2. Introduction

The activities of this group are primarily concerned with experiments using the Crystal Barrel Detector. This detector is installed and operating at the Low Energy Antiproton Ring (LEAR) at CERN.

QCD, the modern theory of the strong interaction, is reasonably well understood at high energies, but unfortunately, low-energy QCD is still not well understood, and is far from being adequately tested. The Crystal Barrel experiments are designed to provide some of the tests. The basic line of research involves meson spectroscopy, analyses bearing on the quark and/or gluon content of nuclear states, and the exploration of mechanisms and rules which govern $p\bar{p}$ annihilation dynamics. The Crystal Barrel Detector detects and identifies charged and neutral particles with a geometric acceptance close to 100%. The principal component of the detector is an array of 1,380 CsI(Tl) crystals. These crystals surround a Jet Drift Chamber (JDC), located in a 1.5 Tesla magnetic field, which measures the momentum and $dE/dx$ of charged particles. One of the very interesting physics goals of the detector is a search for exotic mesonic states - glueballs and hybrids. Annihilation at rest will be studied with both liquid and gaseous hydrogen targets. The gaseous target offers the possibility of triggering on atomic L-shell X rays so that specific initial angular momentum states can be studied.

Our group has been responsible for the construction and operation of the JDC as our major contribution. We have also constructed a beamline proportional chamber, rewritten the Monte Carlo of the detector, and worked on various aspects of the JDC tracking, among other things. The experiment began taking data in 1989 and will continue for several more years.
We have had three runs scheduled for 1992, occurring in April, July and November. The first run was a tune-up run with both 200 MeV/c and 1.6 GeV/c \( \bar{p} \) beams on the liquid hydrogen target. The run in July has just been concluded using a 1.9 GeV/c \( \bar{p} \) beam. The run in Fall/Winter is scheduled also for high-energy, \( p \bar{p} \) collisions at 1.9 GeV/c. The preliminary results from the 1.9 GeV/c data will be discussed. Analysis of previous runs has been on-going at the universities and a large number of PhD and Diploma students have completed their degrees based on this data. (For the complete list, see Appendix.) A few of the theses have reached the stage of publication by the group, and these publication drafts give an excellent summary of the progress of the analysis. Some of these are included in the Appendix as well and are discussed briefly in the text.

The remaining effort of the group is divided into ongoing work at TRIUMF by David Armstrong, which he has continued, and the PSI studies on muon catalysis done by Tom Case as part of his PhD research. These research efforts have produced interesting results and will be reviewed in subsequent sections.

During this year, the progress on the KAON accelerator and the Hadron Spectrometer has been essentially zero. Last year, a Letter of Intent was drafted by members of the Working Group, and it was decided that no function would be served by requesting commitments from the potential user community until a firm decision was made by the Canadian Federal Government, including a satisfactory funding package. As of August 1992, no such decision was visible. As soon as the green light is shown, several steps will be necessary. First, opinions of the user community must be gathered and the physics program re-examined. Second, the draft letter must be examined, and third, the TRIUMF
management must clear the slate with regard to how proposals for major experiments should be handled. Our hadron working group will be ready to respond at the appropriate time. Independent of the timing, this effort will have a serious impact on our work in the next year as presently envisioned. There will be an important related effort in the study of the resolution of the existing JDC in use with the Crystal Barrel. This research will be discussed in connection with the Crystal Barrel experiment, although it is clear that progress in improving resolution will have a major impact on the new Keson spectrometer design.
3. Project Accomplishments - 1992

A. The Crystal Barrel at LEAR

The Crystal Barrel Detector at LEAR allows the complete reconstruction of antiproton-nucleon annihilations into charged or neutral final states. The main components of the detector are a jet drift chamber (JDC) for measuring the momenta of charged particles and a CsI(Tl) calorimeter for measuring the energies of photons. All detector components (See Fig. 1) are positioned inside a solenoid magnet, which provides a field of 1.5 T. A complete description of the detector can be found in The Crystal Barrel Spectrometer at LEAR, E. Aker et al., accepted for publication by Nucl. Instrum. Methods. In the following, we quote the most important information relevant to analyses of final states involving photons and charged particles.

The calorimeter consists of 1380 CsI(Tl) crystals, individually read out with wavelength shifters and photodiodes. With an incoherent noise of 250 keV per crystal and a coherent noise of 50 keV per crystal, we can measure energy depositions down to 1 MeV. The relative energy resolution, determined near 100 MeV and 1 GeV, was found to be consistent with $2.5\% (E/\text{GeV})^{1/2}$. The polar and azimuthal angular resolutions are about 20 mrad for high-energy electromagnetic showers. The quality of the calorimeter can be judged from Fig. 2, which shows the two-photon invariant mass from $\bar{p}p \to 6\gamma$ events.

The jet drift chamber (JDC) sits inside the calorimeter. From an analysis of residuals of fitted charged tracks, we find a spatial resolution of 7 mm in $z$ and 130 $\mu$m in $r/\phi$. The momentum resolution is determined from a combined circle fit to collinear events from $\bar{p}p \to \pi^+\pi^-$ and $K^+K^-$ (see Fig. 3). We obtain a resolution of about 2% at 928 MeV for the
simultaneous fit to both tracks. Scaling with the track length and the momentum dependence results in a resolution of about 3% for a momentum of 300 MeV/c, which is the average momentum in \( \bar{p} p \) annihilations at rest. Inside the JDC are mounted two layers of multiwire proportional chambers, which are mainly used to trigger on specific charged multiplicities in the final state.

**B. Status of the Crystal Barrel Experiment**

At the end of 1991, the Crystal Barrel experiment had accumulated about 40 million events of antiproton annihilations in liquid hydrogen. More than 50% of this data set was taken with special triggers requiring 0-prong, 2-prong, and 4-prong events. This data set also includes about 4 million events taken 'in flight' at antiproton momenta of 0.6 GeV/c and 1.2 GeV/c. Another 12 million events have been recorded using a liquid deuterium target. In total, we have reconstructed about 40 million events, which are thus available for physics analyses.

**C. Physics Motivation**

The main goal of our experimental investigations is the search for new hadronic states like glueballs, hybrids and four-quark states. Such states should be produced strongly in antiproton nucleon annihilations since quarks and gluons (from \( \bar{q} q \) annihilations) are abundant in the intermediate state. We thus expect to provide significant information for tests of phenomenological models of quantum chromodynamics.

Further investigations concern the annihilation mechanism, which has been analyzed
in several phenomenological models. A comparison of predictions with experimental branching ratios allows a test of these models and of specific selection rules of the annihilation dynamics. Finally, we may obtain information on the $s\bar{s}$ content of the proton with measurements of OZI-forbidden decays like $\bar{p}p \rightarrow \pi\phi$. The appended conference publication "Recent Results from the Crystal Barrel Experiment" provides an excellent summary of many of the important physics topics we are addressing.

D. Physics Results

Status of the $X_{2}^{++}(1515)$ as seen in $\bar{p}p \rightarrow 3\pi^0$.

The first major publication of the Crystal Barrel Collaboration [E. Aker, et al. Physics Letter B260 (1991) 249] was based on an early subset of the all-neutral events taken in 1990. The results, stated briefly, were as follows:

Kinematic seven-constraint (7C) fits were applied to a sample of about $10^5$ six-photon events, with the hypotheses:

$$\bar{p}p \rightarrow \pi^0\pi^0, \bar{p}p \rightarrow \eta\eta\eta^0, \bar{p}p \rightarrow \pi^0\eta\eta, \text{ or } \bar{p}p \rightarrow \eta\eta\eta.$$  

This yields about $5.5 \times 10^6$ events having a $3\pi^0$ probability larger than 10%. The background of non-$3\pi^0$ events left in this sample is well below 1%. Ambiguities which could be due to wrong associations of the photon pairs defining the $\pi^0$ are negligible (less than 3% of the $3\pi^0$ sample contains events for which two good 7C fits could be obtained, and these two solutions are generally very close to each other in phase space). The reconstruction efficiency and selection criteria applied to the sample and kinematic fits result in a global efficiency of approximately 30% which is nearly uniform over the total phase space.
Figure 4 shows the $2\pi^0$ mass spectra and the Dalitz plot of the final state. The most significant result of the partial wave analysis of this Dalitz plot is the observation of a resonance $X_2$ with

$$M_{X_2} = 1515 \pm 10 \text{ MeV}, \quad \Gamma_{X_2} = 120 \pm 10 \text{ MeV}, \quad J^{pc} = 2^{++},$$

which represents 26% of the $3\pi^0$ channel (9.5% from $^1S_0$, 8.0% from $^3P_1$ and 8.8% from $P_2$ initial states).

From these results alone, the isospin remains undefined ($I = 0$ or 2) but, if we identify the $X_2$ with either the $J^P = 2^+$ resonance observed at 1565 MeV by May et al. [Phys. Lett. 225B (1989) 450; Zeit. Phys. C46 (1990) 191, 203] in P-state annihilations or with the isoscalar two-pion resonance postulated by Gray et al. [Phys. Rev. D27 (1983) 307] at 1527 MeV, the isospin must be $I = 0$. The $X_2(1515)$ cannot be identified with the well-established $f_2(1525)$, as this assumption would imply a large production of $\bar{p}p \rightarrow \pi^0 f_2 \rightarrow K^0_s K^0_s \pi^0$, which is not observed.

This analysis was done mainly by the University of Mainz group. Dr. Klaus Peters was the major physicist and obtained his PhD on the basis of this research. It was anticipated that there would be a further analysis using a much larger data sample with better quality events as well as better statistics. The analysis method was carefully reviewed and small corrections have been made to the form of the resonance description used in the partial wave analysis. This new analysis is still going on as of August 1992.

\[\bar{p}p \rightarrow \pi^0 \rho^+ \rho^-\]

The analysis of a possible $\rho \rho$ decay of the $f_2(1515)$ shows an enhancement at 1500
MeV (see Fig. 5). A partial wave analysis of this complicated 5-particle final state is in progress.

$$\bar{p}p \rightarrow \pi^0 \eta \eta$$

In the final state $\pi^0 \eta \eta$, we were able to find a sizable contribution from $f_2(1515) \rightarrow \eta \eta$. The branching ratio $f_2 \rightarrow \pi^0 f_2 \rightarrow \eta \eta$ of about 5 from $^1S_0$ and $^3P_1$ initial states is not consistent with the prediction assuming the $f_2(1515)$ to be an $N\bar{N}$ bound state. No prediction of branching ratios exists yet from the model assuming a meson-meson bound state. Note that the $\pi^0 \eta \eta$ final state is dominated by a glueball candidate (see below and the enclosed publication on Antiproton-Proton Annihilation into $\eta \eta \pi^0$ - Observation of a Scalar Resonance Decaying into $\eta \eta$ (C. Amsler et al., submitted for publication in Phys. Lett.).

$$\bar{p}p \rightarrow \gamma 2\pi^0$$

In case $f_2(1515)$ is an $N\bar{N}$ bound state, one expects also radiative transitions $\bar{p}p \rightarrow \gamma f_2$. The search for such transitions is complicated by the feed-down from the $3\pi^0$ final state. Nonetheless, a preliminary analysis shows the presence of such radiative transitions (see Fig. 6). This observation further strengthens the case for an $N\bar{N}$ bound state.

$$\bar{p}n \rightarrow \pi^0 2\pi^0$$

Additional information on the $f_2(1515)$ can be gained from an analysis of the reaction $\bar{p}d \rightarrow \pi^0 2\pi^0 p$: the phase motion of the $f_2$ can be determined. Analyzing the deuterium data
requires the knowledge that Fermi motion in the nucleus and re-scattering of the spectator nucleon do not change the basic process $\bar{p}n \rightarrow \pi^02\pi^0$. To demonstrate this, we have first analyzed the reaction $\bar{p}d \rightarrow 3\pi^0n$. Next, we have analyzed the decay $\bar{p}n \rightarrow \pi^02\pi^0$ and have shown that the phase in the vicinity of 1515 MeV shows clear resonance behavior, ruling out a non-resonant interpretation of the peak observed at 1515 MeV. The $\pi^0\pi^0$ and $\pi^+\pi^-$ invariant mass spectra are shown in Figs. 8a and 8b, respectively.

$\bar{p}d \rightarrow Xn$

Models which predict deeply bound quasi-nuclear states, also require the existence of $NN$ states close to threshold, which thus cannot be reached via pion emission. To search for such states, we have investigated the recoil momentum spectrum of neutrons in the reactions $\bar{p}d \rightarrow X_n$, where $X$ is $3\pi^0, 2\pi^0\eta$, and $\pi^02\eta$. We find at a neutron momentum of about 150 MeV/c an enhancement for $X = 3\pi^0$; Fig. 9 shows the ratio of the neutron momentum spectra for $X = 3\pi^0/X = 2\pi^0\eta$. We are currently investigating if this effect is really due to a resonance some 20 MeV below threshold ($2m_p$), or if it is due to an isospin effect.

$\bar{p}p \rightarrow 3\pi^0$ in flight

In view of the limited phase space for $\bar{p}p$ annihilation at rest to $\pi^0\eta_2(1515)$, it is important to search for the state also in annihilations in flight. Furthermore, a possible energy dependence of the cross section of this reaction may yield information on the nature of this particle. We analyzed our data taken at $\bar{p}$ momenta of 0.6 GeV/c and 1.2 GeV/c
and find clear evidence for the production of the $f_2(1515)$ in flight. Fig. 10a shows the $\pi^+\pi^-$ invariant mass from data taken at 1.2 GeV/c. The $f_2(1515)$ is barely visible; however, after a cut on the angle of the production plane (selecting events perpendicular to the beam axis), the $f_2$ becomes prominent (see Fig. 10b). With the current statistics, it is not yet possible to do a full Dalitz plot analysis. This will be done, however, with the data to be taken in 1992.

$$\bar{p}p \rightarrow \pi^+\pi^-\eta$$

Some four years ago, GAMS observed a resonance decaying to $\pi^+\eta$ with truly exotic quantum numbers: $J^{PC} = 1^{-+}$. However, no other experiment to date has been able to verify the existence of this resonance. Therefore, we have analyzed the annihilation channel $\bar{p}p \rightarrow \pi^+\pi^-\eta$ for the possible presence of this exotic state. Except for well-known resonances, no significant excitation of this state could, however, be found (see the Dalitz plot in Fig. 11a and the $\pi^+\eta$ invariant mass in Fig. 11b). We are currently trying to extract the $\pi^+\eta$ S- and P-waves in order to set limits on the excitation strength of this resonance. Further information is expected from an analysis of $\bar{p}d \rightarrow \pi^+\eta n$, which is in progress.

$$\bar{p}p \rightarrow \pi^+\eta n$$

The analysis of the channel $\pi^+\eta\eta$ is finished, and the paper *Antiproton-Proton Annihilation into $\eta\eta\pi^+$ - Observation of a Scalar Resonance Decaying into $\eta\eta$* by C. Amsler et al. has been submitted for publication to *Phys. Lett* (see enclosed). Of special interest in this final state is the strong excitation of a scalar resonance $f_0(1560)$, decaying to $\eta\eta$. The
Dalitz plot is shown in Fig. 12a, with the $\pi \eta$ and $\eta \eta$ invariant masses in Figs. 12b and 12c. Since no space is left in the corresponding nonet, this state has to be interpreted as an exotic hadron, most likely as the lowest lying scalar glueball, thus providing the normalization point for lattice gauge calculations. In this mass region, another scalar meson has been observed by the GAMS collaboration, it is conceivable that these are the same particles, the $f_0(1590)$. [F. Binon et al., Nuov. Cim. 78A (1983) 313]. It is obviously important to search for other decay modes in order to test the glueonium hypothesis.

\[ \bar{p}p \to \pi \eta \eta' \]

GAMS also observed the decay $f_0(1590) \to \eta \eta'$, with a strength of three times the $\eta \eta$ decay. We have looked for such decays, but have not found a significant signal; our preliminary ratio of branching ratios is significantly below that found by GAMS. Whether this is indicative of two different states or of a problem in one or the other analyses remains to be seen.

\[ \bar{p}p \to \pi \pi \omega \]

The final state $\pi \pi \omega$ was analyzed in view of badly understood $\rho$ vector resonances with masses of 1300 MeV and 1480 MeV, where the latter resonance is considered a candidate for a four-quark state. Our analysis yields, however, only contributions from well-known resonances with $b_1(1235)$ dominating the Dalitz plot (See Fig. 13a). The $\pi \omega$ invariant mass is shown in Fig. 13b. We are currently investigating the possibility of small contributions from the above resonances.
The interest in the $\pi \eta \omega$ channel rests in the possibility to study the $h_1(1380)$ meson, which to date has been seen by one experiment only (LASS). Our Dalitz plot (Fig. 14a) is dominated by one resonance, the $a_0(980)$, and shows no indication of the $h_1$ meson. See also the $\pi \eta$ and $\eta \omega$ invariant masses in Figs. 14b and 14c, respectively. The $a_0$ dominance in this channel can be used to further study this state, which is a candidate for a $KK$ molecule. Together with its decay to $KK$, we intend to perform a coupled channel analysis, extracting its coupling elements to $\pi \eta$ and $KK$.

This final state is dominated by $\pi \phi$ and $K^*K$, which both contribute with nearly equal strengths (see the Dalitz plot in Fig. 15a and the $K_L \pi^0$, $K_S \pi^0$, and $K_S K_L$ invariant masses in Figs. 15B to 15d, respectively). The (near) equality of the two channels suggests that the underlying process is $\overline{p}p \rightarrow \pi^0KK$, and that strong final-state interactions are present. In particular, such an interpretation rules out the need to invoke a strong violation of the OZI-rule to explain the enhanced $\pi \phi$ final state. The corresponding publication is being prepared.

The final state $\pi^0 \pi^0 KK$ can be used to search for the above-mentioned vector meson $\rho(1480)$, which was, despite its production in $\pi$-exchange, found to decay to $\pi \phi$ and was thus considered a candidate for a four-quark state. In this final state, we can clearly isolate the
\(\phi\) meson and observe in the \(\pi\phi\) invariant mass an enhancement at around 1500 MeV. The analysis of this structure is in progress.

E. Branching Ratios

Another main activity of our investigations is the determination of many two-body branching ratios, especially those which have not been determined previously or have been very badly determined. A complete list of branching ratios then allows for a detailed comparison with models of the annihilation dynamics. The following list shows which branching ratios are currently being determined by our experiment.

\[\bar{p}p \rightarrow \pi \pi\]

An analysis of the reactions \(\bar{p}p \rightarrow \pi^0\pi^0\) and \(\pi^+\pi^-\) (Fig. 3) allows the determination of the S- and P-wave contributions to the annihilation. Also, the analysis of \(\bar{p}p \rightarrow \pi^\circ\omega\) and \(\eta \omega\) can, under certain conditions, be used to determine the S- and P-wave contributions. Both analyses are close to being finalized, and publications are being prepared.

\[\bar{p}p \rightarrow \eta X \text{ and } \eta'X\]

An analysis of \(\bar{p}p \rightarrow \eta X\) and \(\bar{p}p \rightarrow \eta'X\), with \(X = \pi^0, \eta\) and \(\omega\), allows a determination of the pseudoscalar mixing angle. The analysis is complete, and we obtain \(\Theta_{PS} = (-17.6 \pm 1.9)^\circ\). The corresponding publication has been submitted to Physics Letters.

\[\bar{p}p \rightarrow 2 \text{ mesons}\]
The determination of precision branching ratios for $\bar{p}p$ annihilation to two mesons $M_1$ and $M_2$ (with $M_i = \pi, K, \eta, \omega$, or $\eta'$) allows precise tests of the models dealing with the annihilation mechanism. As an example, we show in Fig. 16 the momentum spectra of pions and etas from several two-body annihilation channels: $\bar{p}p \rightarrow \pi\eta, \pi\eta', \eta\eta$, and $\eta\eta'$. A publication with a detailed description of the analysis techniques is in progress.

$$\bar{p}p \rightarrow \pi^\circ \phi / \bar{p}p \rightarrow \pi^\circ \omega$$

Ratios of branching ratios for $\phi$ and $\omega$ production yield information on a possible $s\bar{s}$ content in the proton. See also the discussion above on the reaction $\bar{\eta} \rightarrow \pi^\circ KK$. In addition, we analyze the following reaction on neutrons: $\bar{p}n \rightarrow \pi^\circ \phi / \bar{p}n \rightarrow \pi^\circ \omega$.

$$\bar{p}p \rightarrow nX$$

Since an $\eta$ meson is being produced in the $p\bar{p}$ annihilation in about 8 percent of all cases, we can study decays of the $\eta$ meson. Chiral perturbation theory predicts rather accurately the ratio of branching ratios $\eta \rightarrow 3\pi^\circ / \eta \rightarrow \pi^\circ \pi^+ \pi^-$. However, most experimental determinations are at variance among themselves and with the prediction. We have analyzed this ratio and find that our statistical error will be as small as the current error on the average of all previous determinations.

$$\bar{p}p \rightarrow \gamma X$$

A determination of the strengths of radiative transitions $\bar{p}p \rightarrow \gamma X$ allows, in comparison with decays where the photon is substituted by a vector meson, a test of the
vector dominance model. The corresponding publication is in progress.
Figure Captions (1)

Fig. 1 Sketch of the Crystal Barrel detector. (The magnet and the incident antiproton trigger counters are not shown.)

Fig. 2 a) The two-photon invariant mass from a 6-photon event sample. The $\pi^0$ and $\eta$ are clearly visible.
b) The $\eta$ becomes even more prominent after removing those photon pairs from which some combination falls within the $\pi^0$ mass window.

Fig. 3 Momentum spectrum of collinear events $\bar{p}p \rightarrow \pi^+\pi^-$ and $K^+K^-$. The curve is a fit resulting in a momentum resolution of about 2%.

Fig. 4 a) The $\pi^0\pi^0$ invariant mass from $\bar{p}p \rightarrow 3\pi^0$ events. The two peaks on the right side correspond to the $f_0(1270)$ and $f_2(1515)$. The enhancement at low mass is due to the $\pi^0\pi^0$ S-wave and reflections. The solid line is the best fit to the Dalitz plot.
b) The $3\pi^0$ Dalitz plot. The arrows indicate the position of the two resonances $f_0(1270)$ and $f_2(1515)$.

Fig. 5 The $\rho^+\rho^-$ invariant mass squared from $\bar{p}p \rightarrow \pi^0\rho^+\rho^-$ events. The enhancement around 2.3 GeV$^2$ may be due to an excitation of the $f_2(1515)$.

Fig. 6 still missing ($\bar{p}p \rightarrow \gamma \pi^0\pi^0$)

Fig. 7 the $\pi^0\pi^0$ invariant mass from $\bar{p}d \rightarrow 3\pi^0 + n$ events after a cut on the neutron momentum of $p_n < 100$ MeV/c. This mass spectrum is identical in shape to the one obtained from annihilations on free protons, $\bar{p}p \rightarrow 3\pi^0$.

Fig. 8 a) The $\pi^0\pi^0$ and b) $\pi^0\pi^0$ invariant mass spectra from $\bar{p}n \rightarrow \pi^0\pi^0\pi^0$ events. In a) the $f_0(1270)$ and the $f_2(1515)$ are clearly visible. In b) the $\rho$ is the only resonance; the peak at high invariant masses is due to reflections.

Fig. 9 Ratio of the two neutron momentum spectra from $\bar{p}d \rightarrow 3\pi^0 + n$ and $2\pi\eta + n$. The peak near 150 MeV/c may be interpreted as an $NN$ resonance below threshold.

Fig. 10 a) The $\pi^0\pi^0$ invariant mass spectrum from $\bar{p}p \rightarrow 3\pi^0$ events taken at 1200 MeV/c beam momentum. The prominent peak is the $f_0(1270)$; the $f_2(1515)$ is only visible as a shoulder.
b) Same $\pi^0\pi^0$ after different cuts on the angle of the production plane, favoring those events produced preferentially perpendicular to the beam axis. The $f_2(1515)$ becomes very prominent.
Figure Captions (2)

Fig. 11 a) The Dalitz plot from $\bar{p}p \rightarrow \pi^+\pi^-\eta$ events. The prominent structures are due to the $a_2(1320)$. No evidence is seen for an excitation of the exotic state $\rho(1405)$.

b) The $\pi^+\pi^-$ invariant mass clearly shows the $a_2(1320)$ and no $\rho(1405)$.

Fig. 12 a) The Dalitz plot from $\bar{p}p \rightarrow \pi^+\eta\eta$ events. The arrows indicate the positions of the three resonances $a_0(980)$, $f_0(1400)$, and $X = f_0(1560)$. The latter state is currently the best glueonium candidate.

b) The $\pi\eta$ invariant mass showing the $a_0(980)$.

c) The $\eta\eta$ invariant mass showing a clear peak from $f_0(1560)$.

Fig. 13 a) The Dalitz plot from $\bar{p}p \rightarrow \pi^+\eta\omega$ events. The enhancement in the region at the lower left is due to the $b_1(1235)$ and the $\pi^+\pi^-\omega$ S-wave.

b) The $\pi\omega$ invariant mass showing a strong signal from the $b_1(1235)$, which dominates the Dalitz plot.

c) No resonance is visible in the $\eta\omega$ invariant mass.

Fig. 14 a) The Dalitz plot from $\bar{p}p \rightarrow \pi^+\eta\omega$ events. This Dalitz plot is dominated by the excitation of one resonance only, the $a_0(980)$, a $KK$ molecule candidate.

b) The $\pi\eta$ invariant mass showing the strong $a_0(980)$ signal.

c) No resonance is visible in the $\eta\omega$ invariant mass.

Fig. 15 a) The Dalitz plot from $\bar{p}p \rightarrow \pi^+K^-K_L$ events, where the $K_L$ is not detected in the calorimeter. The three bands correspond to the two $K^-$s, and the $\phi$.

b) The $\pi^-K_L$ invariant mass showing the $K^-$.

c) The $\pi^+K_S$ invariant mass showing the $K^*$.

d) The $K_SK_L$ invariant mass showing the $\phi(1020)$.

Fig. 16 Momentum spectra of pions and etas from the following two-body annihilation channels: $\bar{p}p \rightarrow \pi^+\eta, \pi^+\eta', \eta\eta, \text{ and } \eta\eta'$. All particles are detected in their all-neutral decay modes.
Crystal Barrel Detector

Electromagnetic Calorimeter
[ 1380 CsI (TI) Crystals ]

Figure 1
$pp \rightarrow 6\gamma$

Figure 2
$p p \rightarrow \pi^+\pi^-$ and $K^+K^-$

Figure 3
$pp \rightarrow 3\pi^0$

![Graph showing the distribution of $M(\pi^0\pi^0)$ and GeV/c^2 entries.]
$pp \rightarrow 3\pi^0$

Figure 4b
$\bar{p}p \rightarrow \pi^0 \rho^+ \rho^-$

Figure 5
\[ \bar{p}d \rightarrow 3\pi^0 + n \]
\[ p\pi \rightarrow \pi^+\pi^0\pi^0 \]

\[ m(\pi^0\pi^0) \text{ [MeV]} \]

\[ m(\pi^-\pi^0) \text{ [MeV]} \]

**Figure 8**
\( \bar{p}d \rightarrow X + n \)

![Figure 9](image-url)
\( \bar{p}p \rightarrow 3\pi^0 \) at 1200 MeV/c

Figure 10
\( \text{pp} \rightarrow \pi^0 \pi^0 \eta \)

Figure 11a
\( \bar{p}p \rightarrow \pi^0\pi^0\eta \)

Figure 11b
$pp \to \pi^0 \eta \eta$

Figure 12a
$pp \rightarrow \pi^0 \eta \eta$

**Figure 12b**
\[ p p \rightarrow \pi^0\pi^0\omega \]

Figure 13a
\[ \bar{p}p \rightarrow \pi^0 \pi^0 \omega \]

Figure 13b
$pp \rightarrow \pi^0 \eta \omega$

Figure 14a
$pp \rightarrow \pi^0\eta\omega$

Figure 14b,c
$pp \rightarrow \pi^0 K_S K_L$

**Figure 15**
Figure 16
F. Berkeley Contributions to the Crystal Barrel

Our group, as a member of the Crystal Barrel collaboration, has been responsible for the operation of the Jet Drift Chamber. In 1991, a fault in the high voltage was traced to a "bad wire" in the chamber. The wire was removed, and the problem was found to have been caused by intermittent arc-over in one of the insulating pins. The missing wire was not replaced, since its absence has little effect on the electrostatics. In the checkout of the wire, one sense wire was discovered to have a high resistance connection. Attempts to recrimp the wire failed. The wire was removed and replaced in Spring 1992, and the chamber was operated in April with excellent results. This repair was done by Dr. R. Bossingham and Dr. D. Armstrong at a record breaking rate. The validity of the decision to build a spare chamber was dramatically demonstrated, and the construction work begun in Berkeley took on a high priority. The new JDC has several changes which have been introduced to: a) improve the seal for gas leaks on the insulating pins; b) use a new crimping method which provides higher accuracy in the location of the wire within the insulating pins for the sense wire.

During the spring, these problems were studied at CERN, and it was decided to do the wire stringing there instead of at LBL. A suitable location for a clean room was found, and an experienced wiring team has been assembled. They are setting up for the wiring while the parts are being fabricated in the United States. In September 1992, we expect to begin the wiring and have a chamber ready for tests by the end of 1992. The funding for the work in CERN is provided by the University of Hamburg and will be supervised by Dr. Uli Wiedner from Hamburg. Dr. K. Crowe has been and will continue to be closely
involved in the construction at CERN.

In the process of exploring the types of improvements possible for the new JDC, the resolution data and discussions concerning the off-line program which is responsible for converting the JDC pulse data to tracks with reconstructed momenta, analyses, etc., has lead to a focusing of attention on the sources of errors and momentum resolution which are obtained with the JDC. Unfortunately, one scheme which was proposed by Crowe to enlarge the size of the cells near the target by reducing the number of radial sense wireplanes from 30 to 15, cannot be implemented in the new design. However, for evaluation of the present design and proposed alterations, the test JDC prototype made at LBL in 1987 has been rejuvenated and is now refitted with each cell design. Tests will begin in Fall 1992 to evaluate directly the chamber position accuracy and some of the questions concerning the present operating chamber can be explored with the prototype. This work will probably continue into 1993. Unfortunately, it is a major job to convert and rewire either the present chamber or the new chamber. At this point, the information may guide the next generation in the desire to improve the resolution for this style detector.

Currently, the new chamber that is being constructed should be an improvement and provide a back-up chamber to install at our convenience or in case the chamber fails again due to aging effects, radiation damage or a catastrophe resulting from mishandling and damage, for example.

Another contribution by our group has been a major rewrite of the Monte Carlo code for simulating the Crystal Barrel Detector. The old code had been used to study the general parameters of the detector design, but lacked the accuracy, detail and flexibility to make
serious detector studies and corrections. The code, and its documentation, were released for general use in Spring 1992.

G. Muon Program at TRIUMF

One of the remaining open questions in low-energy weak interactions is that of the so-called "induced" form factors in the semileptonic weak interaction. The primordial V-A structure of the weak interaction for processes involving hadrons is modified by the presence of the strong interaction. The most familiar instance of this is the fact that the axial coupling constant of the nucleon is \( g_A = 1.26g_V \) (as determined from neutron decay measurements), rather than the V-A value of \( g_A = g_V \) for purely leptonic processes. In addition to this renormalization of the axial coupling, in general four additional terms arise due to the presence of the strong interaction. For two of these (the scalar and tensor couplings) there are compelling theoretical expectations that they must vanish, which is consistent with the experimental situation, and one (weak magnetism) can be related to well-known electromagnetic form factors (via the conserved vector current hypothesis), and this is confirmed precisely by experiment. However, the final term, the induced pseudoscalar coupling \( g_p \), remains interesting both theoretically and experimentally.

A current algebra approach, using the partially conserved axial current hypothesis PCAC and the assumption of pion-pole dominance, leads to the Goldberger-Treiman prediction that \( g_p = 6.8g_A \) for the nucleon. Deviations from this prediction can be related to chiral symmetry breaking. There is at present no firm prediction for \( g_p \) from QCD (i.e., via lattice gauge calculations). However, it is expected that just as the prediction of \( g_A \) is a
basic test of any model of the nucleon, the ability to predict $g_p$ should be a sensitive benchmark for testing models. Unfortunately, the experimental situation is not yet satisfactory. The induced couplings are essentially unobservable in $\beta$-decay processes, as their effect scales with the momentum transfer $q$ of the process. Thus, $\mu^-$ capture with its higher characteristic $q$ is the ideal system to measure $g_p$. A program of several related experiments to measure $g_p$ has developed at TRIUMF with the active participation of D. Armstrong. With one exception (Exp. 592), all these experiments have been awarded "high priority" by the TRIUMF experimental evaluation committee (EEC).

The flagship experiment in this program is Exp. 452, the measurement of radiative muon capture (RMC) on hydrogen (D. Armstrong with collaborators from TRIUMF, U. British Columbia, Virginia Tech., U. Montreal, U. Kentucky, Queen's U., PSI and U. Melbourne). A large cylindrical drift chamber [1] is used as a pair spectrometer to detect the very rare RMC photons (branching ratio $\sim 10^{-8}$) from $\mu^-$'s stopping in a liquid protium (deuterium-depleted hydrogen) target. RMC on hydrogen has never before been observed, and the goal is to detect on the order of 400 events, which will lead to a precision in $g_p$ of better than ten percent. This will be a substantial improvement on the knowledge of $g_p$ for the proton, as the only information available to date is from ordinary (non-radiative) muon-capture experiments, the most accurate of which (from Saclay in the late 70s) obtained $g_p$ with a 45 percent uncertainty. The experiment began data-taking on protium in 1990, and 1992 has seen the continuation of the very successful data acquisition, with twelve weeks of beam scheduled in total this year. The analysis is well underway, with most backgrounds and systematics understood, and preliminary results have been presented at various
conferences [2,3,4,5]. This same detector has been used for measurements of RMC on a series of nuclei, and the analysis of these data was completed and a paper published in 1992 [6].

The nuclear radiative muon capture measurements are representative of the other topic of interest related to the pseudoscalar coupling $g_\rho$. While the hydrogen RMC measurement will provide a precise value for $g_\rho$ for the proton, the question arises as to whether or not $g_\rho$ remains the same for a nucleon embedded in the nucleus. There appears to be intriguing evidence that some of the nucleon's properties are modified in the nuclear environment (e.g. the EMC effect and "quenching" of $g_\rho$ in nuclei). There are theoretical expectations that $g_\rho$ may also be "renormalized" from its nucleonic value in nuclei; and so measurements of $g_\rho$ in various nuclei are required. Our nuclear RMC data are strongly suggestive of a $Z$-dependent quenching of $g_\rho$ to near zero for high-$Z$ nuclei; however, the interpretation of the results are clouded by uncertainties in the conventional nuclear structure. This characteristic sensitivity to nuclear structure dictates that one should measure other observables in muon capture that are less sensitive to nuclear structure, while retaining sensitivity to $g_\rho$.

Such experiments include Exp. 570 (D. Armstrong spokesman, with U. British Columbia, Valparaiso U., and U. Kentucky) which is a measurement of the angular correlation between the neutrino and a specific nuclear de-excitation gamma ray following muon capture on $^{28}$Si. For a fast gamma transition, such an angular correlation can be observed by measuring the energy distribution of the Doppler-broadened gamma ray. In some cases, this angular correlation is sensitive to the magnitude of $g_\rho$ and rather insensitive
to the nuclear wavefunctions. One such case is the allowed \(0^+ \rightarrow 1^+ \rightarrow 0^+\) muon capture sequence

\[
\mu^+ + {}^{28}\text{Si} \rightarrow V_\mu + {}^{28}\text{Al}^*(2202\text{ keV}) \rightarrow V_\mu + {}^{28}\text{Al}^*(973\text{keV}) + \gamma
\] (1)

Using several high resolution Compton-suppressed Ge crystals as the primary detectors, in coincidence with an array of NaI crystals to suppress backgrounds, a determination of \(g_\mu\) to better than ten percent precision is possible. A feasibility test of this experiment was made during one week of beam in January 1992, and the analysis was completed and presented to the TRIUMF EEC in July 1992. Three weeks of beam were granted to complete the measurement, which will take place in winter 1992-93. The analysis of these data will form the basis of the PhD thesis of a student at U. British Columbia.

A complementary technique is that of Exp. 612 (D. Armstrong, with collaborators from TRIUMF, U. British Columbia and U. Kentucky). Here the hyperfine dependence of the muon capture probability to specific nuclear final states is used to extract \(g_\mu\). This hyperfine dependence can be measured by fitting the time distribution of nuclear gamma rays from the deexcitation of the nuclear final state, in the case where there is an observable hyperfine transition linking the upper and lower muonic hyperfine levels. Since the same nuclear matrix elements apply to the capture from the two hyperfine levels (the only difference being a spinflip of the muon), the ratio of the capture rates is quite nuclear structure independent and quite \(g_\mu\) sensitive. An earlier survey experiment in 1991 showed several candidate transitions in sd-shell nuclei, including \(^{23}\text{Na}, {}^{31}\text{P}\) and \(^{35}\text{Cl}\), and provided an M.Sc. thesis for a U. Kentucky student. In June 1992, a successful two-week run.
concentrated on measuring the hyperfine capture dependence for a transition in $^{23}$Na. The analysis of these data will provide the PhD thesis for a U. Kentucky student.

Finally, Exp. 592 (D. Armstrong with collaborators from TRIUMF, U. British Columbia, Virginia Tech, U. Montreal, U. Kentucky, Queens U, PSI and U. Melbourne) is a measurement of radiative muon capture in $^3$He. Here, the nuclear structure uncertainty should be minimized since good wavefunctions are available from Fadeev calculations, and also since we hope to isolate the final state triton from the breakup channels using scintillation light from liquid $^3$He. This experiment has been deferred by the TRIUMF EEC until target development has demonstrated that the triton can be identified. In 1992, substantial progress has been made on the target design, and the scintillation light has been clearly observed in a prototype $^4$He target. Agreement has also been reached with LLNL to loan the $^3$He needed for the (large) liquid He target.

References


H. Negative Muons at PSI

We have continued our collaboration with an international group doing work in muon-catalyzed fusion and muon capture at PSI. These two areas are intimately intertwined. Muon fusion is a major background in many μ-capture experiments and μ capture can be a difficult background in μCF experiments. Accurate measurements in one field can set the limit of accuracy in the other.

As an example, μ capture on $^3$He is a background to μ capture on p. The $^3$He is formed when the muon catalyzes the fusion of a rare d with a p (even in purified p). d-d catalyzed fusion is a background to μ capture on d. To predict the amount of $^3$He formed in a pd mixture, the exact meso-molecular formation rate $\lambda_{pud}$ must be known. As a result of our recent experiments to measure "sticking" in dt fusion (in a pdt mixture), we have produced the most accurate value for this rate by using the fusion events as unequivocal signals of the muon kinetics. (We also produced the most clear results so far on sticking, which limits the ultimate number of fusions catalyzed by one muon. This improved measurement of $\lambda_{pud}$ is useful in the analysis of backgrounds for the TRIUMF RMC experiment, for example.)

This experiment was done in a novel, high-pressure, ionization chamber (IC) built at Gatchina, Russia. This "active-target" arrangement allows for 100 percent efficiency in the inner sensitive volume due to the implicit $4\pi$ acceptance. This allows for accurate absolute rate measurements. Our plan for 1993 is to use this chamber to make percent-level measurements of the capture rate in $^3$He. This would immediately refine several other basic measurements dependent upon this result.
\[ \mu \text{-capture on } ^3\text{He is complicated by the fact that it does not always branch to } t + \nu \]
but many times breaks up into \( d + n + \nu \) or \( p + n + n + \nu \). At low energies, this has not
been measured accurately. Our active volume will completely contain all charged tracks for
these low energy breakups, so we can simultaneously measure the normal capture process
and these breakup channels.

In 1992, we concentrated on the "sticking" measurement. We were most interested
in the "final sticking," when the muon remains bound to the alpha particle product of the
dt fusion even after it comes to rest. The exact value of final sticking has been reported to
lie considerably below theoretical expectations, and our results have confirmed this. The
Russian IC has performed exceptionally well for this task because it fully contains both \( \alpha^{++} \)
tracks and \( \mu \alpha^+ \) tracks and differentiates them according to dE/dX and track length. Our
experiment also has large arrays to detect the recoil neutrons and decay electrons.

Besides collecting the first clear tracks of these final sticking events and making the
pd fusion rate measurement, we observed unexpectedly fast meso-molecular formation rates
which have since been explained as a normal part of the \( \mu \text{CF kinetics at very short times.} \)
These fast reactions are related to high energy resonances and differences in the \( \mu \) transfer
cross sections at high energies. After a muon transfers between isotopes, the resulting mesic
atom has enough kinetic energy that these phenomena are important. The IC we use and
the special triple mixtures (pdt) have allowed us to effectively slow down the time sequence
for these usually very rapid events to the point that we can understand these tricky
mechanisms in detail.

During these experiments, we have also been able to test out the IC for the future
$^3\text{He}$ experiments. After pd fusions, the muon is left bound to the $^3\text{He}$ and captures 0.3% of the time. This represents a background to the sticking measurement but has also allowed us to test our sensitivity to the $^3\text{He}$ reactions, with good results.
4. Projected Program - 1993 and Beyond

A. Crystal Barrel

To complete the experimental program of the Crystal Barrel experiment will require the accumulation of data sets of similar size with the following beam conditions:

- 12 weeks with antiproton momenta at 1200 MeV/c, 1900 MeV/c, and 600 MeV/c ('in-flight');
- 8 weeks with an antiproton momentum of 100 MeV/c and a gaseous hydrogen target; and
- 12 weeks with various momenta and with very selective triggers.

In the following we will discuss each of these requests in detail and point out the physics motivation.

Data Taking at High Energies

In order to increase the mass range available in antiproton-proton annihilations, our collaboration considers it imperative to focus our strategy for running in 1992 on high antiproton momenta. A 10-day run at the end of 1991 with a momentum setting of 1.2 GeV/c already provided first results on annihilation in flight. One of the main reasons to study annihilations in flight, and thus to increase the available mass range up to 2.4 GeV, is the prediction (e.g. by the flux-tube model) that hybrid states have masses around 2 GeV and thus can only be produced with antiprotons of high momentum. Also, glueballs with $J^{PC}$ other than $0^+$ are expected close to 2 GeV. A search for and the subsequent study of these new states is important for low energy QCD: one such state allows one to
unambiguously fix the mass scale of non-quark model states; decays of such states then allow the testing of phenomenological models and the underlying non-perturbative region of QCD.

For the running in flight, we intend to split the available beam time into two major portions of roughly equal size, all to be taken with the liquid hydrogen target. The main reason for running at different momenta is that the production cross section for different states depends on the antiproton momentum. For example, the two-body cross section is expected to behave like \( p \exp [- A \sqrt{s} - (m_1 + m_2)^2] \). Thus, data taking at the highest energies is desirable only for a search for the highest mass mesons, hybrids and glueballs.

Our first momentum setting will be 1.2 GeV/c, corresponding to a center of mass of about 2.15 GeV, which should allow an easy identification of hybrids or other states below 1.9 GeV. At this momentum, the boost of the events is very modest and data can be analyzed with reconstruction efficiencies very close to those at rest. The second setting at the highest possible beam momentum of about 1.9 GeV will allow us to search for glueballs and hybrids with masses up to about 2.2 GeV, albeit with smaller reconstruction efficiencies. Selective triggers will be enabled to enhance the probability of finding new exotic states, e.g. a trigger on \( \pi^+\eta\pi^+\pi^- \) might provide evidence for the missing glueball candidate state with \( J^{PC} = 2^- \) which is expected to decay to \( \eta\pi^+\pi^- \). Other glueonium states will be searched for in the final states \( \pi^0\pi^0, \eta\eta, \) and \( \eta\eta' \). A search for hybrids will focus on the very promising channels \( \bar{p}p \rightarrow \pi^0 f_1(1285) \rightarrow 3\pi\eta \) and \( \pi f_1(1235) \rightarrow 2\pi\omega \).

In addition, we want to run for a shorter period of about two weeks at 600 MeV/c in order to study the production of the glueball candidate \( \eta(1420) \), which was originally found in \( \bar{p}p \) annihilations at rest. A previous bubble chamber experiment at 600 MeV/c
showed a signal at the same mass position, but no spin-parity analysis was done owing to small statistics. We intend to study this glueball candidate in its decays to $\bar{K}K\pi$ and $\eta\pi\pi$ (again using special triggers). Also of interest at 600 MeV/c are a study of the $f_2(1515)$ - a multiquark candidate - seen by our collaboration in annihilations at rest in the decay to $2\pi^\circ$.

**Data Taking at 100 MeV/c**

Data taking at 100 MeV/c will be done with a gaseous hydrogen target. In gas at NTP, the antiproton-proton annihilates with a probability of 53 percent from P-states, whereas in liquid hydrogen this fraction is only about nine percent (the remainder annihilating from S-wave in both cases). A comparison of data taken in liquid hydrogen (our 200 MeV/c running) and in gaseous hydrogen allows the selection of pure initial S- and P-wave annihilation, and new states may become observable. In particular, annihilations from P-wave have not yet been studied with an experiment able to detect photons and charged particles with good efficiencies. For example, the $f_2(1515)$ state (a multi-quark candidate) was found by our collaboration in the $3\pi^\circ$ final state from annihilation in liquid hydrogen with a P-wave contribution twice as strong as that from S-wave. Its observation was only possible owing to the absence of strong S-wave contributions due to conservation of C-conjugation and the absence of $\rho(770)$ mesons in the $3\pi^\circ$ channel.

As an example, we will study in gaseous hydrogen the production of the above-mentioned $f_2(1515)$ in its decays to $K^+K^-, \eta\eta$, and $\eta\eta'$. Furthermore, the associated production of a $\pi^\circ$ with pseudoscalars like the $\eta(1420)$ is possible only from P-waves. In
addition, all our Dalitz plot analyses of annihilations in liquid hydrogen ($\pi^0\pi^0\pi^0, \pi^0\pi^\pm\eta, \pi^0\eta\eta, \pi^0\pi\omega, \pi^0\eta\omega$) will be repeated for pure P-wave annihilation and thus with substantially greater sensitivity. To do so, data sets of about equal size accumulated with liquid and gaseous hydrogen are needed. The reward will be Dalitz plots which will be easier to analyze and thus will allow for a greater discovery potential for new hadronic states: glueballs and hybrids.

Finally, it should be mentioned that the comparison of data produced in S- and P-wave annihilations will also help answer the question of strangeness in the proton. Today it is known that the only enhanced channel with strangeness in the final state is $\overline{p}p(3S_1)\rightarrow \pi\phi$; all other final states involving $\phi$ mesons follow - with large experimental uncertainties - more or less the prediction of the OZI rule. It is clearly important to search for other enhanced channels with $\phi$ and $f_2(1525)$. The subsequent study of the relative S- and P-wave contribution to the annihilation may help give an answer to the question of constituent strangeness in the proton.

Data Taking with Very Selective Triggers

After the completion of the above-mentioned data taking, we intend to accumulate more data with very selective triggers. All these triggers will be very selective in the sense that they will enhance the desired events on tape by factors of 30 to 100, depending on topology and background. Thus, these triggers will cut hard into the available phase space. It is therefore necessary to first fully understand the background under a signal and to simulate the triggers on sufficiently large data sets. This requires a very good understanding
of the data sets discussed above. Another strategy pursued by our collaboration for the long
term is to increase the data acquisition speed by about a factor of four and correspondingly
loosen the trigger requirements.

Since we have not yet analyzed all the data taken at rest nor have we accumulated
large data sets in-flight, it is impossible to predict which final states will show interesting
new structures which warrant a substantial increase of statistics to allow for a detailed spin-
parity analysis. Clearly, a significant increase in statistics is possible only with dedicated triggers. We have demonstrated that it is possible with the data acquisition system of the Crystal Barrel experiment to trigger on neutral pions and etas in their decay to two photons. For the two decay channels $\bar{p}p \rightarrow \pi^+ \pi^0 \pi^- \eta$ and $\bar{p}p \rightarrow \pi^+ \pi^- \eta$ we have achieved enrichment factors for 40 and 20, respectively, over minimum-bias data taking. In addition, a trigger on missing $K_L$ is possible owing to missing energy and momentum in the calorimeter.

**JDC Hardware**

Since the effort in our group in 1992 has been connected with the maintenance and improvement of the JDC central detector, our group has been almost completely absorbed with hardware problems, preparing for runs and taking our share of data-taking shifts.

This activity will continue into 1993 and beyond; specifically, work on two major efforts are underway. The resolution of the JDC has been studied by using the $\pi^+ \pi^-$ and $K^+K^-$ final states (figure 3). The measured resolution momentum is approximately 30 percent higher (poorer) than predicted by various crude models. In September 1992, a small working group will be assembled to review the data and models. All of our group will be
involved, and this study will undoubtedly recommend both experimental tests to be conducted and modifications in the off-line programs which should be done to get to the causes. We will probably be heavily involved. The second program is the construction of the second, stand-by chamber. In 1993, we will be completing the assembly and testing the chamber. As this is completed, we will replace the present chamber if the improvements are significant. Otherwise, it will be stored, and installed if a major failure of the chamber forces its removal and repair. Since the mechanical precision of the wires in the new chamber has been improved, the resolution should improve and installation should be attempted in 1993 or early 1994.

The work on physics results done by our group have been slowed down by the reduction in the size of the group. Our principal full-time technician, James Bistirlich, who built the JDC in Berkeley and was the person who knew all the details, problems and cures, left LBL and is employed at the SSC. Dr. H. Bossy, who was the senior post-doc, went to a position with the German government in Bonn. His position was eliminated by DOE in the 1991 budget cut. As a result, the remaining people in the group were forced to fill the gap in our JDC hardware responsibility at the expense of the data analysis.

1993 will be a difficult year. The experiment will continue, more data will be collected, and the analysis will be done mainly by our European collaborators. We must add a dedicated data analyst to our group as quickly as possible.

In 1994-95, the Crystal Barrel experiment will request running time to complete the agenda outlined in Section 4A. The emphasis depends on the success of running with the high momentum, 1.9 GeV/c beams, and the low momentum 100 MeV/c tests which are
scheduled in Winter 1992, gas target running as well as deuterium data. Several studies involve new triggers to increase data samples by a factor of 10, so that adequate statistics can be obtained to extract the interesting resonance signals from the backgrounds and measure their spin-parities.

At present, CERN has requested a statement of our plan. In September 1992, a decision from the Program Committee will indicate whether we should continue with another round of running. If we are successful, there will be future meetings (over the next two years) where new physics, extensions, modifications, etc. will be forthcoming from the collaboration. If we are unsuccessful, the detector is already being requested by other European accelerators for their first rounds of experiments. In the interim, there will be several years of intensive analysis of the data in hand, and the Berkeley group expects to play an active role. The interest in our detector and the future results will be featured, for example, in the LEAP 92 Conference in September 1992 at Courmayer. C. Dover will present a major paper on the comparison of data and theory, as well as the conference summary. For a recent published theoretical summary, see Dover, et al. Phys Rev C Vol. 43, 379 and Vol. 44, 1281 (1991), and references contained therein.

Muon Physics at TRIUMF and PSI

Active participation in the muon physics program at TRIUMF is expected to continue in 1993. The radiative muon capture (RMC) experiment on hydrogen (Exp. 452) will likely complete data taking in mid-to-late 1993. The logical successor is Exp. 592 (RMC on $^3$He) which should begin initial data taking after the hydrogen experiment is complete, although
some tests of the target using parasitic beam time are anticipated earlier in the year. The gamma-neutrino angular correlation measurement Exp. 570 will have its major data taking late this year or early in 1993 (3 weeks of beam), and some of the data analysis will be done at LBL. Extension to other nuclei is under consideration, but no proposal will be made until the \(^{28}\)Si data is well understood. No data taking is anticipated for the hyperfine dependence experiment (Exp. 612) for 1993, as effort will concentrate on the analysis of the 1992 \(^{23}\)Na data, as well as on the preparation for publication of results on the hyperfine transition rates obtained from the survey measurement made in 1991. On the longer term, however, measurements of other promising targets identified in the survey run (\(^{35}\)Cl, \(^{31}\)P) are anticipated. In addition, a proposal has been accepted by the EEC (Exp. 656, D. Armstrong with collaborators from U. Kentucky, TRIUMF, Simon Fraser U., U. of Western Ontario) to use the TRIUMF CHARGEX facility to study the Gamow-Teller strength in the \(^{23}\)Na(n,p) reaction as a cross check on the wave functions used in the interpretation of our \(^{23}\)Na data, and beam time will be requested for this measurement in 1993.

The collaboration at PSI will continue doing work, mainly on muon capture in the next year. We are constructing (at Gatchina) a modification of the Russian Ionization Chamber with a geometry specifically designed for the \(^{3}\)He capture experiment. With no major modifications, we should be able to track the stopping muons into the sensitive volume (and locate their stopping positions) with 100 percent efficiency, and trigger on all \(^{3}\)He to \(t+\nu\) events and all breakup channels events below about 5 MeV in the charged particles. Obtaining a one percent accuracy in the separated channels of \(\mu\)-capture on \(^{3}\)He will greatly improve basic measurements derived from \(^{3}\)He capture rates (e.g. tests of lepton
universality, form factors for $^3\text{He}$). In particular, the low energy breakup channels have been poorly measured up until now. Also, these results will be fed back into the $\mu$CF analysis to improve the $^3\text{He}$ background corrections. Some work is also continuing in the $\mu$CF area in the design of a new high-temperature target capable of reaching 2000$^\circ$K at pressures up to 2000 bars to explore some of the fast meso-molecular formation rates only accessible at high temperatures.
APPENDIX

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