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Lifetime Measurement of the π^0 Meson and the QCD Chiral Anomaly

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The $\pi^0 \rightarrow \gamma\gamma$ decay rate is dominated by the chiral anomaly with 4.1$\pm$ 1.0 % isospin breaking chiral corrections(proportional to the mass difference of the up and down quarks). A new measurement at Jefferson Lab using the Primakoff effect(PrimEx) is presented with a total error of 3.0%. Great care was taken to reduce systematic errors; this was checked with pair production and Compton scattering measurements. The result is consistent with previous experiments and the predicted value.

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1. Physics Motivation

The $\pi^0 \to \gamma\gamma$ decay rate is dominated by the QCD chiral anomaly[1].The chiral anomaly represents the explicit symmetry breaking by the electromagnetic field of the chiral symmetry associated with the third isospin component of the axial current[1]. The π^0 decay actually provides the most sensitive test of this phenomenon of symmetry breaking due to the quantum fluctuations of the quark fields in the presence of a gauge field. In the limit of vanishing quark masses the anomaly leads to the $\pi^0 \to \gamma\gamma$ decay amplitude[1, 2]

$$A_{\gamma\gamma} = \frac{\alpha_{em}}{\pi F_\pi} = 2.513 \cdot 10^{-2} GeV^{-1} \tag{1.1}$$

where $F_\pi = 92.42 \pm 0.25 MeV$ [3] is the pion decay constant. The width of the $\pi^o \to \gamma\gamma$ decay predicted by this amplitude is

$$\Gamma = m_\pi^3 \frac{\mid A_{\gamma\gamma} \mid^2}{64\pi} = 7.725 \pm 0.044 eV, \tag{1.2}$$

with a 0.6% uncertainty due to the experimental error in F_π. This prediction, which is the dominant contribution to the π^0 decay rate, has no adjustable parameters.

The decay amplitude given above is exact only in the chiral limit, *i.e.*, when the u and d quark masses vanish. In this case, the anomaly is saturated by the π^o pole and the result for the decay amplitude given above is exact. However, the current-quark masses are non-vanishing and are approximately a few MeV[3, 4]. In addition there is strong isospin breaking due to the mass difference of the up and down quarks[3, 4]. There are two sources of corrections due to this explicit breaking of chiral symmetry. The first and dominant one results from a combined effect that involves the corrections to the decay constants (because of isospin breaking there is a decay constant matrix in the subspace of the π^0, η and η') and an isospin breaking mixing that gives the physical π^0 a non-vanishing component along the pure U(3) states η and η'. In the absence of isospin breaking this source of chiral symmetry breaking boils down to merely replacing the value of F_π in the chiral limit by the measured value determined from π^+ decay[5, 6]. The second source of corrections is due to the fact that the saturation of the matrix elements of the divergence of the axial current also involves excited mesonic states when chiral symmetry is broken by quark masses. This effect is estimated using QCD sum rules[7] and turns out to be much smaller than the mixing effects. Stimulated by the prospect of our new measurement (PrimEx) several new, independent, chiral perturbation theory (ChPT) calculations of the isospin breaking $\pi^0, \eta, \eta^{'}$ mixing corrections have been published in recent years. The first is in the combined framework of (ChPT) and the $1/N_c$ expansion up to $\mathscr{O}(p^6)$ and $\mathscr{O}(p^4 \times 1/N_c)$ in the decay amplitude[8]. The other two papers use QCD sum rules and two flavor ChPT [9]. The η' is explicitly included in these analyses as it plays as important a role as the η in the mixing effects. It was found that the decay width is enhanced by 4.8 $\pm$ 1.0% with respect to the value stated in equation (1). It is gratifying that all three calculations make predictions which are much closer to each other then the theoretical uncertainties of $\simeq$ 1% with a result for $\Gamma_{\pi^0 \to \gamma\gamma} = 8.10$ eV with an estimated uncertainty of less than 1%. The fact that the mixing of both the η and $\eta^{'}$ with the π^0 is required to get the full result is also suggested by a recent QCD sum rule calculation[10]. Here the π^0 mixing with the η is taken into account with a predicted increase in the width of $\simeq$ 2/3 of the other calculations[8, 9]. This is consistent with these calculations when the mixing with the $\eta^{'}$ is omitted.

In summary of the theoretical situation, there is a firm prediction of the decay width of the π^0 with a precision of 1% or better. A modern experiment with a comparable accuracy to these calculations will provide an important test of this fundamental QCD prediction. The fact that such a test is possible is due to the occurrence of chiral symmetry breaking in QCD which, along with the small up and down quark masses, is the reason that pions are the lightest hadrons. Electromagnetism makes the $\pi^{\pm}$ a few MeV heavier then the π^0. This means that the π^0 must decay electromagnetically, primarily into two photons. The magnitude of this decay rate is primarily due to the chiral anomaly which depends upon the Nambu-Goldstone character of the pion.

The current average experimental value for $\Gamma_{\pi^0\to\gamma\gamma} = 7.74 \pm 0.56$ eV given by the Particle Data Group[3] is in reasonable agreement with the predicted value[8, 9]. This number is an average of several experiments. The quoted error of 7.2% is most likely too low[11] since each of the experiments appears to have understated their errors and also, as can be seen in Fig. 4, from the much larger dispersion between the different measurements. Even at the 7% level, the accuracy is not sufficient for a test of such a fundamental quantity, and in particular for the new calculations which take the finite quark masses into account. The data base consists of experiments which are over 25 years old. In many cases the previous experiments were performed with experimental equipment which by now has greatly improved. For the Primakoff effect measurement that is being reported here the advent of CW accelerators, photon tagging, and improved detectors allowed us to perform a significantly better measurement.

2. PrimEx Experiment

The collaboration members and institutions of the PrimEx experiment at Jefferson Lab are shown after the references and represent an international effort which includes many students and post-docs. The experiment was first proposed 10 years ago, run four years ago, and the analysis is now in its final stage. More details can be seen on the collaboration web page[12].

The experiment being reported here was carried out in Hall B of Jefferson Lab using the Primakoff effect. Incident photons of known energy interact with the Coulomb field of a nucleus to produce π^0 mesons which quickly decay into two photons and are detected in a forward calorimeter as shown schematically in Fig. 1. In the experiment, tagged photons of energy 4.9-5.5 GeV from the Hall B photon tagging facility were used to measure the absolute cross section of small angle π^o photoproduction from C and Pb nuclei. The invariant mass, energy, and angle of the pions were reconstructed by detecting the decay photons from the $\pi^o \to \gamma\gamma$ reaction in the forward calorimeter (HYCAL). The high angular and energy resolution achieved by this apparatus are illustrated in Fig.2 for the invariant mass($\simeq$ 1.2%) which allowed us to identify the produced π^0 mesons with a high signal/background ratio. The energy of the emerging pions is also measured with good resolution($\simeq$ 1.5%) in HYCAL. Also shown in Fig.2 is the distribution of π^0 mesons as a function of their elasticity x = E_{π^0}/k (the total pion energy divided by the photon energy). From curves like this for each pion angle, the backgrounds are empirically subtracted in order to obtain the π^0 yield.

The schematic diagram (Fig. 1) does not show the shielding. This and the clean electron beam were sufficient to allow for a low background experiment with a sensitive forward calorimeter.

Compared to the previous Primakoff effect measurements which used bremsstrahlung beams we took advantage of the CW nature of the Jefferson Lab electron beam to produce tagged photons with an energy resolution of 0.1 %. We also took advantage of the clean, highly collimated beam to deploy a sensitive forward calorimeter (HYCAL) with an angular resolution of 0.015 degrees, constructed for this experiment. The PbWO4 crystals which formed the heart of the detector are 2 cm by 2 cm by 20 radiation lengths, which were 7.5 meters from the target. As can be seen in Fig. 1 there is an aperture of 2 by 2 crystals for the highly collimated photon beam. Targets of C and Pb, approximately 5% of a radiation length were used. The target thickness was precisely measured in separate experiments using X ray absorption. The magnet, which was placed directly behind the targets, swept the produced electrons away from the detector. Detectors were placed behind the magnet to monitor the luminosity using pair production. We also placed a total absorption counter behind HYCAL to monitor the tagging efficiency This has to be done at very low currents. The pair production monitors are linear in the flux region for the higher flux production runs and the low flux tagging efficiency runs. Compton scattering was measured by turning off the magnet and observing both the scattered photon and the emerging electron. We checked the accuracy of our measured cross sections with pair production and the Compton effect. The data agreed with experimental predictions within the systematic error of $\simeq 1.5\%$. This demonstrated that the experimental technique used to extract the cross sections from the experimental yields was accurate to within the systematic error. Space does not allow a detailed description of the the experimental effort. This will be published in the near future. It is important to say that a great deal of effort was made to perform the Primakoff experiment at the 2 % level as will be discussed in Sec.4. To my knowledge this is the most accurate measurement of a photon induced cross section in this general energy region.

3. π^o Photoproduction Cross Section

The photoproduction of pions from a complex nucleus, $\gamma + A \rightarrow \pi^0 + A$, can be described by the sum of Coulomb T_C and Strong T_S amplitudes. Including incoherent production, the differential cross section is:

$$\begin{aligned}
\frac{d\sigma}{d\Omega} &= \mid T_C + e^{i\phi} T_S \mid^2 + \frac{d\sigma_{inc}}{d\Omega} \\
&= \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_S}{d\Omega} + \frac{d\sigma_{inter}}{d\Omega} + \frac{d\sigma_{inc}}{d\Omega} \\
\frac{d\sigma_P}{d\Omega} &= \mid T_C \mid^2 = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 sin^2\theta_\pi \\
\frac{d\sigma_S}{d\Omega} &= \mid T_S \mid^2 = C_S A^2 |F_S(Q)|^2 sin^2\theta_\pi \\
\frac{d\sigma_{inter}}{d\Omega} &= 2 \mid T_C \mid\mid T_S \mid cos(\phi + \phi_S - \phi_C)
\end{aligned} \tag{3.1}$$

where T_C, T_S are the Coulomb (Primakoff) and strong amplitudes, the phase ϕ originates from the $\gamma p \rightarrow \pi^0 p$ amplitude and is fitted to the data. The first two terms in the first line represents the coherent cross section for which the nucleus is left in its ground state. $d\sigma_i/d\Omega$ (i = P,S,inter,

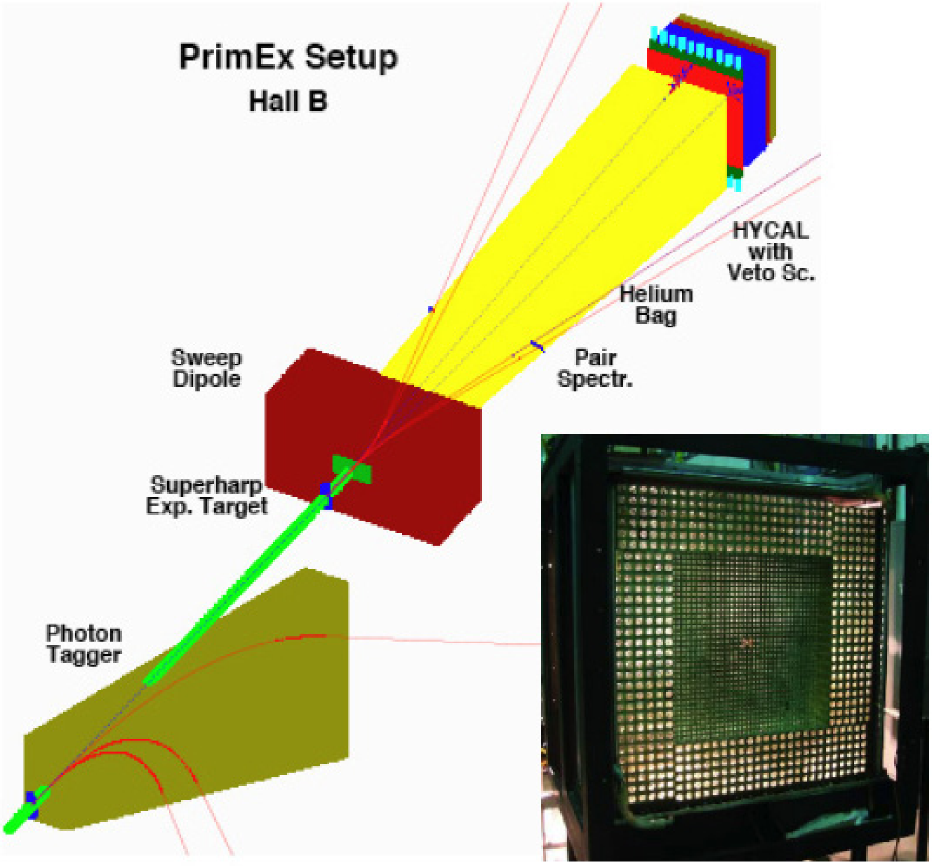

Figure 1: Schematic layout of the *PrimEx* experimental setup showing the incident electron beam, photon energy tagging system, target, sweeping magnet, He bag, electron pair spectrometer, veto counter, and HYCAL detector; shown in more detail in the insert. It consists of an inner section of PbWO4 crystals and an outer section of Pb-glass detectors.

inc) are the cross sections for Primakoff, strong, interference, and incoherent processes (the latter involving target nucleus excitation or break up). $\Gamma_{\gamma\gamma}$ is the pion decay width (the primary objective of the experiment), Z is the atomic number, m, β, θ_π are the mass, velocity and production angle of the pion, E is the energy of incoming photon. For the spin 0 targets employed in this experiment the coherent cross sections have a $sin(\theta_\pi)^2$ dependence since they are non-spin flip. Q is the momentum transfer to the nucleus, and $F_{e.m.}(Q), F_S(Q)$ are the nuclear electromagnetic form factor and strong form factors, corrected for final state interactions of the outgoing pion[13, 14, 15]. The calculations for the form factors used in this experiment were performed using the Glauber multiple scattering method and taking photon shadowing into account[15]. The shape of the strong cross section $d\sigma_S/d\Omega$ is determined by the dependence of the absolute value of the strong form factor $\mid F_S(Q) \mid$ and the $sin(\theta_\pi)^2$ factor. The Coulomb-strong interference cross section $d\sigma_S/d\Omega$ depends not only on the magnitudes of the form factors but their relative calculated phases ϕ_C, ϕ_S[15] as well as the nucleon phase ϕ. Note that this cross section also has an additional $sin(\theta_\pi)^2$ factor which is

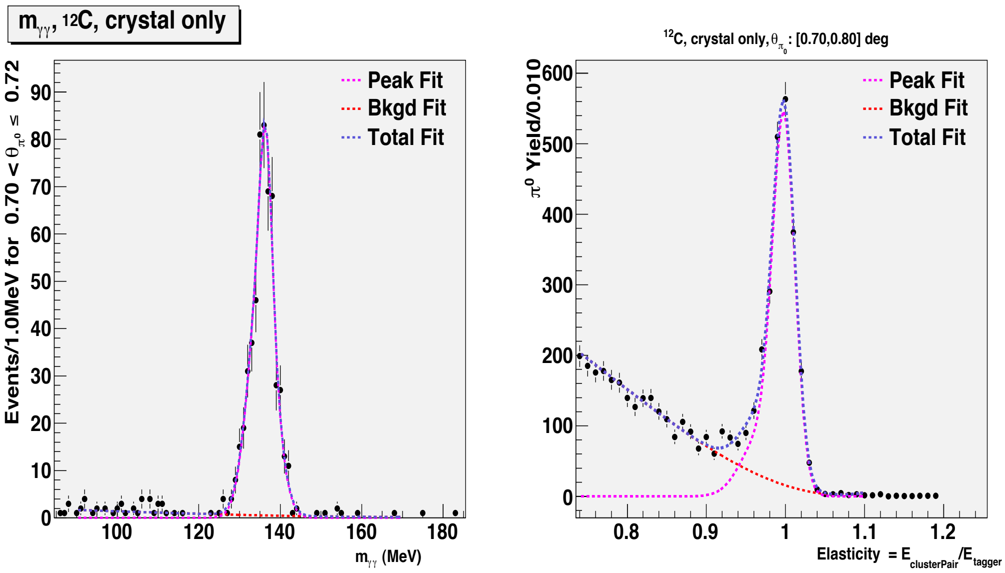

Figure 2: Observed invariant mass(left) and inelasticity distribution data. See text for discussion.

not explicitly displayed. As will be discussed in the next section, the experimental results were fit with the theoretical cross sections with four free parameters $\Gamma_{\gamma\gamma}, C_S, C_{inc}, \phi$. The fitting parameter C_{inc}, which is not shown in Eq. 3.1, is introduced to vary the magnitude of the theoretical incoherent cross sections[15, 16].

4. Experimental Results

The cross sections for forward angle π^0 photoproduction was measured on C and Pb targets with an average photon energy of 5.2 GeV. The apparatus and experimental techniques were briefly discussed in Sec.2. The π^0 mesons are identified by the peak in the invariant mass distribution of their two photon decay mode. Great care was taken to measure the luminosity and detection efficiency of the apparatus. The resulting experimental cross sections for C and Pb are shown in Fig.3 along with the individual contributions to the cross section as discussed in Sec.3. The data was fit by varying the magnitude of each of the four contributions of Eq.3.1. These are the Primakoff, strong, interference, and incoherent cross sections by varying the four parameters $\Gamma_{\gamma\gamma}, b_S, \phi, b_{inc}$. The resulting cross section fits are also shown in Fig.3. It can be seen that the large forward peak $\simeq 0.02$ deg. is dominated by the Primakoff effect which allows the value of $\Gamma_{\gamma\gamma}$ to be accurately extracted. It can be seen that the magnitude of this peak scales with the nuclear charge as Z^2(as expected). Both the predicted position of the Primakoff peak and its separation from the strong π^0 production peak are essential in the interpretation of the data.

The strong (nuclear coherent) peak would scale in cross section as A^2 (A = atomic number) if there is no final state interaction and as $A^{2/3}$ when the mean free path of the outgoing pion is significantly smaller then the nuclear radius. In our case it scales closer to the latter case ($\simeq A^{0.9}$). This makes the relative magnitudes of of the strong relative to the Primakoff peaks smaller in Pb then in C. The angle for which the the strong cross section peaks is smaller in Pb then in C, due to its larger radius (which increases $\simeq A^{1/3}$). The strong- Primakoff interference cross section is the only nuclear contribution near the Primakoff peak ($\simeq 0.02^0$) and is at the few % level. Its strength reflects the positions and magnitudes of the strong and Primakoff cross sections. Thus the values of the radiative width $\Gamma_{\gamma\gamma}$ obtained from the C and Pb data pose a stringent test on the model dependence of the result. We have obtained consistent results for $\Gamma_{\gamma\gamma}$ from the data for these two targets. This supports the idea that the small (few %) nuclear effects being subtracted under the Primakoff peak are well described by the theoretical calculations whose magnitudes are fit to the larger angle data.

The systematic errors of the experiment are summarized in Table1. The two largest uncertainties are 1.0% for the photon flux and 1.6% for the yield extraction. The uncertainty in the flux is due to instabilities in the photon beam and detection. The error in the yield extraction is primarily due to uncertainties in the background subtraction as illustrated in Fig.2. The total error of 2.1% was obtained by summing the errors in quadrature, since there are no known correlations between them. As was stated above this is the smallest systematic error for a photon induced cross section that I am aware of. The ability to accurately measure cross sections with this apparatus was tested by measurements of the Compton effect and pair production which are accurately predicted. The measurements agree with theory to $\simeq$ 1.5% which is better then the systematic error for the Primakoff effect shown in Table1.

The PrimEx data was independently analyzed by several groups in the collaboration. The present result is $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 2.2\% \pm 2.1\%$ where the first error is statistical and the second is systematic. Combining them in quadrature gives a total error of 3.0%. We anticipate publishing the final result in the near future. This result for $\Gamma_{\gamma\gamma}$ is within one standard deviation of the theoretical prediction[8, 9] and most of the results of previous measurements[3] as shown in Fig.4. The data base consists of experiments performed with three different techniques (for references see[3]). The earliest experiments, published in 1970 and 1974, were performed at DESY, Tomsk, and Cornell with the Primakoff technique using bremsstrahlung beams. It is not understood why the first (DESY) measurement is so far from the other results. The present experiment, which has been performed with significant improvements, outlined in Sec.2, agrees with the results from Cornell and Tomsk. The direct measurement was performed at CERN and measured the decay length of π^0mesons produced by 450 GeV protons incident on a thin tungsten foil. It has a result which is significantly lower then the chiral prediction[8, 9] and somewhat lower then our experimental result. This result depends on an understanding of the momentum spectrum of the produced π^0 mesons which was not directly measured, but was inferred from the extrapolated spectra of $\pi^\pm$ mesons. In my opinion this is a potential source of error and a possible reason that the experimental error is too small[11]. The point marked e^+e^- was a measurement of the cross section for the $e^+e^- \to \gamma\gamma \to \pi^0 \to \gamma\gamma$ reaction in the Doris storage ring at DESY. This is the only published paper for which I find the quoted error convincing[11]. Assuming that this is correct the particle data book average[3] of $\simeq$ 7.2% is also too low. Nevertheless the overall picture that emerges from Fig.4 is primarily one of overall agreement, which considering the almost 40 year history of this measurement and the number of different techniques involved, is gratifying.

There is a significant need for future experimental improvements to fully test the chiral calculations. At the present time theory is ahead of experiment in that the estimated theoretical error of 1% in the chiral calculations[8, 9] is significantly smaller then the experimental errors. It is of

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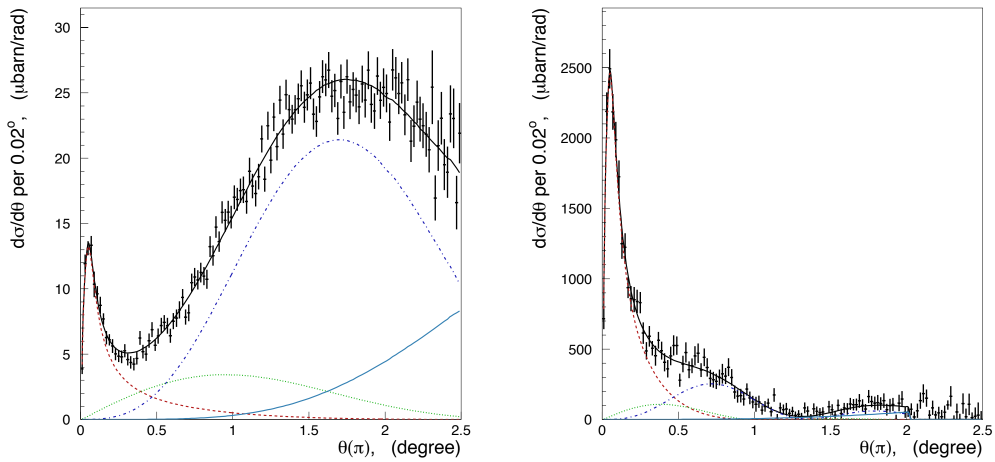

Figure 3: Cross sections $d\sigma/d\theta$ in μbarn/rad versus the lab pion angle for C and Pb at an average photon energy of 5.2 GeV. The individual contributions were obtained by a fit to the data (see text for discussion). The Primakoff contribution peaks $\simeq 0.02^0$, the strong contribution(red dotted curve) peaks $\simeq 1.6^0, 0.8^0$ in C and Pb with a smaller secondary maximum$\simeq 1.8^0$ in Pb. The interference contribution (green dotted curve) peaks $\simeq 0.9^0, 0.3^0$ in C and Pb. The incoherent contribution(solid blue curve) rises gently with θ_{π^0}.

great significance to check the predicted increase in $\Gamma_{\gamma\gamma}$ due to the isospin breaking chiral corrections which are proportional to the mass difference of the up and down quarks[8, 9]. It would be very useful to have modern experiments performed with all of the three techniques. The PrimEx experiment has an approved experiment planned at Jefferson Lab in the next few years in which the projected overall error is $\simeq 1.4\%$. As far as I know there are no corresponding plans to perform new measurements with the direct or e^+e^- techniques, although such experiments would be possible at CERN (for the direct measurement) and Frascati or Belle (for e^+e^-) . On the theoretical side further progress probably requires lattice calculations in the anomaly sector. To make progress beyond the present chiral calculations we particularly need calculations of the $\eta, \eta^{'}$ mixing and decay rates. I look forward to future developments.

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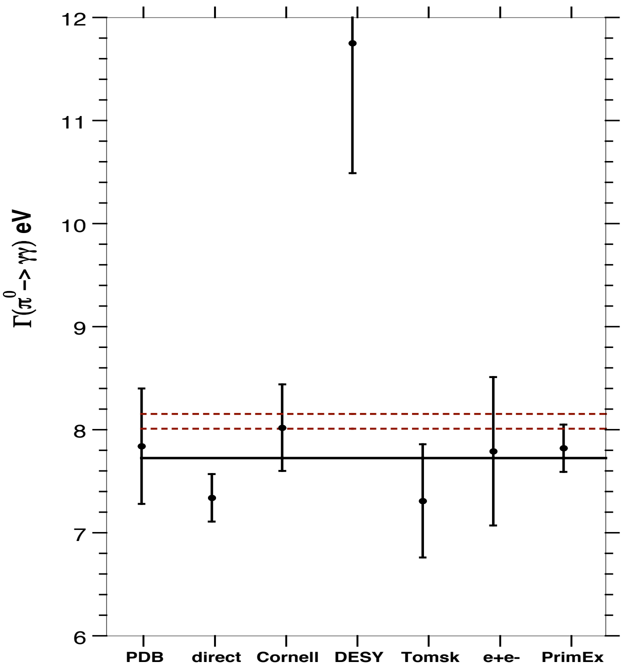

Figure 4: $\Gamma(\pi^0 \to \gamma\gamma))$ in eV (note the suppressed scale). The experimental points with errors are the particle data book average[3], the direct measurement of the distance that high energy π^0s travel before decaying(1985), the three previous Primakoff measurements performed at Cornell(1974), DESY(1970), and Tomsk(1970), a two photon production cross section measurement in e^+e^- collisions(1988), and the present PrimEx result. For references to the previous experiments see the particle data book[3].See text for discussion.

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photon flux	1.0%
target thickness	0.1%
Yield extraction	1.6%
HYCAL efficiency	0.5 %
beam parameters	0.4%
trigger efficiency	0.1 %
veto efficiency	0.4 %
π^o detection acceptance	0.3 %
model error (theory parameters)	0.3 %
physics background	0.25 %
branching ratio	0.03%
Total	2.1%

Table 1: Systematic Error

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