A New Measurement of the $\pi^0$ Radiative Decay Width

I. Larin,1,2 D. McNulty,3 E. Clinton,4 P. Ambrozevic,2 D. Lawrence,4,5 I. Nakagawa,6,7 Y. Prok,3 A. Teymurazyan,6 A. Ahmadouch,2 A. Arsatyan,1 K. Baker,8 L. Benton,2 A. M. Bernstein,3 V. Burkert,5 P. Cole,9 P. Collins,10 D. Dale,9 S. Danagoulian,9 G. Davidenko,1 R. Demirchyan,2 A. Deur,5 A. Dolgolenko,1 G. Dzyubenko,1 R. Eit,5 A. Evdokimov,1 J. Feng,11,12 M. Gabrielyan,6 L. Gan,11 A. Gasparian,2 2 S. Gevorkyan,13,14 A. Glamazdin,15 V. Goryachev,1 V. Gyurjyan,5 K. Hardy,2 J. He,16 M. Ito,5 L. Jiang,11,12 D. Kashy,5 M. Khanka,1,2,17 P. Kolesnikov,6 M. Konch люди Russian,15 A. Korcheva,1,17 W. Korch,6 S. Kowalski,1 M. Kubantsev,1,18 V. Kubarovsky,5 X. Li,11 P. Martel,4 V. Matveev,1 B. Mecking,5 B. Milbrath,19 R. Minehart,20 R. Miskimen,3 V. Mochalov,21 S. Mtingwa,2 S. Overby,2 E. Pasit,5,10 M. Payen,2 R. Pedroni,2 B. Ritchie,10 E. Rodrigues,22 C. Salgado,17 A. Shahinyan,13 A. Sitnikov,1 D. Sober,23 S. Stepanyan,5 W. Stephens,20 J. Underwood,2 A. Vasiliev,21 V. Vishnyakov,1 M. Wood,4 and S. Zhou12

(PrimEx Collaboration)

1Alinkhanov Institute for Theoretical and Experimental Physics, Moscow, Russia
2North Carolina A&T State University, Greensboro, NC 27411, USA
3Massachusetts Institute of Technology, Cambridge, MA 02139, USA
4University of Massachusetts, Amherst, MA 01003, USA
5Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
6University of Kentucky, Lexington, KY 40506, USA
7RIKEN Nishina Center for Accelerator-Based Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
8Hampton University, Hampton, VA 23666, USA
9Idaho State University, Pocatello, ID 83209, USA
10Arizona State University, Tempe, AZ 85287, USA
11University of North Carolina Wilmington, Wilmington, NC 28403, USA
12Chinese Institute of Atomic Energy, Beijing, China
13Yerevan Physics Institute, Yerevan, Armenia
14Joint Institute for Nuclear Research, Dubna, 141980, Russia
15Kharkov Institute of Physics and Technology, Kharkov, Ukraine
16Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
17Norfolk State University, Norfolk, VA 23504, USA
18Northwestern University, Evanston/Chicago, IL 60208, USA
19Pacific Northwest National Laboratory, Richland, WA 99352, USA
20University of Virginia, Charlottesville, VA 22904, USA
21Institute for High Energy Physics, Protvino, Russia
22University of São Paulo, São Paulo, Brazil
23The Catholic University of America, Washington, DC 20064, USA

(Dated: August 30, 2010)

High precision measurements of the differential cross sections for $\pi^0$ photoproduction at forward angles for two nuclei, $^{12}$C and $^{208}$Pb, have been performed for incident photon energies of 4.9 - 5.5 GeV to extract the $\pi^0 \rightarrow \gamma\gamma$ decay width. The experiment was done at Jefferson Lab using the Hall B photon tagger and a high-resolution multichannel calorimeter. The $\pi^0 \rightarrow \gamma\gamma$ decay width was extracted by fitting the measured cross sections using recently updated theoretical models for the process. The resulting value for the decay width is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.82 \pm 0.14$ (stat.) $\pm 0.17$ (syst.) eV. With the 2.8% total uncertainty, this result is a factor of 2.5 more precise than the current PDG average of this fundamental quantity and it is consistent with current theoretical predictions.

PACS numbers: 11.30.Rd, 13.40.Hq, 13.60.Le

The $\pi^0 \rightarrow \gamma\gamma$ decay represents one of the key processes in the anomaly sector of QCD. It provides the main test of the chiral anomaly and at the same time of the Nambu-Goldstone nature of the $\pi^0$ meson. The $\pi^0 \rightarrow \gamma\gamma$ decay amplitude is determined by the chiral anomaly resulting from the coupling of quarks to the electromagnetic field. In the limit of vanishing quark masses (chiral limit) the amplitude is exactly predicted and is expressed in terms of the fine structure constant, the $\pi^0$ decay constant, and the number of colors of QCD. In the real world there are corrections due to the non-vanishing quark masses. These corrections are primarily a result of state mixing effects in the $\pi^0$ meson, which result from the isospin symmetry breaking by $m_u \neq m_d$. The corrections have been analyzed in the framework of Chiral Perturbation Theory (ChPT) up to order $p^6$ (NLO in Fig. 1) and shown to lead to an enhancement of about 4.5% in the $\pi^0$ decay width with respect to the case where state mixing is not included (LO in Fig. 1). The estimated uncertainty in the ChPT predic-
tion is 1% [4]. Corrections to the chiral anomaly have also been performed in the framework of QCD using dispersion relations and sum rules [7] (Ioffe07 in Fig. 1). The fact that the corrections to the chiral anomaly are small and they are known at the 1% level makes the $\pi^0 \to \gamma\gamma$ decay channel a benchmark process to test one of the fundamental predictions of QCD.

The current average experimental value for the $\pi^0$ decay width given by the Particle Data Group (PDG) [8] is $\Gamma(\pi^0 \to \gamma\gamma) = 7.74 \pm 0.55$ eV. This value is an average of four experiments with much larger dispersion between both the decay width values and their quoted experimental uncertainties, as shown in Fig. 1. The most precise Primakoff type measurement was done at Cornell by Browman et al. [9] with a 5.3% quoted total uncertainty: $\Gamma(\pi^0 \to \gamma\gamma) = 7.92 \pm 0.42$ eV. This result agrees within experimental uncertainty with the theoretical predictions. Two other measurements [10, 11] with relatively large experimental uncertainties (≈11% and ≈7%) differ significantly from each other and do not agree with the theoretical predictions. The most precise measurement of the $\pi^0$ decay width, prior to the current PrimEx experiment, was made by Atherton et al. [12] using the direct method of measuring the mean decay length of $\pi^0$s produced by a high energy proton beam at CERN. Their result with the quoted 3.1% total uncertainty, $\Gamma(\pi^0 \to \gamma\gamma) = 7.25 \pm 0.18 \pm 0.14$ eV, is ≈4σ lower than the NLO ChPT prediction of Ref. [4].

Clearly, a new Primakoff type experiment with a precision comparable to, or better than, the direct method measurement [12] was needed to address the experimental situation on this fundamental quantity.

The PrimEx experiment [13] was performed in fall 2004 at the Thomas Jefferson National Accelerator Facility. It utilized the Hall B high precision photon tagging facility [14] together with a newly developed high resolution electromagnetic calorimeter. The combination of these two techniques greatly improved not only the angular resolutions, which are critical for Primakoff type measurements, but significantly reduced the systematic uncertainties that were present in previous experiments.

Tagged photons with known timing and energy were incident on two 5% radiation length targets of $^{12}$C and $^{208}$Pb [13]. The photon tagging efficiencies were continuously measured during the experiment with a $e^+e^-$ pair spectrometer (PS) consisting of a ~1.7 T-m large aperture dipole magnet and two telescopes of scintillating counters located downstream of the targets. The absolute normalization of the photon beam was measured periodically with a total absorption counter (TAC) at low beam intensities.

The decay photons from $\pi^0 \to \gamma\gamma$ were detected in a multichannel hybrid electromagnetic calorimeter (HyCal) located 7.5 m downstream from the targets to provide a large geometrical acceptance (~70%). HyCal consists of 1152 PbWO$_4$ crystal shower detectors (2.05 × 2.05 × 18.0 cm$^3$) in the central part, surrounded by 576 lead glass Cherenkov counters (3.82 × 3.82 × 45.0 cm$^3$). Four crystal detectors were removed from the central part of the calorimeter (4.1 × 4.1 cm$^2$ hole in size) for passage of the high intensity (~ $10^7$ γ/s) incident photon beam through the calorimeter [14]. Twelve 5-mm-thick scintillator counters, located in front of HyCal, provided rejection of charged particles and effectively reduced the background in the experiment. To minimize the decay photon conversion in air, the space between the PS magnet to HyCal was enclosed by a helium bag at atmospheric pressure. The photon beam’s position stability was monitored during the experiment by an X-Y scintillating-fiber detector located downstream of HyCal.

The experimental trigger was formed by requiring coincidences between the photon tagger in the upper energy interval (4.9 - 5.5 GeV) and HyCal with a total deposited energy greater than 2.5 GeV. The combination of the photon tagger and the calorimeter defined the following main event selection criteria in this experiment: (1) timing between the incident photon and the decay photons in the calorimeter ($\sigma_t = 1.1$ ns); (2) ratio of the total energy in the calorimeter and the tagger energy, “elasticity”, ($\sigma_{el} = 1.8\%$); (3) invariant mass of the two photons ($M_{\gamma\gamma}$) reconstructed in the calorimeter (shown in Fig. 2).

The event yield (number of $\pi^0$ events for each produc-
The extraction of differential cross sections from the experimental yields requires an accurate knowledge of the total photon flux for each tagger energy bin, the number of atoms in the target, the acceptance of the experimental setup and the efficiencies of the detectors. The uncertainty reached in the photon flux measurement, as described above, was at the level of 1% [17]. Different techniques have been used to determine the number of atoms in both targets with an uncertainty less than 0.1% [18].

The acceptance and detection efficiencies and their uncertainties were calculated by a GEANT-based Monte Carlo code that included accurate information about the detector geometry and response of each detector element. Other than accidental backgrounds, some physics processes with an energetic $\pi^0$ in the final state can potentially contribute to the extracted yield. The $\omega$ photoproduction process through the $\omega \to \pi^0 \gamma$ decay channel is the dominant contribution to the background. The fit of the experimental data, as described below, with the subtracted physics background changes the extracted $\pi^0$ decay width by 1.4% with an uncertainty of 0.25%.

The resulting experimental cross sections for $^{12}$C and $^{208}$Pb are shown in Figs. 3 and 4 along with the fit results for individual contributions from the different $\pi^0$ production mechanisms. Two elementary amplitudes, the Primakoff (one photon exchange), $T_{Pr}$, and the strong (hadron exchange), $T_{S}$, contribute coherently, as well as incoherently in $\pi^0$ photoproduction from nuclei at forward angles. The cross section of this process can be expressed by four terms: Primakoff ($Pr$), nuclear coherent ($NC$), interference between strong and Primakoff amplitudes ($Int$), and nuclear incoherent ($NI$):

$$
\frac{d\sigma}{d\Omega} = \left| T_{Pr} + e^{i\varphi} T_{S} \right|^2 + \frac{d\sigma_{NI}}{d\Omega},
$$

where $\varphi$ is the relative phase between the Primakoff and the strong amplitudes. The Primakoff cross section is proportional to the $\pi^0$ decay width, the primary focus of this experiment [9]:

$$
\frac{d\sigma_{Pr}}{d\Omega} = \Gamma(\pi^0 \to \gamma\gamma) \frac{8\alpha Z^2 \beta^3 E^4}{m^3} \left| F_{EM}(Q) \right|^2 \sin^2 \theta\pi,
$$

where $Z$ is the atomic number; $m$, $\beta$, $\theta\pi$ are the mass, velocity and production angle of the pion; $E$ is the energy of the incident photon; $Q$ is the four-momentum transfer to the nucleus; $F_{EM}(Q)$ is the nuclear electromagnetic form factor, corrected for final state interactions (FSI) of the outgoing pion. The FSI effects for the photoproduced pions, as well as the photon shadowing effect in nuclear matter, need to be accurately included in the cross sections before extracting the Primakoff amplitude. To achieve this, and to calculate the $NC$ and $NI$ cross sections, a full theoretical description based on the Glauber method was developed, providing an accurate calculation of these processes in both light and heavy nuclei [18, 19]. For the $NI$ process, an independent method based on the multi-collision intranuclear cascade model [20] was also used to check the model dependence of the extracted decay width. The uncertainty in the decay width from model dependence and the parameters inside of the models was estimated to be 0.3%.

The $\Gamma(\pi^0 \to \gamma\gamma)$ decay width was extracted by fitting the experimental results with the theoretical cross sections of the four processes mentioned above folded with the angular resolutions ($\sigma_{\theta\pi} = 0.6$ mrad) and the measured energy spectrum of the incident photons. In the fitting process, four parameters, $\Gamma(\pi^0 \to \gamma\gamma)$, $C_{NC}$, $C_{NI}$, $\varphi$, were varied to calculate the magnitude of the Primakov, $NC$, $NI$ cross sections and the phase angle, respectively. Independent analyses of the experimental data by two groups within the PrimEx collaboration yielded the weighted averages of the extracted decay widths for $^{12}$C and $^{208}$Pb presented in Table II.

The extracted decay width combined for the two targets is $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14$ (stat.) $\pm 0.17$ (syst.) eV. The quoted total systematic uncertainty (2.1%) is the quadratic sum of all the estimated uncertainties in this experiment. The systematic uncertainties were verified by measuring the cross sections of the Compton scattering and the $e^+e^-$ production processes. The extracted cross sections for these well-known processes agree with the theoretical predictions at the level of 1.5% and will
be published separately. The PrimEx result, with a total experimental uncertainty of 2.8%, is the most precise Primakoff type measurement of the $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ to date. It is a factor of two-and-a-half more precise than the current average value quoted in the Particle Data Group (PDG), Phys. Lett. B 667, 1 (2008).

This project was supported in part by the National Science Foundation under a Major Research Instrumentation grant (PHY-0079840). The Southern Universities Research Association (SURA) operated Jefferson Lab under U.S. Department of Energy Contract No. DE-AC05-84ER40150 during this work.

* Corresponding author: gasparan@jlab.org

We acknowledge the invaluable contributions of the Accelerator and Physics Divisions at Jefferson Lab which made this experiment possible. We thank the Hall B engineering staff for their critical contributions in all stages of this experiment. Theoretical support provided by Jose Goity throughout this project is gratefully acknowledged.

This project was supported in part by the National Science Foundation under a Major Research Instrumentation grant (PHY-0079840). The Southern Universities Research Association (SURA) operated Jefferson Lab under U.S. Department of Energy Contract No. DE-AC05-84ER40150 during this work.

| Target | $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ | $C_{NC}$ | $\varphi$ | $C_{NI}$ |
|--------|-------------------------------------|----------|----------|----------|
| $^{12}$C | 7.79±0.18 | 0.83±0.02 | 0.78±0.07 | 0.72±0.06 |
| $^{208}$Pb | 7.85±0.23 | 0.69±0.04 | 1.25±0.07 | 0.68±0.12 |

TABLE I: The fit values extracted from the measured cross sections on $^{12}$C and $^{208}$Pb. The values for the decay widths are the weighted averages from two analyses. The uncertainties shown here are statistical only (see text for notations).