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I. INTRODUCTION

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Medium energy meson DOE grant continuation. In 1989, the research group's activities were divided into several components. The major activity was Experiment PS 197 at CERN-LEAR with the Crystal Barrel detector. This report will deal mainly with the results of our experiment to date and the future of the program at LEAR. The second effort was the completion of several projects which are in the data analysis and publication phase: muon-catalyzed fusion, which will be the thesis of Tom Case; muon decay η parameter, the thesis of Roy Bossingham; and several other publications which are appearing or have appeared this year. The third area being pursued involves the KAON Factory at TRIUMF, where a working group on hadron spectroscopy has been formed. Responsibilities for program organization are shared by Ken Crowe and Martin Comyn of TRIUMF. In July 1990, a major meeting was held with this group. There was a week-long series of sessions reviewing the progress, updating the design and planning the program for both the periods before and after the final approval of KAON by the Canadian government. There were over two hundred participants in the meeting.

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II. ACCOMPLISHMENTS - 1990

A. Physics with the Crystal Barrel

1. Purpose of Experiment PS 197

The PS 197 experiment is studying $\bar{p}p$ annihilation at rest and at $\bar{p}$ momenta up to 2 GeV/c into channels involving η 's and/or several neutrals channels which have not been studied so far. The main motivations are to search for glueballs and other exotic mesons and to determine the branching ratios for annihilation into various final states which are relevant to low-energy QCD inspired phenomenology.

2. Status of the apparatus

Following last year's set-up, the Crystal Barrel is now operational. The initial difficulties with beam size and beam alignment have been alleviated through insertion of four thin silicon counters in the target cryostat to define the incident beam. The preliminary γ energy resolution of the CsI barrel is $\sigma/E = 0.028/[E(\text{GeV})]^{1/4}$, comparable to the energy resolution obtained by the Crystal Ball. The crystals have been calibrated by using minimum ionizing pions from $\bar{p}p$ annihilation at rest; these deposit 170 MeV when traversing the crystals. A better calibration using the γ 's from π^0 decay is under way and should lead to an improved resolution. Photodiode/preamplifier noise, which strongly influences the resolution below 100 MeV, typically corresponds to 250 keV (rms). In the jet drift chamber (JDC), a positional resolution of $\sigma_{r\phi} = 125\mu$ has been obtained in the plane transverse to the magnetic field. The resolution along the magnetic axis, obtained through charge division, is $\sigma = 8\text{mm}$ (rms).

The typical data acquisition rate is 10 Hz (limited by the tape-writing speed) and the reaction rate (equal to the incident flux for annihilation at rest) is of order 10^4 s^{-1} , limited by pile-up in the CsI crystals. Hence, final state triggers are required. The various stages of the final-state multiplicity trigger (charged-particle multiplicity, cluster multiplicity in the barrel calorimeter, total energy, π^0 and η triggers) are also operational but have not been tested for efficiency, so far, nor used to collect statistically significant data samples.

The event reconstruction program requires 300 ms (CERN units)* for a minimum-bias event or about 50 hours (CERN units) for each day of data taking. So far, the data have been processed on the CERN central computers and on the computing facilities of the participating institutions.

3. Preliminary results

The first physics data for annihilation of p's at rest in liquid hydrogen were taken in November and December 1989 when we collected 4×10^5 minimum-bias events and 10^6 all-neutral events with a trigger requirement of no hits in the first several layers of the JDC. These data show that the detector is able to reconstruct up to at least several ten γ 's (channel $\pi^0\pi^0\eta$, $\eta \rightarrow 3\pi^0$). A selection of 6γ events leads to the following reconstructed final states:

- The channel $\pi^0\pi^0\pi^0$ (50k events) shows the production of the $f_2(1270)$ and the production of a state with mass 1520 MeV and width 105 MeV, decaying into $\pi^0\pi^0$.

*CERN units correspond, roughly, to the computing power of a VAX-780.

The Dalitz plot and its projection are shown in Fig. 1. A spin-parity analysis gives $J^{PC}=2$ for the state at 1520 MeV. This state is likely to be the AX discovered earlier by the ASTERIX collaboration at LEAR [1] in the $\pi^+\pi^-\pi^0$ final state for annihilation in hydrogen gas. It is either a two-quarks two-antiquarks state or one of the long-sought baryonium bound states [2]/. AX is mainly produced from $I=1$ atomic P states. This is not necessarily contradicted by its present observation in liquid hydrogen, since $3\pi^0$ is a pure $I=1$ state and $I=1$ annihilation into $\pi^+\pi^-\pi^0$ from P states dominates $I=0$. Hence, one expects an enhancement of p-wave annihilation in liquid into $3\pi^0$.

- The channel $\pi^0\eta\eta$ (3k events) shows the production of a state around 1550 MeV decaying into $\eta\eta$ (Fig. 2). No spin-parity analysis is available yet. It could be the AX or the 0^{++} glueball candidate observed by the GAMS collaboration [3].

- The channel $\omega\omega$ ($\omega \rightarrow \pi^0\gamma$) was observed for the first time with very little background (Fig. 3). This shows the capability of the detector to search for the states decaying into $\omega\omega$, recently reported by GAMS [4].

In addition, we have 12k events for $\pi^0\pi^0\eta$ and 230 events for $\eta\eta\eta$. The former channel is being analyzed to search for the exotic 1^{++} state at 1400 MeV, decaying into $\pi^0\eta$, reported by GAMS [5]. Clearly, more statistics will be required for these channels which are observed for the first time.

The 4γ events show the channels $\pi^0\pi^0$, $\pi^0\eta$ and $\eta\eta$ with very little background (Fig. 4). Most branching ratios for two-neutral mesons are unknown and some of the rates, determined earlier from the inclusive π^0 or η momentum spectrum, are not consistent within experiments [6,7]. These and other branching ratios, like $\pi^0\eta$, $\eta\eta$, $\phi\pi^0$ and $\eta\phi$, are

essential as input to quark models of $\bar{p}p$ annihilation [8]. The production of ϕ mesons seems to exceed the prediction of the OZI rule by large factors when assuming no strange quark in the nucleon. This is an important point to clarify by comparing $\phi\pi^0$ to $\omega\pi^0$.

From $\pi^+\pi^-\pi^0\pi^0$ we obtain the channel $\pi^0\omega$ (Fig. 5) and, from $\pi^+\pi^-\pi^0\eta$, the channel $\eta\omega$. These channels are also observed in the 5γ final state with $\omega \rightarrow \pi^0\gamma$. A determination of the branching ratios for the signals shown in Fig. 3-5 is in progress. Finally, a further sample of 1.3×10^6 neutral events and 10^6 minimum-bias events was collected during our first run of 1990, in June.

Figure 4: $\gamma\gamma$ -invariant masses for $\bar{p}p \rightarrow 4\gamma$.

(3 combinations per event). The accumulation of events in the bottom left corner is due to $\bar{p}p \rightarrow \pi^0\pi^0$; that near 500 MeV is due to $\pi^0\eta$; and the one in the center of the plot is due to $\eta\eta$.

Figure 5: $\pi^+\pi^-\pi^0$ mass for $\bar{p}p$ annihilation into two pions and 3 to 5 γ 's.

Figure 2: $\eta\eta$ invariant mass in $\bar{p}p \rightarrow \eta\eta\pi^0$.

Figure 3: Lego plot of $m(\pi^0\gamma)$ vs. $m(\pi^0\gamma)$ in $\bar{p}p \rightarrow \pi^0\pi^0\gamma\gamma$. The peak is due to $\omega\omega$.

Figure 1: Dalitz plot of $\bar{p}p \rightarrow 3\pi^0$ (a) and its projection (b).

B. Muon Catalyzed Fusion, Pion-Proton Bremsstrahlung

In the fall of 1989, before the PSI accelerator was shut down for upgrading, the μ CF collaboration had a second run with the ionization chamber developed by the Leningrad Nuclear Physics Institute at Gatchina (USSR). The purpose was to directly measure the sticking fraction, ω , for the muon to remain on the nucleus after the $d\mu T$ fusion has occurred. This sticking production is the major bottleneck in the fusion cycle and it is usually measured indirectly from the cycling rate. The recoiling μ ^4He nucleus in the ionization chamber can be separated from the free ^4He nucleus by operating the chamber in the saturation mode such that the high charge density track of the α produces a smaller pulse than the same energy ($\mu\alpha$) recoiling ion. The major background, coming from the pile up of α 's, must be corrected carefully. By demanding that another fusion occur after the recoil, the background can be measured. The pulse shape of the recoil ion depends upon the angle of the track. The tracks in the plane of the chamber will have sharp timing pulses and vertical tracks will have a long pulse with the amplitude increasing as the particle slows down. Mr. Case has developed a number of off-line checks to evaluate the signal and backgrounds. The collaboration has reported on the preliminary analysis of this last data set and the abstracts for the papers contributed to the June 1990 μ CF conference at Vienna are as follows. The written contributions are being prepared.

A copy of the Pion-Proton Bremsstrahlung publication is also included in this section. This is the final publication of these experiments.

1. Direct Measurement of DT Sticking

C. Petitjean, K. Lou
(P. Scherrer Institute)

P. Ackerbauer, W.H. Breunlich, M. Fuchs, S. Fussy, M. Jeitler, P. Kammel, J. Marton, J. Werner, J. Zmeskal
(Austrian Academy of Sciences, Institute for Medium Energy Physics, IMEP, Vienna)

H. Bossy, T. Case, K. Crowe
(Lawrence Berkeley Laboratory, LBL, University of California, Berkeley)

D. Balin, V. Baturin, Yu. S. Grigoriev, A. Ilyin, E. Maev, G.E. Petrov, G.G. Semenchuk, A.A. Vorobyov
(Leningrad Nuclear Physics Institute, LNPI, Gatchina)

P. Baumann, H. Daniel, F.J. Hartmann, P. Hofmann, R. Huber, R. Lipowsky, P. Wojciechowski
(Physics Department, Technical University of Munich, TUM, Munich)

The muon catalyzed deuterium-tritium cycle has attracted great attention, since extremely large fusion yields per muon were observed in experiments at PSI, LAMPF and KEK. The limitations of yield seem mainly to be due to $\mu\alpha$ sticking after the reaction

with sticking probability ω_s .

In the previous experiments sticking was determined from neutron disappearance rates which included other loss channels as well, causing considerable discrepancies among experiments and theory. To solve this issue, we have performed a new experiment at PSI aiming at a direct observation of ω_s .

Our apparatus consists of a modular ionisation chamber (IC) as the central part which collects the $\alpha/\mu\alpha$ track charges in a sensitive volume of 3 cm³. The IC is surrounded by a large array of 20 thick plastic counters for the detection of 14 MeV neutrons from the dt fusion reaction. The chamber was filled with a mixture of 90% protium, 10% deuterium and 0.05% tritium at 170 bar/300 K and operated in a 50 kV/cm electrical field.

The principle of the measurement is to separate doubly charged α^{++} from ("sticking") $\mu\alpha^+$ -events by the different charge recombination factors and by the different track lengths.

However, since the expected number of $\mu\alpha$ events is small ($\sim 1/2\%$ of the α 's), extremely clean experimental conditions and the detailed understanding of the systematics are required.

Using 6-bit-flash ADC's for IC signal analysis, we have recorded more than one million fusion events, 25% of which are in neutron coincidence. In addition, a test run was made with reduced pressure (47 bar) to simulate $\mu\alpha$ track lengths by α 's. In mixtures without tritium, we also studied events induced by $d\mu d$ fusion which constitute one of the backgrounds to the sticking measurement. A second background component is due to $\alpha - \alpha$ pile up from 2 fusion events in close succession.

The preliminary results of a first analysis at PSI are presented and discussed

2. Neutron Analysis of the 89 PSI Sticking Experiment

T. Case, H. Bossy, K. Crowe
Lawrence Berkeley Laboratory, UC Berkeley

K. Lou, C. Petitjean
Paul Scherrer Institute, (PSI), Villigen Switzerland)

P. Ackerbauer, W.H. Breunlich, M. Fuchs, S. Fussy, M. Jeitler, P. Kammel, J. Marton, J. Werner, J. Zmeskal
Austrian Academy of Sciences, Institute for Medium Energy Physics, IMEP, Vienna

D. Balin, V. Baturin, Yu. S. Grigoriev, A. Ilyin, E. Maev, G.E. Petrov, G.G. Semenchuk, A.A. Vorobyov
Leningrad Nuclear Physics Institute, LNPI, Gatchina

P. Baumann, H. Daniel, F.J. Hartmann, P. Hofmann, R. Huber, R. Lipowsky, P. Wojciechowski
Physics Department, Technical University of Munich, TUM, Munich

In 1989, an experiment to directly measure DT sticking using an ionization chamber (IC)/active target was run at PSI with an HDT mixture at 170 bar. The IC was surrounded by 19 thick (20 cm) plastic neutron counters covering about 40% solid angle. Included was one liquid counter to examine gamma backgrounds and a layer of electron counters inside of the array to distinguish decay electrons.

These neutron counters are used to eliminate DD fusion background and to evaluate the time distribution of DT fusions that would contribute to double fusion pile-up events which are a major background. Also, because of the different track lengths of alpha and stuck mu-alpha, the fiducial volumes for the two events are slightly different and must be corrected using knowledge of the event geometry and angular response of the neutron detectors.

The large amount of material in the high pressure, high voltage (50kV) IC environment can scatter many neutrons before they interact in a neutron counter and the original recoil angle is not obvious. To understand this process, a special lower pressure run was taken to give longer alpha tracks and hence, more accurate information on the angle of the recoiling neutron. Preliminary results on the angular response of the detector array was presented.

3. μ CF Sticking: History and Recent Developments

H. Bossy

Lawrence Berkeley Laboratory, Berkeley, CA

Soon after the experimental discovery of muon catalyzed fusion in 1957, it was realized that "dead end" processes, ie., the sticking of muons to their fusion products, will ultimately limit the number of cycles a muon can catalyze.

Since then, various experiments have been performed to establish experimental values of the sticking probability. In the case of deuterium-tritium fusion, experiments disagree on the magnitude of the density dependence of the sticking probability, the discrepancy being largest at low densities.

During the past years, theoretical efforts have been concentrated on calculating the sticking probability beyond the Born-Oppenheimer approximation as well as refining the calculation of the reactivation probability (the muon may be stripped off during thermalization of the recoiling muonic helium system). However, up to now there still exists a discrepancy between theoretical predictions and experimental results.

In the talk, an historical overview was presented and the most recent experimental and theoretical developments were discussed.

4. New μ CF Experience With the Modular LNPI Ionization Chamber

K. Lou, C. Petitjean
(Paul Scherrer Institute, PSI, Villigen, Switzerland)

P. Ackerbauer, W.H. Breunlich, M. Fuchs, S. Fussy, M. Jeitler, P. Kammel, J. Marton, J. Werner, J. Zmeskal
(Austrian Academy of Sciences, Institute for Medium Energy Physics, IMEP, Vienna)

H. Bossy, T. Case, K. Crowe
(Lawrence Berkeley Laboratory, LBL, University of California, Berkeley)

D. Balin, V. Baturin, Yu. S. Grigoriev, A. Ilyin, E. Maev, G.E. Petrov, G.G. Semenchuk, A.A. Vorobyov
(Leningrad Nuclear Physics Institute, LNPI, Gatchina)

P. Baumann, H. Daniel, F.J. Hartmann, P. Hofmann, R. Huber, R. Lipowsky, P. Wojciechowski
(Physics Department, Technical University of Munich, TUM, Munich)

An experimental method based on the use of a modular high pressure ionization chamber (IC) for detection of charged particles from dd and dt-fusion reactions, developed by LNPI¹ and applied now in a new experiment at PSI, will be described. The method aims at a direct measurement of the sticking parameter ω_s in the muon catalyzed dt fusion.

The IC, serving also as active target, detects charged particle tracks (μ , α , $\alpha\mu$, p, t, ^3He , etc.) by collection of the negative charges on 19 separate anodes (total area of 2.5 cm^2 , gap 1.1 cm). Separation between doubly charged α^{++} and singly charged $\alpha\mu^+$ is made due to the charge-dependent recombination effect. The IC readout electronics uses 6-bit flash ADC's, which store the resulting one word every 10 ns , covering a range of $10\text{ }\mu\text{s}$.

The drift velocity of about $0.5\text{ cm}/\mu\text{sec}$ and modularity of the anode allow to precisely determine position and time of muon stop and fusion.

More than one million fusion events have been recorded in fall 1989 runs at PSI. The ongoing offline system studies of IC with HD and HDT mixtures will be described. Detailed investigations reveal many interesting ionizing phenomena of the IC. Preliminary results obtained at PSI will be presented and discussed.

**5. The ionization-chamber experiment for the direct measurement of dt sticking:
A comparison of Monte-Carlo calculations with experimental results**

D. Balin, V. Baturin, Yu. S. Grigoriev, A. Ilyin, E. Maev, G.E. Petrov, G.G.
Semenchuk, A.A. Vorobyov
(Leningrad Nuclear Physics Institute, LNPI, Gatchina)

P. Baumann, H. Daniel, F.J. Hartmann, P. Hofmann, R. Huber, R. Lipowsky, P.
Wojciechowski
(Physics Department, Technical University of Munich, TUM, Munich)

P. Ackerbauer, W.H. Breunlich, M. Fuchs, S. Fussy, M. Jeitler, P. Kammel,
J. Marton, N. Naegle, J. Werner, J. Zmeskal
(Austrian Academy of Sciences, Institute for Medium Energy Physics, IMEP, Vienna)

H. Bossy, T. Case, K. Crowe
(Lawrence Berkeley Laboratory, LBL, University of California, Berkeley)

K. Lou, C. Petitjean
(Paul Scherrer Institute, PSI, Villigen, Switzerland)

It is very important to understand how the fusion products are detected in the ionization chamber used for the direct determination of sticking in muon-catalyzed dt fusion [1]. Therefore, a Monte-Carlo program was developed to simulate the detection process [2]. It keeps track of all charged fusion products in the chamber, including those from background reactions like dd fusion and from pile-up processes. The program allows to investigate the effect of track origin and orientation on height and length of the collected charge signal. The results of the Monte Carlo calculations on total collected charge, signal length and delay are compared with results from the recent experiment at Paul Scherrer Institute.

[1] C. Petitjean et al., contribution to μ CF 1990, Vienna.

[2] V.A. Volchenko, et al., Preprint No. 1368, Leningrad Institut Yadernoi Fisiki, 1988.

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