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**STRONG INTERACTIONS STUDIES WITH
MEDIUM ENERGY PROBES**

Progress Report
for Period December 1, 1992 - November 30, 1993

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I. INTRODUCTION

This progress report refers to the period August 1992 to August 1993, which includes the first year of the three year period December 1, 1992 - November 30, 1995 of our existing research contract. The budget proposal for the year 1993-1994, is also presented.

As anticipated in the 1992-95 proposal our major preoccupation during 1992-93 was with Fermilab experiment E760. This experiment, whose primary objective is to make very high-resolution study of Charmonium Spectroscopy via proton-antiproton annihilations, has turned out to be a veritable gold-mine of exciting hadronic physics in other areas as well. A large fraction of the data from E760 have been analyzed during this year and several papers have been published. The follow-up experiment E835 has been approved by the Fermilab.

In addition the E760 experiment at Fermilab, we have made continued progress in our earlier nuclear physics related experiments at LAMPF, MIT and NIKHEF and to prepare their results for publication. These are also described in the following pages.

II. RESEARCH PROGRAMS

In the following we describe the progress made in our various research programs during 1992-1993.

II.A. THE QCD - RELATED RESEARCH PROGRAM

This part of our program is based on our Fermilab experiment E760 which received six months of beam during the last year. Following is a report of the progress made.

II.A1. CHARMONIUM SPECTROSCOPY

The energy resolution realized in our experiments to date is illustrated by fig.1. At an incident antiproton momentum of 4.07 GeV at the J/Ψ resonance, the mass resolution realized is $\Gamma \approx 600$ keV. This is a factor 5-10 better than the best resolution obtained at J/Ψ in the e^+e^- annihilation experiments. For the χ states this is better by a factor of about 50. These experiments have led to the following results:

II.A1.1 THE J/Ψ AND Ψ' STATES

We have calibrated the antiproton orbit length in the accumulator by the known energy of the Ψ' resonance, 3686.00 ± 0.10 MeV. With this calibration we find that the mass of $J/\Psi = 3096.87 \pm 0.03$ (stat) ± 0.03 (sys) MeV. This value is in agreement with the literature value [3] of 3096.93 ± 0.09 MeV, but has smaller errors.

The total widths of J/Ψ and Ψ' states are used for the determination of the strong coupling constant, α_s . In the e^+e^- experiments these widths are determined indirectly by measuring the leptonic and hadronic branching ratios for the decays of J/Ψ and Ψ' and making substantial corrections for bremsstrahlung. Our energy resolution is good enough to allow direct measurement of the widths by analyzing the shapes of the excitation curves. Further, the

J/ Ψ Double Scan

Fig. 1. A typical energy scan of the J/Ψ (3S_1) resonance of Charmonium. The measured $\text{FWHM} = 600 \text{ KeV}$ is mainly due to the energy width of the antiproton beam.

radiation corrections are much smaller since $m_p/m_e \approx 2000$. The preliminary results of our measurements are that

$$\Gamma(J/\Psi) = 99 \pm 12 \text{ (stat)} \pm 6 \text{ (sys)} \text{ keV}$$

$$\Gamma(\Psi') = 306 \pm 36 \text{ (stat)} \pm 16 \text{ (sys)} \text{ keV}$$

Both these widths are larger than their literature values: $\Gamma(J/\Psi) = 68 \pm 10 \text{ keV}$, and $\Gamma(\Psi') = 243 \pm 43 \text{ keV}$ [1]. These values in turn lead to the branching ratios $\text{BR}(R \rightarrow p\bar{p})$, which are also found to be different from those in the literature. A paper describing these results has been published[2].

II.A.1.2 THE $\chi(^3P_J)$ STATES

Papers describing our measurements of the masses and the widths of the χ_1 and χ_2 were published earlier[3,4]. These have been accepted as definitive in the 1992 Review of Particle Properties [1].

II.A1.2.1 Angular Distribution for $\chi_J \rightarrow \gamma + J/\Psi \rightarrow \gamma + e^+ + e^-$

It has been pointed out that a measurement of $\chi_J \rightarrow \gamma J/\Psi$ angular distribution is of great potential importance. Multipole analysis of such an angular distribution, e.g., for χ_2 , can lead to the determination of the magnetic quadrupole moment, a_2 of the c-quark. In the lowest order in which one of the c-quarks radiates a photon, the simple prediction is that

$$a_2 = \frac{-3E\gamma}{4\sqrt{5}m_c}(1+k)$$

where k is the anomalous magnetic moment of the c-quark. A large value of k would indicate constituent structure of the c-quark itself.

E760 has taken some data for the χ_2 radiative decay. The preliminary results are that the decay proceeds primarily via the helicity 1 state of the $p\bar{p}$ system $B_1^2 = 1.00 \pm 0.12$, $B_0^2 = 0.05 \pm 0.12$, and the magnetic quadrupole moment

$$a_2 = -0.14 \pm 0.06.$$

This is a very reassuring result in view of the fact that an earlier experiment, R704 at CERN had indicated preference for a positive value of a_2 . However, the precision of our result is not enough to determine the anomalous magnetic moment, the present result being $k = 0.46 \pm 0.62$. A paper describing these results has been published[5].

It is quite clear that much more data on this decay are needed to determine the magnetic moment with the required precision. Further, it would be very important to confirm the result by measuring the angular distribution for the radiative decay of χ_1 . It is proposed to make these measurements as a part of E835.

II.A1.2.2 Two Photon Decay, $\chi_2 \rightarrow \gamma\gamma$

This is the analog of the two photon decay of positronium, a purely electromagnetic process for which the predictions of perturbative QCD should be quite reliable. It can therefore be used to determine the derivative of radial wave function of χ_2 since in the lowest order

$$\Gamma(\chi_2 \rightarrow \gamma\gamma) = \frac{64}{45} \frac{\alpha_s^2}{m_c^4} |R'_p(0)|^2$$

This in turn can be used to determine the strong coupling constant α_s from our own measurement of χ_2 hadronic width. Our measurements give the preliminary result

$$\text{BR}(\chi_2 \rightarrow \gamma\gamma) = (1.60 \pm 0.45) \times 10^{-4}$$

This is much smaller than the current result [1],

$$\text{BR}(\chi_2 \rightarrow \gamma\gamma) = (11 \pm 6) \times 10^{-4}$$

With the one-loop radiative corrections applied to the first order PQCD prediction, this results in

$$\alpha_s = 0.36 \pm 0.04$$

This value is about twice as large as α_s determined from the ratio of the leptonic and hadronic widths of J/Ψ . This discrepancy may arise due to any one or more of the several major shortcomings of the present theoretical calculations: effect of the confinement part of the potential, relativistic corrections, and the inadequacy of the one loop radiative corrections.

A paper describing these results has been published[6].

II.A1.3 THE η_c (1S_0) STATES OF CHARMONIUM

The study of the singlet $c\bar{c}$ states presents a formidable challenge. These states can not be formed in e^+e^- annihilations or by E1 decays from the strong 1^{--} states. In e^+e^- experiments evidence for these state was sought in the M1 decays of J/Ψ and Ψ' . The η_c state at 2980 MeV has since then been confirmed, but η'_c has not. Indeed, η'_c has been omitted from the Particle Data Book summary [1]. It is one of the major objects of E760 to study these states.

The width of η_c (2980) is quoted in the PDB summary [1] as $10.3^{+3.8}_{-3.4}$ MeV. Actually, this average of three measured values is highly suspect, the three measured values being

$$7.0^{+7.5}_{-7.0} \quad , \quad 10.1^{+33.0}_{-8.2} \quad , \quad \text{and } 11.5 \pm 4.5 \quad \text{MeV.}$$

It is extremely important that a better measurement of this width be made. Because the major decay modes of η_c are hadronic, and the present E760 detector is optimised for the detection of electromagnetic decay products, this presents a serious challenge to E760. In the 1991 run we observed η_c in the $\eta_c \rightarrow \gamma\gamma$ channel. A branching ratio, $\text{BR}(\eta_c \rightarrow 2\gamma) = (3 \pm 1) \times 10^{-4}$ was

measured. This is a rather small branching ratio which makes it very difficult to measure the width of η_c in this channel. The mass of η_c has, however, been measured accurately, $M(\eta_c) = 2988 \pm 3$ MeV. This is significantly higher than the current PDB value.

An attempt was also made to identify η_c' . A search was made at ~ 3594 MeV where the Crystal Ball group had claimed its existence. No evidence was found. Another search was made in the vicinity of 3615 MeV where potential model calculations predict this state to lie. No evidence was found there either. It has become clear that a rather wide region search will be required to find η_c' . Such a search can only be undertaken with the much larger instantaneous luminosity which is expected during the running of E835. A paper describing our current results for η_c and η_c' is in preparation.

II.A1.4 THE 1P_1 STATE OF CHARMONIUM

The identification of the 1P_1 state of charmonium is extremely important in order to understand the spin-spin interaction between quarks. Two previous searches have failed to find this state [7,8] in e^+e^- and $p\bar{p}$ experiments. A major effort was made to find this state in our last six-month long run. Nearly 50% of all the available beam-time was spent in looking for this state in the channels

$$\begin{aligned} p\bar{p} &\rightarrow ^1P_1 \rightarrow \pi^0 + J/\Psi \rightarrow (\gamma\gamma) + (e^+e^-) \\ p\bar{p} &\rightarrow ^1P_1 \rightarrow \pi^0 + \pi^0 + J/\Psi \rightarrow (4\gamma) + (e^+e^-) \end{aligned}$$

The effort was successful and the state was identified at $M = 3526.2 \pm 0.15 \pm 0.12$ MeV in the single π^0 channel. This is illustrated in Fig.2. A paper describing this discovery has been published[9]. A factor ~ 5 -10 improvement in luminosity is expected in our expt E835, and, it is intended to make a more detailed study of 1P_1 with improved statistics.

Fig. 2. The energy scan for the $1P_1$ resonance of Charmonium. The resonance is identified at 3526.2 ± 0.15 MeV.

II.A2 PROTON FORM-FACTOR IN THE TIME-LIKE REGION

Nucleon structure presents one of the most challenging problems for hadronic physics, and measurements of electric and magnetic form factors, G_E and G_M , as functions of four-momentum transfer q^2 , constitute the primary testing ground for QCD inspired models of nucleon structure [10-12]. For space-like momentum transfers ($q^2 > 0$) we now have precision data for up to $q^2 = 31 \text{ GeV}^2$ [13]. Perturbative QCD predicts [12] that for large q^2 , $q^4 G_M(q^2)$ should be nearly proportional to the square of the running strong coupling constant, $\alpha_s^2(q^2)$. The data in the space-like region are in remarkable agreement with this prediction for q^2 as small as 5 GeV^2 . Since by analytic continuation it can be shown that asymptotically the same behavior, i.e., proportionality of $q^4 G_M(q^2)$ to $\alpha_s^2(q^2)$, is expected for large time-like momentum transfers, it is of great interest to measure $G_M(q^2)$ for large time-like momentum transfers. Unfortunately, precision data for time-like q^2 have only been obtained recently, and are confined to the small region above threshold, $4m_p^2 \leq |q^2| \leq 4.2 \text{ GeV}^2$ [14].

In the E760 experiment we have measured cross sections for the reaction

$$p\bar{p} \rightarrow e^+e^-$$

at $-q^2 = 8.9, 12.4$ and 13.0 GeV^2 . These cross sections are very small, ranging from $\sim 7 \text{ pb}$ to 0.9 pb . Nevertheless, we have been able to obtain values of G_M with sufficient precision to test the PQCD prediction. Fig. 3 shows $q^4 G_M(q^2)$ measured by us, together with the results of earlier small momentum transfer experiments. The curve is a fit to the predicted $\alpha_s^2(q^2)$ behavior. The agreement with the data is rather remarkable. A paper describing these results has been published.[15]

During the running of E835 it is intended to search for 1D_2 and 3D_2 states of charmonium. We should then be able to extend these $G_M(q^2)$ measurements to $\sim 15 \text{ GeV}^2$.

Fig. 3. Proton form factors in the time-like region plotted as $q^4 G_M(q^2)/\mu_p$ versus $-q^2$. The curve illustrates the $\alpha_s^2(q^2)$ behavior predicted by perturbative QCD.

II.A3 PROTON-ANTIPROTON FORWARD SCATTERING

No understanding of the nucleon-nucleon interaction can be considered fundamental and complete unless it leads to a simultaneous understanding of the nucleon-antinucleon interaction. However, $N\bar{N}$ data above about 500 MeV are very sparse. There are almost no scattering data of good, or even fair, quality in the 1-10 GeV region. The problem is illustrated in Fig.4 in terms of one of the most important parameters of scattering, the ρ -parameter. The ρ -parameter, defined as the ratio of the real and the imaginary parts of the forward scattering amplitude, $f(0)$,

$$\rho = \frac{\text{Re } f(0)}{\text{Im } f(0)}$$

provides insight into the real part of the scattering amplitude, just as total cross section gives the imaginary part of the scattering amplitude (via the 'optical theorem'). As fig.5 illustrates, while precision measurements of ρ exist at $p_L \geq 300\text{ GeV}$, there are no data from 70 GeV to 10 GeV, and only data with very large errors below $p_L = 10\text{ GeV}$. If the old data are to be believed there is a great amount of 'activity' in ρ below 10 GeV, and it is necessary to make precision measurements of the parameters of forward elastic scattering, the total cross section (σ_T), the slope parameter (b), and the ρ -parameter in the 3-9 GeV region. The E760 experiment has done this by measurement of recoil particles in a small region around 90° . The preliminary results of our measurement of ρ are shown in Fig. 5. A paper describing these results is in preparation.

Fig. 4. A collection of the world-data on the ρ -parameter of forward angle proton-antiproton elastic scattering.

Fig. 5. Preliminary results for $\rho \equiv \text{Re}f(0^\circ)/\text{Im}f(0^\circ)$ obtained from the E760 experiment. For comparison, see Fig. 4.

II.A4 QCD SCALING LAWS

Brodsky and his associates[16, 17] have shown that for exclusive processes the rates can be factorized into two parts. The first part, which he calls the distribution amplitude, contains all the non-perturbative QCD dynamics. The second part contains an amplitude which can be calculated in terms of simple dimensional counting. These considerations lead to the well-known fixed angle scaling law

$$\frac{d\sigma}{dt} (AB \rightarrow CD) \sim s^{2-n} f(t/s)$$

for t/s fixed and $s \rightarrow \infty$. Here n is the total number of elementary fields (leptons, photons, and quark components). A specific prediction is that

$$p\bar{p} \rightarrow M\bar{M} \quad d\sigma/d\Omega \sim (\sqrt{s})^{-14} f^{M\bar{M}}(\cos\theta, \ln \sqrt{s})$$

where M denotes a meson. E760 has been able to test this prediction both in $\pi^0\pi^0$ and $\eta\eta$ decays. A paper describing these results is in preparation.

II.A5 LIGHT QUARK SPECTROSCOPY

II.A5.1 THE E760 EXPERIMENT AT FERMILAB

The E760 experiment is not designed to do detailed spectroscopy of light-quark systems. However, it is ideally suited for this purpose if the light-quark (u,d,s) 'system' has a dominant electromagnetic decay channel. Such an opportunity is provided by the recent discovery [18] of $A_1(1520)$ in the $2\pi^0$ invariant mass in the decay $p\bar{p} \rightarrow 3\pi^0$. Since these data were taken with $\bar{p}$ at rest and the observed enhancement occurs at the end of the phase space, there has been some controversy as to whether the enhancement is truly indicative of a new resonance or whether it is just an artifact produced by the end of the phase space. The controversy has been beautifully resolved by our observation of this resonance in the middle of the invariant mass spectra in our measurements of the $p\bar{p} \rightarrow 3\pi^0$ reaction at both at $\sqrt{s} = 2.98$ and $\sqrt{s} = 3.10$ GeV. A paper describing these results has been published[19].

In a similar analysis of the decay channels

$$\begin{aligned} p\bar{p} &\rightarrow \pi^0 + \eta + \eta \\ \text{and, } p\bar{p} &\rightarrow \eta + \eta + \eta \end{aligned}$$

three new resonances have been discovered, with masses 1488(10), 1748(10), and 2104(20) MeV. The results have been published[20].

II.A5.2 THE CRYSTAL-BARREL EXPERIMENT AT LEAR (CERN)

The Principle Investigator joined the Crystal Barrel project (PS 197) at the LEAR facility at CERN, and participated in two data taking runs during the year. This project is very similar to the E760 project at Fermilab; both experiments are devoted to the study of $p\bar{p}$ annihilations. The energy range of antiprotons available at Fermilab, 2-9 GeV/c, makes E760 ideal for the study of charmonium spectroscopy, while the lower energies at LEAR make the CB project ideal for the study of light quark ($q = u, d$ and s) mesons ($q\bar{q}$), hybrids ($q\bar{q}g$), and multiquark states ($q\bar{q}q\bar{q}$), and glueballs. It therefore complements our work with c-quarks in a very natural way.

The groups of medium energy physicists at CERN who are presently in antiproton physics at LEAR have long aspired to have a dedicated antiproton facility with up to 10-15 GeV/c. This would enable one to not only do the physics of Charmonium but well beyond it, enabling the searches for charmed exotics, for example. We, who have experience of E760, appreciate fully well the advantage of having a dedicated facility with $10^3 \text{ cm}^2 \text{ s}^{-1}$ luminosity. The principal investigator has joined the CERN physicists in developing a program of physics for such a facility.

II.B THE NUCLEAR PHYSICS RELATED RESEARCH PROGRAM

II.B1 HIGH RESOLUTION ELECTRON SCATTERING.

The analysis of our experiment on high resolution electron scattering on Mg-26 done at NIKHEF has been completed. Transverse/longitudinal separations have been done for 75 states. A paper describing the results for the 3^+ states has been submitted for publication in Phys. Rev. Letters[21] (A copy of the manuscript is appended). A larger paper is under preparation.

II. B2 QUASI-FREE ELECTRON SCATTERING

The analysis of our quasi-free electron scattering experiment at BATES done in collaboration with the MIT group of C. Williamson, has been completed. A paper describing the results has been published[22].

As a result of this work, we feel that it is quite likely that the longitudinal response sum-rule is not quenched at high momentum transfers. This is in direct opposition to the conclusions reached in the Saclay experiments [22]. In order to resolve this controversy, we have proposed a new series of measurements at BATES. A Letter of Intent was submitted to the BATES PAC in 1991. Their response was extremely encouraging. We have therefore started work on the upgrade of the BIGBITE spectrometer. A formal proposal for the proposed experiment will be submitted soon.

II.B3. LOW ENERGY PION DOUBLE CHARGE EXCHANGE

A few years ago Auerbach et. al[23]. proposed a theoretical model (the AGGK model) for pion double charge exchange in which the effect of two-body correlations enters in a very simple way, especially for nuclei which have low-lying states of good seniority zero. The DCX amplitude for transitions between two such seniority zero states of $J^\pi = 0^+$ consists of two complex amplitudes A and B, with A arising from uncorrelated nucleons and monopole transitions ($0^+ \rightarrow 0^+ \rightarrow 0^+$), and B arising from correlated pairs with non-analog intermediate states and 'non-monopole transitions ($0^+ \rightarrow \ell^\pi \rightarrow 0^+$). The model involves three parameters, A, B, and the phase between them. So far the model has been 'tested' only in the $f_{7/2}$ shell primarily with the three isotopes of

calcium, ^{42}Ca , ^{44}Ca , and ^{48}Ca . In LAMPF 1198, we proposed to test it on four isotopes of nickel, $^{58,60,62,65}\text{Ni}$, all of which have very good seniority zero ground states. This experiment has the potential of providing a completely independent test of the AGGK model.

The experiment was approved with A priority and run during the summer of 1991. Unfortunately, during the run the LAMPF accelerator performance was very poor and beam availability was $< 25\%$ of that expected. ^{58}Ni was successfully run, but none of the other isotopes could be run. Because of operational difficulties at LAMPF, the experiment is currently in the queue of unscheduled experiments.

II.B4. SPECTROSCOPY OF LIGHT EXOTIC NUCLEI BY A NOVEL TECHNIQUE (LAMPF expt. #1274)

This experiment, planned in collaboration with Russian physicists from Moscow, was approved with A priority. It is ready for data taking, but remains unscheduled so far. We are promised a 1994 scheduling.

II.B5. DEEPLY BOUND PIONIC STATES IN HEAVY NUCLEI (LAMPF expt #1280)

This experiment, planned in collaboration with an Oak Ridge group, was approved with A priority. It is ready for data taking, but remains unscheduled so far. We are promised a 1994 scheduling.

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III. DISSEMINATION OF RESEARCH RESULTS (1992-93)

A. PAPERS PUBLISHED

1. E760 Collaboration, "Observation of the 1P_1 State of Charmonium", Phys. Rev. Lett. D47 (1993) 772.
2. E760 Collaboration "Measurement of the J/ψ and ψ' Resonance Parameters in $p\bar{p}$ Annihilations", Phys. Rev. D47 (1993) 772.
3. E760 Collaboration, "Proton Electromagnetic Form Factors in the Timelike Region from 8.9 to 13.0 GeV^2 ", Phys. Rev. Lett. 70 (1993) 1212.
4. E760 Collaboration, "Measurement of the $\gamma\gamma$ Partial Width of the χ_2 Charmonium Resonance", Phys. Rev. Lett. 70 (1993) 2988.
5. E760 Collaboration, "Production of $\eta\eta$ Resonances in Antiproton-Proton Annihilations at $2950 < \sqrt{s} < 3620 \text{ MeV}/c^2$ ", Phys. Lett. B308 (1993) 394.
6. E760 Collaboration, "Production of the $f_2(1520)$ Resonance in Antiproton-Proton Annihilations at $\sqrt{s} = 2980 \text{ and } 3620 \text{ MeV}/c^2$ ", Phys. Lett. B307 (1993) 399.
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8. K.K. Seth, "Charmonium and the Nucleus", Proc. International Workshop on Flavour and Spin in Hadronic and Electromagnetic Interactions", edited by F. Balestra et al., (EdiFrice Compositori, Bologna 1993). pp. 179-200

B. LECTURES AND SEMINARS

1. A series of four lectures on "Charmonium and Nuclei" at the 8th International Summer School on Intermediate Energy Physics", L'Aquila (Italy).
2. Lectures on "Charmonium and Charm in Nuclei" at
 - a) Universities of Pavia (Italy), Grenoble (France), Wuppertal (Germany), Geneva (Switzerland), Strassbourg (France) and Granada (Spain)
 - b) National laboratories at Saclay (France), Julich (Germany) Frascati (Italy) and Brookhaven (USA).

IV. PERSONNEL

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