the calibration was established it had to be stable over a long period of time however with no possibility to control it in a direct way. In order to maintain the calibration, data were taken with the light-pulser source described above approximately once every 4 hours for a few minutes and stored on magnetic tape. A survey of these data and a comparison with the source data showed that the accuracy was much better for the LP data, and thus the source data were only used for a consistency control.

This scan of the data from the light pulser showed very different features for the different run periods of 1979 and 1980. As a consequence, the high voltage supply of the photomultipliers was changed between the runs. The modification thus made proved to be satisfactory and the 1980 LP data did not vary by more than $\pm1.2\%$ for any module except for short periods which were anyhow disregarded in the data analysis for other reasons. Therefore it was decided after tests that no off-line correction were needed for the 1980 data and therefore the following procedure was only applied to the 1979 data.

The off-line calibration was done after the full run period so that all the information about the performance of the modules was known in advance. Therefore, after comparing the LP data and the source data the decision was taken not to further correct the 1980 data. After establishing a reference value, the LP data were fitted for each time interval with a second degree polynomial. This procedure gave an individual time-dependent expression for each module. The coefficients thus obtained were then introduced into the off-line analysis program "SECTOR".

Once it was known that the light-pulser data and the source data gave consistent results we could use the LP results alone since they were more accurate and more frequent.

Finally, the light-pulser itself had to be stabilized in order to avoid additional errors from instabilities in the light bulb or gain shifts in the PM's and amplifiers. Thus a time-dependent coefficient for the reference value $A_{ref}$ defined as $A_{ref} = P_{Source}(t) / P_{Source}(0)$ where $P_{Source}(t)$ is the peak position at time $t$ was applied to the data.

**Data - taking system**

The data-taking, the control of the experiment and the monitoring were all done with a PDP 11/34* computer. For interfacing between the computer and the electronics a standard CAMAC interface was used.

The fast trigger $T$ was built from standard NIM units (see Figure 16). The master trigger was defined as

$$M = T(p_{stop}) \cdot s_\gamma$$

where $s_\gamma$ denotes that the inner 24 modules contained more than 10 MeV equivalent energy and no veto plastic scintillator was fired. This trigger opened a gate (700 ns) for the all ADC's of the "Sector". After conversion the data were read into a buffer in the computer, together with the other relevant information. In order to take data for tests and calibration (e.g. LP-data), the computer could change the trigger by means of output registers in a well defined way. Only in the case of $\pi^-$ data the trigger had to be changed manually.

The data-taking program used was meanwhile developed by the CERN DD/OC group to be CERN's standard data-taking program for PDP's. As this program was not final at the set-up of the experiment a considerable time was invested in testing the program to secure data integrity.

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* PDP 11/34 is a trademark of Digital equipment corporation
The main trigger and the different test triggers are all built together. The open ends are constant levels used by the computer to control the experiment. The symbols are T = Timing filter amplifier, C = Constant fraction amplifier and FP = Front plastic (the charge veto counters).

A. A. MILNE, Winnie-the-Pooh

The object of the analysis was the inclusive $\gamma$-spectra from $\bar{p}p$ and pHe annihilation at rest. If the annihilation at rest results in two particles they both have well defined energies depending on their masses only. On the other, when hand an annihilation at rest results in three or more particles, it gives rise to a continuous energy distribution. Thus, when one particle is produced together with a single $\gamma$-ray the recoil of the particle is visible in the $\gamma$-spectrum as a monoenergetic peak. Also, if one particle is produced together with a $\pi^0$ this can be seen in the $\gamma$-spectrum, since the $\gamma$-rays from a monoenergetic $\pi^0$ decay in motion will be distributed as a "box" in the laboratory frame. Details about the relevant kinematics for two-body annihilation are given in Appendix A.

The analysis consists of three parts.

1) Analysis of the singles $\gamma$-ray inclusive spectra from $\bar{p}p$ annihilation at rest, where we were interested in:

- monoenergetic $\gamma$-rays with $90 \text{ MeV} < E_\gamma < 938 \text{ MeV}$
- monoenergetic $\pi^0$ revealing themselves as box edges with $E_{\gamma_{\text{max}}} < 933 \text{ MeV}$

where because of statistical reasons only the high energy box edge ($E_{\gamma_{\text{max}}}$) can be observed.

2) Analysis of the singles $\gamma$ inclusive spectra from pHe annihilation at rest. This analysis is different from the search for monoenergetic $\gamma$-rays in $\bar{p}p$ data. Here we studied in particular the region $50 < E_\gamma < 500 \text{ MeV}$ because of the presence of neutrons and Fermi motion of the nucleons.

3) Analysis of the coincidence spectra between the two detectors, the SECTOR and the 12" NaI(Tl). Where we studied the $\pi^0$ and $\eta$ spectra at low momenta. This in-
vestigation should be considered mainly as a pilot experiment for future experiments at LEAR.

Items 1, 2, 3 are commented more in detail in the following subchapters.

**Singles $\gamma$-ray inclusive spectrum analysis**

In the singles $\gamma$-spectrum we searched the data for any structures corresponding to $pp \rightarrow \gamma + X$ where $90 \text{ MeV} < E_\gamma < 550 \text{ MeV}$. For the region $E_\gamma > 550 \text{ MeV}$ the analysis was restricted to the data from 1979 because of the worse resolution at high energy in the 1980 data. For the same reason the search for structures corresponding to $pp \rightarrow \pi^0 + X$ (which is visible at higher energies only) was limited to the 1979 data sample.

The analyses of the processes $pp \rightarrow \gamma + X$ and $pp \rightarrow \pi^0 + X$ described below required an estimate of the shape of the inclusive $\gamma$-spectrum. As the detector is modular, and the shower properties are such that the energy is distributed in several modules, the $\gamma$-spectrum had to be constructed off-line after the data-taking was finished. This estimate and the construction of the resulting from background processes were common for both analyses and consisted of the following steps.

1) Off-line reconstruction of the energy spectrum including final calibration and stabilization.

2) Monte-Carlo (MC) simulation of the background originating both from known two- and multi-body final states.

3) Parametrization of this background.

The analysis of the singles $\gamma$-spectrum is described below in two parts ($pp \rightarrow \gamma + X$ where $X$ is unknown and $pp \rightarrow \pi^0 + X'$ where $X'$ is a known meson).

**Off-line reconstruction of the inclusive singles $\gamma$-spectrum**

The modular structure of the SECTOR and the nature of shower production distributed the energy from one $\gamma$ into several modules. Thus, the energy deposited in different modules had to be added up. To do that in a consistent and correct way we had to intercalibrate the modules absolutely and keep track of any drift during data-taking. Furthermore, we had to veto any charged particles and assure that one and only one $\gamma$ is measured. This was done with the veto plastic scintillators and some topological cuts in the algorithm used for adding the individual energy information from each module.

The first step in the off-line analysis was to establish the absolute intercalibration. This was done with data from the reactions

$$(\pi^- p)_{\text{rest}} \rightarrow n \gamma \quad \text{and} \quad (\pi^- p)_{\text{rest}} \rightarrow n \pi^0 \rightarrow n \gamma \gamma$$

taken before each run period as described above.

We found a calibration factor $a_\nu$ for each module ($\nu$) in the following iterative way. Starting with the rough source calibration by setting $a_\nu^{(1)} = 1$ we calculated the peak position $c_{\nu}$ for each module whenever that module contained more than 60 % of the total energy. Now a new calibration factor $a_\nu^{(2)}$ could be calculated as

$$a_\nu^{(2)} = 1 + \left( \frac{\bar{c} - c_{\nu}}{c_{\nu}} \right)$$

where $\bar{c}$ denotes the average peak position. The process converged satisfactorily after three iterations. This procedure worked well for the inner 24 modules but for the other 30 a small correction had to be applied to correct for energy escapes. This correction was estimated with a Monte Carlo simulation using the program EGS [53]. The result of this intercalibration can be seen in Figure 17a, where we in this way obtained an FWHM of 5.5 % as compared to 12 % from the rough source intercalibration. The energy scale was determined from the peak position 129.4 MeV for $p^- p \rightarrow n \gamma$ and the two box edges (54.9 and 83.0 MeV) from $\pi^- p \rightarrow n \pi^0 \rightarrow n \gamma \gamma$ corrected for the detector resolution. In the final fitting procedure we could also check the calibration at 774 MeV and 938 MeV (see below).

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**Figure 17**

Result of intercalibration (from paper I)

The spectra from the reaction $\pi^- p \rightarrow n \pi^0$ and $\pi^- p \rightarrow n \gamma$ ([a] as obtained from the calibration run, [b] 2 month later]. Open dots (O) in (a) show the 129.4 MeV peak as obtained from the source calibration alone. Open dots (O) in (b) show the 129.4 MeV peak as obtained without light-pulser correction.

To maintain this calibration during the whole data-taking period we used the data taken with the light-pulser described above. Tests showed that the modules were stable.
over the data-taking period in 1980, but corrections had to be made for the 1979 data. As we stored the real time for each event on tape we preferred to have a continuous time-dependent correction in order not to introduce any discrete effects in the energy spectra. Thus, we constructed a time-dependent reference value

$$A_{ref}(t) = \frac{P_{LP}^{ref}(0) \cdot P_{Source}(t)}{P_{LP}^{ref}(t) \cdot P_{Source}(0)}$$

where $P_{LP}^{ref}$ is the peak position of the light pulser signal for the reference and $P_{Source}$ is the source peak position for the reference. From this reference value the final time dependent calibration factors $a_v$ were obtained for each module as

$$a_v = \frac{P_{LP}(0)}{A_{ref}P_{LP}(t)}.$$ 

The result of this stabilization can be seen in Figure 17b where an improvement of almost 50% for a two month period is displayed. For stabilization "switched on" we got a FWHM of $\approx 7\%$ for a period of two months, as compared to $\approx 11\%$ without stabilization. The resolution $7\%$ should be compared with the value of $\approx 5.5\%$ obtained as best value at the start of the period.

Before the final adding of the energy output from the modules there were some cuts applied in order to avoid the counting of double hits and to obtain a good resolution for showers. Thus, one of the inner 24 modules, the trigger module, had to contain at least 40% of the total energy registered in each event. Further, the trigger module plus its twelve closest neighbours had to contain $90 \left[ 1 - \exp \left( -E \frac{\text{MeV}}{58} \right) \right] \%$ of all energy deposited except for the lowest total energies. Only the trigger module plus the two neighbouring rings were added to avoid noise from modules into which no part of the showers could enter (Figure 18). No event with the plastic veto counter firing was taken into accounts.

Using this process of adding several modules which were individually stabilized off-line we got a reconstruction of the inclusive $\gamma$-spectra which above 70 MeV was energy-independent, giving a resolution of $3.3\%/\sqrt{E(\text{GeV})}$. This result could be kept almost stable for several weeks.

**Tonne analysis**

The Tonne-detector was the result of an attempt to construct a simple and fairly cheap facility to measure the charged and neutral multiplicity related to the $p\bar{p}$ annihilation in a relatively large solid angle. It showed several drawbacks, e.g. (i) charged particles might give a signal also in the neutral photon detector, (ii) photon showers might spread into two or three adjacent detectors, (iii) there was no coincidence requirement for the charged particle detector which lead to noise and efficiency problems, (iv) geometrical overlap made it possible for charged particles from certain annihilation positions in the target to fire two charged particle detectors, (v) the detector did not cover the full solid angle.

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**Figure 18**

How the modules are added up.

We see two rings of "12" and "24" modules around the module hit, i.e. the one with most energy deposited in it. These rings are added up separately and compared with each other and the total energy. The distribution has to be reasonable in order to accept the event. In the right case some of the inner 24 modules come outside the physical detector.

---

All these drawbacks made it difficult to uniquely determine the charged and/or neutral particle multiplicity of a given event. Furthermore, some effects were so difficult to control that a reliable Monte Carlo simulation could not be made. The conclusion is that unfortunately we were not able to use this detector for any quantitative analysis. As an example the full linear spectrum is compared with the best approximation of two charged particles as a recoil to the detected $\gamma$-ray in Figure 19, which shows how the $\rho/\omega$ "box" becomes visible for the unguided eye. However, the fit quality and normalization are better for the original spectrum due to the Tonne detector limitations discussed above.

**Monte-Carlo simulation of annihilation channels**

A Monte-Carlo simulation of the $\gamma$-ray spectra expected from the annihilation channels as known from bubble-chamber experiments (Table 1) was performed in two steps both dealing only with phase-space and containing no apparatus effects.

The many-body channels marked MC in Paper II, Table 2 were simulated by the CERN standard routines for many-body decays. They were then added in the correct proportions. As the purely neutral channels were poorly known it was in this step assumed that these channels — as well as other ones containing strange particles — did not
change the spectral shape in any significant way. This assumption is correct in a first approximation because of the weak intensity of these channels.

The \( \gamma \)-spectra from a two-body channel of the type \( \pi^0 \) or \( \eta + \) one other particle (\( \pi^0, \eta, \rho, \eta', \omega, \gamma, \ldots \)) can be described analytically as a monoenergetic \( \pi^0 \) or \( \eta \) decaying into two \( \gamma \)-rays, giving a box-like distribution in the laboratory system (see Appendix A). The spectral intensity of such a channel \( \nu \) is given by the expression:

\[
B_\nu(E_\gamma) = B_{pp\rightarrow\gamma\gamma} = \frac{\Gamma_{a\rightarrow\gamma\gamma}}{\Gamma_{a\rightarrow\gamma\gamma}} B_a(E_\gamma) + \frac{\Gamma_{b\rightarrow\gamma\gamma}}{\Gamma_{b\rightarrow\gamma\gamma}} B_b(E_\gamma)
\]

and where \( B^{a,b}(E_\gamma) \) is defined by the function:

\[
B^{a,b}(E_\gamma) = \frac{N^{a,b}_{\gamma}}{E_{\gamma} - E_{\gamma}^{a,b}} \quad \text{for} \quad E_{\gamma}^{a,b} < E_\gamma < E_{\gamma}^{a,b}_{\max}
\]

where \( N^{a,b}_{\gamma} \) is the number of monoenergetic \( \gamma \)-rays into which the particles \( a \) or \( b \) decay at rest.

**Parametrization of the many-body final state background**

The simulated spectrum from the known many-body final states was fitted with the following purely phenomenological shape function:

\[
f(E_\gamma) = N \left[ (E_0 - E_\gamma)^{\alpha_1} \cdot e^{\beta_1} + (E_0 - E_\gamma)^{\alpha_2} \cdot e^{\beta_2} + \alpha_3 \cdot e^{\alpha_3} \right]
\]

where \( E_0 = 938.28 \) (MeV) and \( N \) is a normalization constant (the average number of \( \gamma \)-rays per annihilation). The other six parameters were fit parameters and were kept fixed after this fit. The fit gave a \( \chi^2/\text{d.f.} \) of 1.33 with the following values of the fit parameters: \( \alpha_1 = 4.1548, \alpha_2 = 1.6732, \alpha_3 = 0.0327 \) (MeV\(^{-1}\)), \( \beta_1 = -33.4948, \beta_2 = -19.9818, \beta_3 = -0.006921 \). The average number of \( \gamma \)-rays from \( pp \) annihilation, \( N \), is a sum of several \( N_i \) (one from each channel). With \( N_i = R_i N_i \), where \( R_i \) is the branching ratio to channel \( i \) and \( N_i \) the average number of \( \gamma \)-rays from this channel, and using our final results giving 0.11 \( \gamma \)-rays per annihilation from two-body annihilation, we get \( N = N_i - 0.11 = 3.52 (\pm 0.24) \), where \( N_i \) is the average total number of \( \gamma \)-rays as found from Paper II, Table 2 (or calculated from Table 1 in this thesis).

The total \( \gamma \)-spectrum from the \( pp \) annihilation at rest was then assumed to be a superposition of the many-body final state MC-spectra and the two-body final state (analytical) box-shaped spectra. Thus, the final spectra to be compared with the measured spectra had the form

\[
F(E_\gamma) = A_0 f(E_\gamma) + \sum_i R_i B_i(E_\gamma)
\]

where \( A_0 \) represents the total number of annihilations contributing to the measured spectrum when the integral

---

**Figure 19**

Result from multiplicity counting

The spectra shows the raw spectra and our best approximation of two charged particles and no neutral particles in the TONNE. One can see the upper "box" edges from the annihilation channels: \( pp\rightarrow \pi^0 + \rho/\omega, \) since \( \rho \) (and \( \omega \)) decays into low multiplicity channels.
\[ \int_0^\infty \frac{F(E_n)}{A_0} dE \]

was normalized to be the average number of γ-rays per annihilation \( N_\gamma \). The value of \( A_0 \) was determined by fitting \( F(E_n) \), after folding with the experimental energy resolution, to the measured spectrum in the range from 400 to 600 MeV. The number 0.11 for two-body annihilation was the second free parameter determined at this moment. The accuracy of this determination of \( A_0 \) was ±5% and independent of errors in solid angle, stop rate and other experimental parameters.

**Analysis of two – body final states at higher energy**

After fitting \( A_{\text{box}}(E_n) = A_0 \sum_r R_r B_r(E_n) \), folded with the resolution of the apparatus, to the measured spectrum minus the many-body background \( f(E_n) \), the only remaining free parameters were the searched branching ratios \( R_v \). Unfortunately, all \( R_v \) are not independent. Particularly the \( \eta \) meson channels are strongly correlated with \( \pi^0 \) for the same recoil meson. The \( \pi^0 \rho^0 \) channel interfered with the resolution and was thus not treated independently. Variation of the parameter \( \alpha_2 \) showed a correlation with \( \pi^0 \omega \) and \( \pi^0 \eta \) yields but no other channel, but the parameter was still kept fixed as derived from the Monte-Carlo calculations.

The channel \( \pi^0 \rho^0 \) was well known from bubble chamber experiments. Thus, during the final analysis we kept it fixed, but for tests we also varied it in steps for different detector resolutions. The value \( R(pp \rightarrow \pi^0 \rho^0) = 1.6 \% \) adopted to the final fits is higher but compatible with the values listed in Table 1 and favoured by the present data. We also kept the favoured value for the resolution \( 5%/\sqrt{E(\text{GeV})} \) fixed for the final fits.

It was impossible to resolve the channels \( (\eta + \text{meson}) \) and \( (\pi^0 + \text{meson}) \). Instead we used a fixed ratio \( \eta/\pi^0 \) of 0.16, taken from bubble chamber data (Table 1). In order to estimate systematic errors the \( \eta/\pi^0 \) ratio was also varied in steps between the limits \( 0 \leq \eta/\pi^0 \leq 0.33 \).

Also the \( \pi^0 \eta^0 \) channel was kept fixed with a branching ratio of 0.4 %, a value favoured by our error analysis (see below) and one earlier measurement [6] but in contradiction to another one [5].

The fitting was then done similarly for the channels \( \pi^0 \eta', \pi^0 \omega, \pi^0 \eta, \) and \( \pi^0 \gamma \).

**Errors**

In order to get a good fit we had to introduce one more parameter which we treated as a hypothetical process \( pp \rightarrow \pi^0 X \) or \( \gamma X \) where \( m_X \) correspond to \( \approx 680 \text{ MeV} \).

For the fitting procedure this two processes worked equivalently well but if they were real physical processes, \( pp \rightarrow \pi^0 X \) would have been strongly favoured. The statistical errors were obtained from a MINOS [54] error analysis. To estimate systematic errors we used the maximum and minimum values for each branching ratio obtained under different conditions for the following "fix" parameters; the \( \pi^0 \pi^0 \) branching ratio, the \( \pi^0 \rho^0 \) branching ratio, the \( \eta/\pi^0 \) ratio, the detector resolution and the constant \( \alpha_2 \).

The results summarized in Table 7 were obtained in an all-parameters-free fit but with
the above-mentioned restrictions on the channels \( pp \rightarrow \pi^0 \pi^0, \eta \rho \) and the \( \eta/\pi^0 \) ratio. To obtain a reasonable \( \chi^2/\text{dof} \) we had to introduce a correction which however also could be an unknown particle with a rest mass \( \approx 680 \text{ MeV} \).

**Analysis of the two - body final states at lower energy**

For the region below 400 MeV a small background remained after subtracting the MC distribution which was probably due to the absence of purely neutral and strange channels in this background distribution. After subtracting a smooth function (a third degree polynomial) the remaining structures were fitted with all parameters free except for the width which was limited downwards by the detector resolution. The structures then found were only considered as candidates of the process \( pp \rightarrow \gamma + \gamma + X \) rather than \( pp \rightarrow \pi^0 + X \), although some unsuccessful attempts were made to fit a box edge instead of a line shape.

The results should be compared with the data obtained in a previous experiment [18] made by a Basle-Karlsruhe-Stockholm collaboration (see Paper III, Table 1 and Figure 1). We found similar structures but the yields were systematically lower in the new experiments. Further, we found new structures with a similar significance. These new results do not contradict the old data since the statistics in the former case were much lower and the efficiency not energy-independent. Although no single experiment confirmed structures with a high significance the significance of the combined experiments is quite high since the experiments should be considered as independent.

As a conclusion we confirmed two narrow structures at energies 1694 and 1638 MeV also found in an earlier experiment but then with a higher yield. We also measured the branching ratios for the annihilation channels \( pp \rightarrow \pi^0 \omega, \pi^0 \eta, \pi^0 \eta, \pi^0 \gamma \) and an upper limit for \( pp \rightarrow \pi^0 \gamma \) in an analysis of "box edges".

**Analysis of \(^4\text{He} \rightarrow \gamma + \text{anything} \)**

Having indications for several narrow states from \( pp \) annihilation at rest, the most natural continuation was to study the \( pp \) annihilation on nuclei. Hence, we studied the reaction \( (p^4\text{He})_{\text{rest}} \rightarrow \gamma + X + \text{nucleons} \) by measuring the \( \gamma \) spectrum in the same fashion as we studied the \( pp \) annihilation.

In 1979 we stopped about one fifth of the available antiprotons in \(^4\text{He} \). We treated this data in exactly the same way as the \( pp \) data described above and after calibration and stabilization we obtained the raw spectra in Paper II, Figure 1 (and figure 19). A comparison with \( pp \) data shows a similar shape but the energy range is extended to 1150 MeV. Furthermore, the spectra has a monotonic increase towards the lowest energies. Finally, one can see that the \( \rho^0, \omega \) box is less pronounced.

The very similar shapes of the raw \( \gamma \) spectra from \( pp \) and \(^4\text{He} \) suggest that the annihilation mechanisms are closely related. In order to relate the spectra quantitatively we adopted the working hypothesis that the antiproton annihilates on one single nucleon.

The main differences between \( p \) annihilation on \( p \) and \(^4\text{He} \) is that the antiproton can annihilate on both protons and neutrons and that the neutron are not at rest, but perform a Fermi motion. The implications of the possible annihilation on neutrons will be discussed later.

To estimate the number of \( \gamma \)-rays per \(^4\text{He} \) annihilation we assume that the multipionic final state branching ratios are the same for \( pp \) and \(^4\text{He} \) annihilations. Then charge conservation implies that the number of \( \gamma \)-rays per annihilation is the same for \( pp \) and \(^4\text{He} \) for all the channels in the Monte-Carlo calculation. The continuous background thus obtained plus the contribution from two-body final states scaled from results obtained as described above (see also Paper IV, Table 1) then leads to a \( \gamma \)-spectrum in the \( p\text{N} \) rest frame. However, the \( p\text{N} \) system was not at rest when annihilating, since the nucleus performs Fermi motion and since in addition the \( p \) gains momentum when falling from an atomic orbit.

When we took the Fermi motion into account (details in Paper IV) we were able to fit the experimental spectrum with the shape based on the \( pp \) data with only two new free parameters, the number of annihilations and the total branching of two-body channels. Also in this case there had to be an arbitrary contribution at low energies.

After subtracting the background one clearly sees two peaks in the region 100 - 300 MeV. The fit shows that those peaks are compatible with or slightly broader than what could be expected by the detector resolution plus the Fermi motion and the above-mentioned momentum gain.

The somewhat lower \( \gamma \)-energy for the peaks in the \(^4\text{He} \) spectrum is compatible with the binding energy difference between the initial state and possible final states of \(^3\text{H} \) or \(^3\text{He} \) in one case and \(^3\text{H} \) or \(^3\text{He} \) or \(^3\text{N} \) in the other (here \( 3\text{N} \) denotes three free nucleons). The yield, \( \approx 1 \% \), was about three times the yield from \( pp \), but no structures corresponding to 100 and 550 MeV could be seen. This is, however, compatible with different possible assignments of the isospin for the corresponding states. Thus, only \( 1 \geq 1 \) states would be visible in \(^4\text{He} \) with our present statistics. The increased widths of the peaks can also be an indication of a possible charge splitting.

**Coincidence analysis**

The two \( \gamma \)-rays emerging from a decaying \( \pi^0 \) or \( \eta \) are correlated, and having two \( \gamma \)-energy calorimeters enabled us to measure \( pp \rightarrow \pi^0 + \text{anything} \) and \( pp \rightarrow \eta + \text{anything} \). However, for several reasons the effective solid angle for such a measurement becomes very small and we detected only about \( 10^3 \) true \( \pi^0 \) and still fewer \( \eta \). Thus, the experiment should be seen mainly as a pilot test for a further experiment at LEAR (see Appendix D).

There are three decay parameters (see Appendix A and B) describing the \( \pi^0 \) (\( \eta \)) decay: \( E_{\gamma 1}, E_{\gamma 2} \) and \( \phi_{\gamma 2} \). From those parameters there exist several possible estimators to estimate the \( \pi^0 \) or \( \eta \) energy. However, most of the \( \gamma \)-rays did not even originate from the same \( \pi^0 \) or \( \eta \). Figure 2 in Paper V indicates that in the invariant mass peak region for \( \pi^0 \) there was a signal to noise ratio of 1 to 3 and for the \( \eta \) the situation was even worse. Assuming that all \( \gamma \)-pairs were uncorrelated we could estimate the background for the invariant mass as

\[
\text{back}_{in} = \sqrt{F_1(E_{\gamma 1})F_2(E_{\gamma 2})}
\]

where \( F_1(E_{\gamma 1}) \) and \( F_2(E_{\gamma 2}) \) were individual shape functions for the two detectors. The
normalization of this background was taken from regions well outside the physical invariant masses, since estimates based on solid angles are good only to \( \approx 20\% \). In this way we could identify 1000 \( \pm 55 \) \( \pi^0 \) and 272 \( \pm 48 \eta \).

After cutting the invariant mass spectra the \( \pi^0 \) and \( \eta \) energies were estimated by the sum \( E_{\pi^0,\eta} = E_{\eta} + E_{\eta} \).

The resulting (Figure 4a in Paper V) spectra still contained about 2/3 background. However, with the estimator above it was simple to estimate the background. The final \( \pi^0 \) total energy spectra were, as expected, dominated by a Panofsky peak at 138.3 MeV. For higher energies the very unfavourable detector efficiency decreased the number of counts and we could only give an upper limit of 8 \% for a reaction \( pp \rightarrow \pi^0 \rightarrow \pi^0 \) \( \pi^0 \) + \( X \) (\( m_X \approx 1650 \) MeV) where the \( \pi^0 \) total energy corresponds to 220 MeV.

As regards the \( \eta \) we could detect them only in the most favourable region and as nothing was known earlier about the shape of the \( \eta \) spectrum this result was not conclusive.

\section*{CHAPTER 5

CONCLUSIONS AND DISCUSSION}

"Forty-two!" yelled Loongquawl. "Is that all you've got to show for seven and a half million years' work?"

'I checked it very thoroughly,' said the computer, 'and that quite definitely is the answer. I think the problem, to be quite honest with you, is that you've never actually known what the question is.'

DOUGLAS ADAMS, The Hitchhiker's guide to the galaxy

In spite of the large effort spent on studying certain aspects of the \( pp \) annihilation it is not well understood. In particular the knowledge is poor about \( pp \) going to only neutral particles and \( pp \) resulting in many neutral particles + charged particles. In the stage of evaluation there are several experiments at LEAR which will hopefully give very accurate new information on such processes. Before this facility was constructed we were stimulated by other related works and performed a study of \( pp \) annihilation at rest for three particular cases: (i) \( pp \rightarrow \pi^0 \) \( \pi^0 \) + one other particle, by studying the \( \gamma \)-rays from the decaying \( \pi^0 \) or \( \eta \). (ii) \( pp \rightarrow \pi^0 \) \( \pi^0 \) or \( \eta \) + one other particle, by studying the decay \( \gamma \)-rays from \( \pi^0 \) or \( \eta \) in coincidence, (iii) \( pp \rightarrow \gamma \) + anything, searching for monoenergetic \( \gamma \)-rays which might reveal deeply bound nuclear states or four-quark states (Baryonium). (iv) Finally, we studied the \( p^4 \)He annihilation at rest searching for monoenergetic \( \gamma \)-rays with the aim to reveal any isospin dependence.

A summary of the data can be seen in Figures 20 and 21.

(i) The process \( pp \rightarrow \pi^0 \) \( \pi^0 \) + one other particle was studied by the detection of one of the decay \( \gamma \)-rays from the \( \pi^0 \) or \( \eta \). This enabled us to measure the annihilation channels \( pp \rightarrow \pi^0 \omega, \pi^0 \eta, \pi^0 \gamma \). Whereas the \( \pi^0 \gamma \) branching ratio is in accordance with the expectation of the vector dominance model, the large \( \pi^0 \omega \) branching ratio is surprising. Thus, the S-wave dominance in \( pp \) annihilation at rest does not seem to hold. This conclusion is also supported by the large \( \pi^0 \eta \) branching ratio and the mere existence of the \( \pi^0 \pi^0 \) channel. It was not possible to distinguish neither \( pp \rightarrow \pi^0 \omega \) from \( pp \rightarrow \eta \omega \) nor \( pp \rightarrow \pi^0 \eta \) from \( pp \rightarrow \eta \eta \), and thus an overall ratio for \( \eta/\pi^0 \) had to be used. Our upper limit for this ratio (0.50) could possibly explain some of the \( \pi^0 \omega \) as coming from \( \eta \omega \). However, it can only decrease the \( pp \rightarrow \pi^0 \omega \) yield by 0.5 \% and would then still be in disagreement with other experiments \([55]\) on inclusive \( \eta \) production. One feature of our data analysis which has to be explained is the need for introducing the channel \( pp \rightarrow \pi^0 X^0 \) with \( mx \approx 680 \) MeV. The omission of this channel would increase the \( \pi^0 \omega \) yield by a factor \( \approx 1.5 \) which does not seem very plausible. It would be very tempting to..."
ii) The study of $\pi^0$ and $\eta$ with coincidence techniques. The count rate with this setup was only enough to make it possible to detect about 1000 true $\pi^0$ and 275 true $\eta$. An upper limit for processes of the type $pp \rightarrow \pi^0 + X^0$ (here $X^0$ is any neutral particle) of 8% in the low energy region ($E_{\pi^0} \leq 250$ MeV) could be obtained.
(iii) The search for monoenergetic \( \gamma \)-rays from pp annihilation. Although the result of our experiment does not fully confirm the yields claimed by Pavlopoulos et al. [18] for the processes \( pp \rightarrow \gamma \) + anything, where \( E_\gamma \approx 180, 220 \) and 420 MeV, we found structures in the \( \gamma \)-ray spectra at the same energies but with less yield. There could be several explanations for this observation. The main reason is probably that the trigger conditions are different and the yields from the experiments described here are normalized and with an unbiased trigger, whereas the old experiment by Pavlopoulos required at least two charged particle hits in a simple charged particle counter set-up around the target. Thus one has to conclude that the peaks at about 180 MeV and 220 MeV appear in the spectrum but with lower yields than first measured. For the 420 MeV peak the situation may be somewhat different due to the \( E/\lambda \) mesons, which should appear at 380–400 MeV. The structure in the 420 MeV region in Pavlopoulos' experiment could possibly be due to a recoil of one or both of these mesons because of the calibration uncertainties and trigger bias involved in the experiment. In our experiment the energy calibration is much better but as the trigger is unbiased we cannot make a definite conclusion. It would not be possible to fit and resolve two broad structures in our data even if we knew in advance that they were present. In a future experiment one would have to detect other decay products in order to separate \( \gamma \) and \( \lambda \) and other possible states.

(iv) The search for monoenergetic \( \gamma \)-rays from pHe annihilation at rest. We find two prominent peaks in these data, both related to the previous findings in pp annihilation data. The yield for these peaks is about 3 times higher than in the pp case. This and a slightly larger width than the calculated one might indicate the presence of states with \( I \geq 1 \).

It should finally be concluded that the appearance of monoenergetic \( \gamma \)-rays of energies \( \approx 180 \) MeV and \( \approx 220 \) MeV in three different experiments on hydrogen and one experiment on helium can be interpreted as long-lived objects with masses \( \approx 1690 \) and \( \approx 1640 \) MeV. However, it must be admitted that so far it has not been possible to confirm these results in experiments of the type \( pp \rightarrow X^\pm + \pi^\mp \) and \( pp \rightarrow X^0 + \pi^0 \). It can therefore not be excluded that the \( \gamma \)-ray peaks at 180 MeV and 220 MeV originate in processes which we have not been able to identify. Thus, it is still an open question if Baryonium states are narrow objects or so wide that they disappear in the \( \gamma \)-ray continuum, if they exist at all.

### APPENDIX A

**SOME KINEMATICS FORMULAE**

"A lord of wisdom throned he sat,
swift in anger, quick at laugh;
an old man in a battered hat
who leaned upon a thorny staff."

J. R. R. TOLKIEN *The Lord of the rings*

A.1 Notation and some basic formulas

The experimental methods used this thesis are based on a few very basic principles of physics, energy and momentum conservation and Lorentz invariance. Below follow a few results which are easily derived from those principles. For a detailed description see any basic textbook in elementary particle physics [56]. We use the four-vector \( X \) with components \((E, p)\) where \( E \) is the energy of the particle and \( p \) the three-momentum and \( p^2 = E^2 - m^2 \). Also, we use the usual convention where \( h = c = 1 \) (Planck's const./2\( \pi \) = speed of light = 1).

A.1.1 Conserved quantities

The total energy is conserved \( E_{\text{tot}} = E_1 + \ldots + E_n \).

The total momentum is conserved \( p_{\text{tot}} = p_1 + \ldots + p_n \).

The rest mass is invariant \( m_0^2 = E^2 - p^2 \) for one particle. Note also that \( E = p \) in all frames for a massless particle.

A.1.2 Lorentz transformations

A.1.2.1 Lorentz transformation of energy and momentum

If the four-vector \( X \) is seen from a second frame with relative velocity \( \beta \) in the z direction the components \( X' \) in the second frame are

\[
E' = \gamma E - \beta \gamma p_z \\
p_x' = p_x - \beta \gamma E \beta \\
p_y' = p_y \\
p_z' = p_z - \beta \gamma E \beta
\]

where

\[
\gamma^2 = \frac{1}{1 - \beta^2}
\]
A.1.2.2 Lorentz transformations of angles

A.1.2.2.1 General

We can find the transformations for angles from the relation above. Suppose that a particle is moving with an angle $\alpha$ relative to the z-axis in frame A, and $\alpha'$ in frame A', and let * denote that a quantity is calculated in the primed frame. We see that the transverse component of the momenta is equal in both systems.

\[
P_T = \sqrt{p_z^2 + p_y^2} = p'_T
\]

We get

\[
\tan \alpha' = \frac{p_T}{p'_z} = \frac{1}{\gamma} \cdot \frac{p \sin \alpha}{p \cos \alpha + \beta' \gamma' E}
\]

A.1.2.2.2 The Lorentz-transformation for a massless particle (photon)

For a massless particle where $E = p$ in both systems we can also get another relation used below.

Consider a photon propagating at an angle $\theta$ relative to the z-axis in system A, and an angle $\theta'$ in system A'. Then we get the relations

\[
\cos \theta' = \frac{p_y'}{p'} = \frac{p_y'}{E'} = \frac{\gamma \cdot (p_z + \beta p)}{\gamma \cdot (p + \beta p_z)} = \frac{\cos \theta + \beta}{1 + \beta \cos \theta}
\]

A.1.3 The two-body decay kinematics

A.1.3.1 Introduction

The distinctive feature of the two-body decay is that if the total energy (and momentum) of the initial particle is known, the decay is completely determined by measuring one of the decay particles. This important theorem in physics has been the ground for several spectacular discoveries, e.g. the postulation of the neutrino [57] by Pauli when the $e^-$-spectrum showed properties which could not be explained by two outgoing particles.

A.1.3.2 Formulas

In the rest frame of the decaying particle, energy and momentum conservation and some algebra yield:

\[
E_1 = \frac{M^2 + m_1^2 - m_2^2}{2M}
\]

\[
|p_1| = p = \sqrt{\frac{[M^2 - (m_1 + m_2)^2][M^2 - (m_1 - m_2)^2]}{4M^2}}
\]
Figure A.1
Recoil energies for $\bar{p}p \rightarrow \gamma$ or $\pi^0 +$ one body (X).

Recoil $\gamma$-energy [GeV/c$^2$]

Recoil $\pi^0$ energy and momentum [GeV/c$^2$] [GeV/c]

$\gamma$ energy for the process $\bar{p}p \rightarrow \gamma +$ one other particle (X)

$\pi^0$ energy (above) $\pi^0$ momentum (below) for the process $\bar{p}p \rightarrow \pi^0 +$ one other particle (X)
Thus, in our case, by detecting one outcoming particle from pp annihilation at rest, we have an enhancement in the energy (or momentum) spectra whenever the energy corresponds to a two-body decay. Specializing to one massless particle (e.g. photon) we have the mass and momentum for the recoiling particle

\[ m_x = \sqrt{4m_p(2p_p - p_\gamma)} \]
\[ p_x = p_\gamma = m_p - \frac{m_x^2}{4m_p} \]

in Figure A.1 this relation is shown graphically and with possible non-strange recoil particles indicated.

APPENDIX B
SOME DECAY PROPERTIES OF THE $\pi^0$ AND THE $\eta$

"Hunc mundum tipice laberinthus denotat illo"

"Intranti largus, redeunti sed nimis artus"

UMERTO, ECO Il nome della rosa

B.1 Decay properties for $\pi^0$ and $\eta$ to $\gamma \gamma$

The $\pi^0$ and $\eta$ decay to $\gamma \gamma$ with a branching ratio of 98.8 % and 39.0 %, respectively. The lifetimes and masses are $8 \times 10^{-17}$ s, $8 \times 10^{-18}$ s, 134.96 MeV and 549 MeV, respectively. Below are given some of the decay properties $\pi^0 \rightarrow \gamma \gamma$ used in this thesis. The figures consider $\pi^0$ but all formulas are also true for $\eta \rightarrow \gamma \gamma$.

For a $\pi^0$ decaying in the CM system with the parameters $\theta_1$, $\theta_2$, $\gamma_1$ and $\gamma_2$ where $\theta_1 + \theta_2 = 180^\circ$, the formulas in Appendix A give us $E_{\gamma 1} = E_{\gamma 2} = M_{\pi^0}/2$.

After calculating the quantities in the lab frame moving relative to the CMS with

\[ \beta = \frac{p_{\pi^0}^{\text{lab}}}{E_{\pi^0}^{\text{lab}}} \]

they are denoted $\theta'_1$, $\theta'_2$, $\gamma_1$, $\gamma_2$ and $\theta'_1 + \theta'_2 = \varphi_{1,2}$. We want to calculate $E_{\gamma 1}'$, $E_{\gamma 2}'$ and $\varphi_{1,2}$. From Appendix A we know that

\[ \cos \theta'_1 = \frac{\cos \theta + \beta}{1 + \cos \theta} \]

and thus

\[ \cos \theta'_2 = \frac{\beta - \cos \theta}{1 + \beta \cos \theta} \]

Now we can calculate...
\[
\cos \varphi_{1,2} = \beta^2 (1 + \sin^2 \theta) - 1 \quad \text{and} \quad \cos \left( \frac{\varphi_{1,2}}{2} \right) = \frac{\beta \sin \theta}{\sqrt{1 - \beta^2 \cos^2 \theta}}
\]

Minimizing this we obtain
\[
\cos \left( \frac{\varphi_{1,2}}{2} \right)_{\text{min}} = \beta \quad \text{or} \quad \cos \varphi_{1,2\text{min}} = 2\beta^2 - 1
\]
and \(\theta_{\text{max}} = 180^\circ\).

The energy \(E_{1\text{f}}'\) and \(E_{2\text{f}}'\) for the extreme angles are (from Appendix B.2)
\[
E_{1\text{f}1,2\text{min}}' = \frac{E_{1\text{f}0}}{2}
\]
and
\[
E_{2\text{f}\text{max}}' = \frac{1}{2} (p_{p^0} + p_{p^0}) \quad \text{E}_{2\text{f}\text{min}}' = (p_{p^0} - p_{p^0})
\]

The energy distribution is uniform between these extreme values and vanishes elsewhere (proof in Appendix B.2).

Finally, we give the probability for a decay to \(\varphi_{1,2}\) from ref. [58].

\[
W(\varphi_{1,2}) = \frac{1 - \beta^2 \cos (\varphi_{1,2}/2)}{2\beta \sin^2 (\varphi_{1,2}/2)} \sqrt{\beta^2 - \cos^2 (\varphi_{1,2}/2)}
\]
with \(\Theta(x) = 1\) for \((x > 0)\) and \(= 0\) for \((x \leq 0)\).

Those parameters are summarized in Figure B.1.

**B.2 THE BOX SHAPE OF THE (monoenergetic) \(\pi^0\) DECAY SPECTRA**

**Theorem:**

The energy distribution of a massless particle originating from the two-body decay of a monoenergetic particle is flat between a maximum and a minimum value and 0 elsewhere.

The proof below considers \(\pi^0 \rightarrow \gamma \gamma\) but it is of course true also for \(\eta \rightarrow \gamma \gamma\). A small modification shows that the single \(\gamma\) from i.e. \(\omega \rightarrow \pi^0 \gamma\) is also getting the same box distribution.

**Proof:**

We consider the decay \(\pi^0 \rightarrow \gamma \gamma\). In the \(\pi^0\) rest frame (denoted by *) the emitted gamma rays are monoenergetic with \(E^*_\gamma = p^*_\gamma = m_{\pi^0}/2\), and collinear: \(p^*_{\gamma 1} = -p^*_{\gamma 2}\). Their angular distribution is isotropic.

The number of gamma rays emitted into a CMS solid angle \(d\Omega^\ast\) is
\[
dN_\gamma = 2N_{\pi^0} \cdot \frac{d\Omega^\ast}{4\pi}
\]
with the normalization \(\int dN_\gamma = 2N_{\pi^0} \frac{1}{4\pi} \int d\Omega^\ast = 2N_{\pi^0}\).
In order to prove that the inclusive gamma spectrum has a rectangular shape, i.e. that the number of gamma rays per energy bin is constant, we have to show that the ratio of the CMS solid angle to the corresponding energy bin is constant. This is achieved by performing a Lorentz-transformation from the $\pi^0$ rest frame to the laboratory frame and by establishing the relations of the kinematical variables in both systems.

Assume the $\pi^0$ moves along the z-axis with a momentum $p_{\pi^0}$, carrying a total energy $E_0$. Its relativistic parameters of motion are

$$\beta = \frac{p_{\pi^0}}{E_0}, \quad \gamma = \frac{E_0}{m_{\pi^0}}, \quad \eta = \frac{p_{\pi^0}}{m_{\pi^0}}.$$

Note that $\eta = \beta \gamma$.

$$\gamma^2 = \frac{1}{1 - \beta^2}, \quad \gamma^2 - 1 = (\gamma + 1)(\gamma - 1) = \beta^2 \gamma^2 \quad (1).$$

The Lorentz-transformation for the energy and the momentum of a gamma emitted into any direction is given by

$$E^* = \gamma E - \eta p, \quad p^* = p - \eta \cdot \frac{E + E^*}{\gamma + 1} \quad \text{(Lab \rightarrow CMS)}.$$

If $\delta$ denotes the emission angle formed with the z-axis we can write

$$E^* = \gamma E - \eta p \cos \delta = \gamma E - \eta E \cos \delta = \gamma E(1 - \beta \cos \delta).$$

$$E = \frac{E^*}{\gamma}, \quad \frac{1}{1 - \beta \cos \delta} = \frac{m_{\pi^0}}{2 \gamma}, \quad \frac{1}{1 - \beta \cos \delta} \quad (2).$$

The gamma ray has a maximum energy if it is emitted in the forward direction (along the $\pi^0$ trajectory): $E_{\text{max}} = E(\delta = 0^\circ)$, while it achieves its lowest energy under backward emission: $E_{\text{min}} = E(\delta = 180^\circ)$.

These energies are, respectively,

$$E_{\text{max}} = \frac{m_{\pi^0}}{2 \gamma} \left(1 + \beta \right) \left(1 - \frac{1}{\gamma^2} \right) = \frac{1}{2} \left(E_{\pi^0} + p_{\pi^0}\right),$$

$$E_{\text{min}} = \frac{1}{2} \left(E_{\pi^0} + p_{\pi^0}\right).$$

One also obtains

$$\frac{dE}{d \cos \delta} = \gamma \left(1 - \beta \cos \delta \right)^2 \quad (3).$$

The momentum components are transformed as

$$p_x^* = p_x, \quad p_y^* = p_y,$$

$$p_z^* = p_z - \frac{E + E^*}{\gamma + 1} \cos \delta - \frac{E^*}{\gamma + 1} \cos \delta.$$

$$E \cos \delta - \eta \left[\gamma + 1 \left(1 + \beta \gamma \cos \delta\right)\right] = E \cos \delta - \eta E \left(1 + \gamma - \beta \gamma \cos \delta\right) = 0,$$

$$E \cos \delta - \eta \left(1 + \frac{1 - \gamma}{\gamma + 1} \right) - \frac{\beta \gamma}{\gamma + 1} \cos \delta = E \cos \delta - \left(\gamma - \frac{\eta^2}{\gamma + 1}\right) \cos \delta.$$
\[
\frac{d\Omega^*}{d\Omega} = \frac{1}{\beta \gamma E^* \cos \delta} \frac{dE}{d\Omega} \frac{d\Omega^*}{d\Omega} = \frac{2}{m_\gamma \beta \gamma d\Omega} d\phi
\]

\[
\frac{d\Omega^*}{d\Omega} = \frac{2 \gamma d\Omega}{d\phi}
\]

Hence the number of gamma rays per energy bin \( dE \) is proportional to the corresponding solid angle \( d\Omega^* \) but independent of the gamma energy in the laboratory frame. This was to be shown.

The coincidence spectra did only yield in a weak upper limit for the process \( pp \rightarrow \pi^0 + X^0 \) where \( m_X \approx 1650 \text{ MeV} \). This result is due to the low coincidence count rate and the fact that in most events the two \( \gamma \)-rays do not originate from the same \( X^0 \). In Figure C.1 we show a method [59] which visualize the \( \pi^0 \) in the coincidence spectrum with the following description: from the matrix of \( \gamma - \gamma \) coincidences \( M_{ij} \) obtained under the assumption of no correlation between the \( \gamma \)-rays. The matrix of correlated events \( \Delta N_{ij} \) is then constructed as

\[\Delta N = N_{ij} - M_{ij} = N_{ij} - \sum_i N_{ii} \sum_k N_{kj} \sum_k N_{ki} \]

\[\Delta N_{ij} \leq \text{is put to 0 in the display}\]

Although this procedure is not entirely correct, since the \( N_{ij} \) matrix does contain correlated events, it is clearly showing in Figure C.1 that we are able to study \( \pi^0 \) spectra with this coincidence technic at LEAR.
APPENDIX D

THE QUARK CONTENT OF THE ORDINARY MESONS

"He stood upon the bridge alone
and Fire and Shadow both defied;
his staff was broken on the stone
in Khazad-dûm his wisdom died."

J.R.R. TOLKIEN The Lord of the rings

THE SU(6) WAVE FUNCTIONS

\[ \pi^+ = \sqrt{2} (u_1 d_1 - u_1 d_1 - d_1 u_1 + d_1 u_1), \]
\[ \pi^- = \sqrt{2} (-u_1 d_1 + d_1 u_1 - u_1 d_1 - d_1 u_1 + d_1 d_1 + d_1 d_1), \]
\[ \rho_1^+ = \sqrt{2} (u_1 d_1 + d_1 u_1), \]
\[ \rho_2^+ = \sqrt{2} (u_1 d_1 + u_1 d_1 + d_1 u_1 + d_1 u_1), \]
\[ \rho_1^- = \sqrt{2} (u_1 d_1 + d_1 u_1), \]
\[ \rho_2^- = \sqrt{2} (-u_1 d_1 + u_1 d_1 + d_1 d_1 + d_1 d_1), \]
\[ \rho_1 = \sqrt{2} (d_1 d_1), \]
\[ \rho_2 = -\sqrt{2} (d_1 d_1), \]
\[ \omega_1^+ = \sqrt{2} (u_1 u_1 + d_1 u_1 + d_1 u_1), \]
\[ \omega_2^+ = \sqrt{2} (u_1 u_1 + u_1 u_1 + d_1 u_1 + d_1 u_1), \]
\[ \omega_1^- = \sqrt{2} (u_1 u_1 + u_1 u_1 + d_1 d_1 + d_1 d_1), \]
\[ \omega_2^- = \sqrt{2} (-u_1 u_1 - d_1 u_1 + u_1 u_1 + d_1 d_1), \]
\[ \eta_1 = \sqrt{2} (u_1 u_1 - u_1 u_1 - u_1 d_1 - u_1 d_1 - d_1 d_1). \]
"I like to work: it fascinates me. I can sit and look at it for hours. I love to keep it by me: the idea of getting rid of it nearly breaks my heart."

JEROME K. JEROME, *Three Men in a Boat*

This appendix contains a reprint of the following five papers which the thesis is based on.


Proton-antiproton annihilations at rest into $\pi^0\omega$, $\pi^0\eta$, $\pi^0\eta'$, $\pi^0\pi^0$, and $\pi^0\pi^0$, Nuclear Physics B228(1983)424.


New results in the search for narrow states in the $p\bar{p}$ system below threshold, Physics Letters 126B(1983)284.

