Exp.-Nr. A2/ 6-03
Eingang:
an PAC:

Mainz Microtron MAMI

Collaboration A2: “Real Photon Experiments”
Spokesperson: R. Beck

Proposal for an Experiment

Measurement of the Photon Asymmetry in Neutral Pion Production from the Proton near Threshold.

Collaborators :

CrystalBall@MAMI collaboration

Spokespersons for the experiment : D. Hornidge - Mount Allison University, Sackville

Abstract of Physics :

We propose to perform a precise measurement of $p(\vec{\gamma},\pi^0)p$ close to threshold in order to test Chiral Perturbation Theory. This is accomplished through determination of the S-wave and all three P-wave amplitudes, along with their energy dependence, from the differential cross section and photon asymmetry.

Abstract of Equipment :

We require a beam of tagged, linearly polarized photons incident on a liquid-hydrogen target and the 4π Crystal Ball photon spectrometer in combination with TAPS as forward wall. The Glasgow tagging system will provide the intense, linearly polarized photon beam.

MAMI–Specifications :

beam energy	380 MeV
beam current	$<$ 100 nA
time structure	cw
polarization	linearly polarized photons

Experiment–Specifications :

experimental hall/beam	A2
detector	Crystal Ball and TAPS as forward wall
target	liquid hydrogen

Beam-Time Request :

set–up without beam	will be done in conjunction with the CB/TAPS installation
set–up/tests with beam	24 hours
data taking	200 hours

Title: **Measurement of the Photon Asymmetry in Neutral Pion Production from the Proton near Threshold.**

Participants: J. Brudvik, B.M.K. Nefkens, S.N. Prakhov, J.W. Price, and A. Starostin
University of California, Los Angeles, USA

J. Ahrens, H.J. Arends, R. Beck, D. Drechsel, D. Krambrich, M. Lang, S. Scherer, S. Schumann, A. Thomas, L. Tiator, M. Unverzagt, D. von Harrach and Th. Walcher
Institut für Kernphysik, University of Mainz, Mainz, Germany

S. Altieri, A. Braghieri, P. Pedroni, and T. Pinelli
INFN Sezione di Pavia, Pavia, Italy

J.R.M. Annand, R. Codling, E. Downie, D. Glazier, K. Livingston, J.C. MacGeorge, I.J.D. MacGregor, D. Protopopescu and G. Rosner
Department of Physics and Astronomy, University of Glasgow, Glasgow, UK

C. Bennhold and W. Briscoe
George Washington University, Washington DC, USA

S. Cherepnya, L. Fil'kov, and V. Kashevarov
Lebedev Physical Institute, Moscow, Russia

B. Boillat, M. Kotulla, B. Krusche and F. Zehr
Institut für Physik, University of Basel, Basel, Switzerland

R. Gregor, V. Metag, S. Lugert, R. Novotny, M. Pfeiffer and S. Schadmand
II. Physikalisches Institut, University of Giessen, Giessen, Germany

D. Branford, K. Foehl, C.M. Tarbert and D.P. Watts
School of Physics, University of Edinburgh, Edinburgh, UK

V. Lisin, R. Kondratiev and A. Polonski
Institute for Nuclear Research, Moscow, Russia

G. O'Rielly
University of Massachusetts, Dartmouth, USA

D. Hornidge
Mount Allison University, Sackville, Canada

P. Grabmayr and T. Hehl
Physikalisches Institut Universität Tübingen, Tübingen, Germany

H. Staudenmaier
Universität Karlsruhe, Karlsruhe, Germany

M. Manley
Kent State University, Kent, USA

M. Korolija and I. Supek
Rudjer Boskovic Institute, Zagreb, Croatia

T.D.S. Stanislaus
Valparaiso University, Valparaiso, USA

D. Sober
Catholic University, Washington DC, USA

M. Vanderhaeghen
College of William and Mary, Williamsburg, USA

Spokesperson: D. Hornidge, Dept. of Physics, Mount Allison University, Sackville, Canada
Tel: (506) 364-2586, Fax: (506) 364-2583,
email: dhornidge@mta.ca

Abstract

We propose to perform a precise measurement of $p(\vec{\gamma},\pi^0)p$ close to threshold in order to test Chiral Perturbation Theory. This will be accomplished through precise determination of the S–wave and all three P–wave amplitudes, along with their energy dependence, from the differential cross section and photon asymmetry. The experiment will use the Glasgow-Mainz tagger with a diamond radiator to produce linearly polarized photons, a liquid hydrogen target, and the 4π Crystal Ball/TAPS set-up as a π^0 spectrometer.

1 Motivation

1.1 Theory

Low–energy theorems (LETs) for pion photoproduction were introduced by Kroll and Ruderman [1] in 1954 and improved by Fubini *et al.* [2] and De Baenst [3] in 1970. These theorems are formally exact, model independent, and based on symmetries underlying the interactions, such as gauge invariance and the partially conserved axial current. They are very useful tools that enable one to make exact statements about some amplitudes in field theories in the limit of small or vanishing incident projectile energies. In pion production, LETs predict the value of the S–wave threshold amplitude E_{0+} in a power series in $\mu = m_\pi/m_N$, the ratio of the masses of the pion and nucleon.

The advent of high duty factor accelerators enabled the first precise measurements of the $\gamma p \to \pi^0 p$ reaction at Saclay [4] and Mainz [5]. The experimental values for E_{0+} at threshold were however in conflict with the LET prediction. Most calculations also failed to predict the strong dependence of E_{0+} on the photon energy between the π^0–threshold and 160 MeV, where a unitary cusp due to the two–step process $\gamma p \to \pi^+ n \to \pi^0 p$ [6] was seen in the Mainz measurement.

These disagreements motivated several theoretical and experimental investigations. New experiments were performed at Mainz [7] and Saskatoon [8], measuring the total and differential cross sections close to threshold. The extracted values of E_{0+} confirmed the strong energy dependence and were again nearly a factor of two smaller than the LET prediction at threshold. This discrepancy was explained by Bernard, Kaiser and Meißner [9], who investigated threshold pion photoproduction in the framework of heavy–baryon chiral perturbation theory (ChPT), which showed that additional contributions due to pion loops in μ^2 must be added to the old LET.

In the following years, refined calculations within heavy–baryon ChPT [10] led to descriptions of the four relevant amplitudes at threshold by well–defined expansions up to order p^4 in the S–wave amplitude E_{0+} and p^3 in the P–wave combinations P_1, P_2 and P_3, where p denotes any small momentum or pion mass, the expansion parameters in heavy–baryon ChPT. To that order, three low–energy constants (LECs) due to the renormalization counter terms appear, two in the expansion of E_{0+} and an additional LEC b_P for P_3, which have to be fitted to the data or estimated by resonance saturation. However, two combinations of the P–wave amplitudes, P_1 and P_2, are free of low–energy constants. Their expansions in μ converge rather well leading to new LETs for these combinations. Therefore, the P–wave LETs offer a significant test of heavy–baryon ChPT. However, for this test the S–wave amplitude E_{0+} and the three P–wave combinations P_1, P_2 and P_3 have to be separated. This separation can be achieved by measuring the photon asymmetry using linearly polarized photons, in addition to the measurement of the total and differential cross sections.

The CM differential cross section can be written

$$\frac{d\sigma}{d\Omega}(\theta_\pi) = \frac{q}{k}(A + B\ \cos(\theta_\pi) + C\ \cos^2(\theta_\pi))\ , \tag{1}$$

where θ_π is the CM pion emission angle with respect to the beam direction and q and k denote the CM momenta of pion and photon, respectively. The coefficients $A = |E_{0+}|^2 + |P_{23}|^2$, $B = 2\Re(E_{0+}P_1^*)$ and $C = |P_1|^2 - |P_{23}|^2$ are functions of the multipole amplitudes with $P_{23}^2 = \frac{1}{2}(P_2^2 + P_3^2)$.

One can see that using unpolarized photons, it is not possible to separate P_2 and P_3. However, using the photon asymmetry obtained by measuring with linearly polarized photons, this is possible.

The differential cross section for linearly polarized photons is given by

$$\frac{d\sigma}{d\Omega}(\theta_\pi, \phi) = \frac{d\sigma}{d\Omega}(\theta_\pi)\,[1 - p_\gamma \Sigma \cos(2\phi)] \tag{2}$$

where p_γ is the degree of linear photon polarization, ϕ is the angle measured between the polarization vector and the production plane, and Σ is the photon asymmetry given by:

$$\Sigma = \frac{1}{p_\gamma}\frac{d\sigma^\perp - d\sigma^{||}}{d\sigma^\perp + d\sigma^{||}} \propto P_3^2 - P_2^2. \tag{3}$$

Here $d\sigma^\perp$ is the cross section where the pion is detected perpendicular to the plane defined by the polarization vector and the direction of the tagged photon, and for $d\sigma^{||}$ the pion is detected in this plane. Since the asymmetry is proportional to $P_3^2 - P_2^2$, a measurement of it enables the disentanglement all three P–waves and the E_{0+}.

Moreover, the S–wave amplitude has both real and imaginary parts and can be written

$$E_{0+}(E_\gamma) = A^{p\pi^0}(E_\gamma) + i\,\beta\,q_{\pi^+}\ , \tag{4}$$

where q_{π^+} is the π^+ CM momentum. The first part, $A^{p\pi^0}$ is due to the direct process and the second part arises from the two–step process. Below π^+–threshold, one must analytically continue $q_{\pi^+} \to i|q_{\pi^+}|$. Thus E_{0+} is purely real and has the value $E_{0+} = A^{p\pi^0} - \beta|q_{\pi^+}|$, where β is the product of the S–wave amplitude $E_{0+}^{n\pi^+}$ for π^+–production and the scattering length $a_{n\pi^+ \to p\pi^0}$. Above π^+–threshold, E_{0+} is complex with $E_{0+} = A^{p\pi^0} + i\,\beta|q_{\pi^+}|$ and $\Im\{E_{0+}\} = \beta|q_{\pi^+}|$, the cusp function. In the threshold region the imaginary parts of the P-waves are negligible because of the small πN–phase shifts.

1.2 Previous Measurements

Earlier, unpolarized experiments [5, 7, 8] were able to extract E_{0+}, P_1, and P_{23}, although the results are not in complete agreement (see Figure 1). The small systematic differences in the total cross section result in a different energy dependence in the E_{0+} amplitude.

It was not until a Mainz measurement using linearly polarized photons covering a range of $E_\gamma = 144 - 166$ MeV by Schmidt et al. [14], in which they were able to obtain the photon asymmetry (see Figure 2), that the E_{0+} and all three P–waves were extracted. Using a fit to the data, they were also able to extract the parameter β and thus the imaginary part of

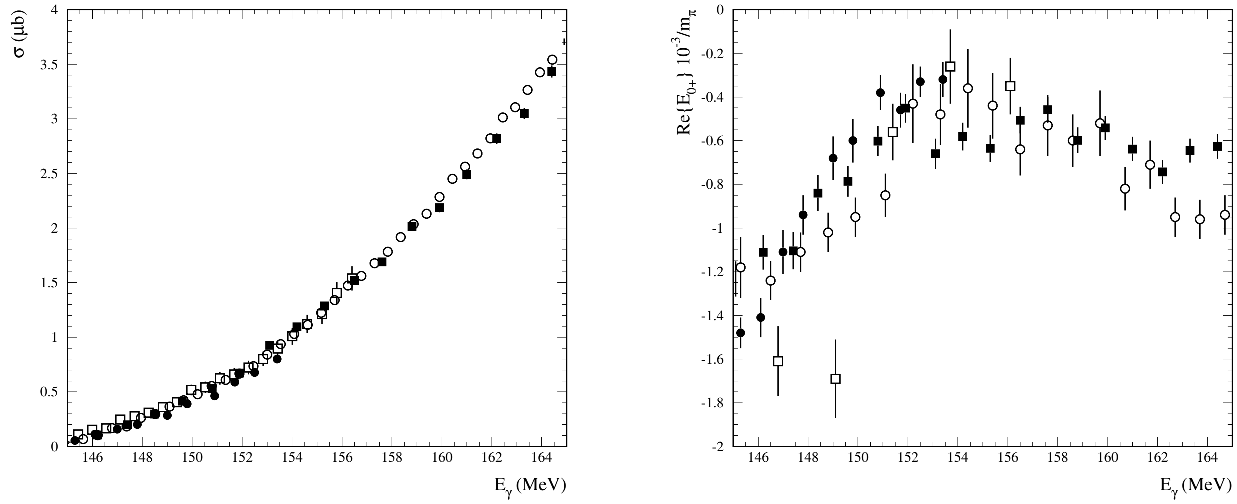

Figure 1: Total cross section and the real part of the E_{0+} amplitude as a function of the incident photon energy. Open squares are from [5], closed circles are from [7], open circles are from [8] and solid squares are from [14]. One can see that small systematic differences in the total cross section manifest themselves in a different energy dependence of the E_{0+} amplitude.

the E_{0+}. Results for this experiment compared to those of previous measurements [7, 8], along with those from a ChPT calculation [10, 11] and from a dispersion-relation theoretical approach [12] are given in Table 1. Due to poor statistics, however, the photon asymmetry as a function of pion angle was extracted at only one incident photon energy, resulting in larger-than-desired errors for the P–waves. In addition, the experimental uncertainty in the energy dependence of the P–wave amplitudes then resulted in a large uncertainty in β (and thus $\Im\{E_{0+}\}$).

2 Experiment

To produce the linearly polarized photon beam, we will use the Glasgow-Mainz tagging facility and coherent bremsstrahlung from a diamond radiator. The left frame of Figure 3 shows the polarization in the threshold region from a previous measurement [14]. We will use the identical set-up to produce coherent bremsstrahlung for this measurement.
In order to detect the two π^0-decay photons, the Crystal Ball multi-photon spectrometer will be used as the central detector with TAPS as a forward wall, which is the standard set-up described in detail in the accepted proposal MAMI/A2/1-02. Having TAPS at 1.80 m, the set-up covers 96% of 4π, with an extremely high efficiency for two photons (see the right frame of Figure 3). The distributions were obtained with a GEANT-based Monte Carlo simulation code developed for the experiments with the Crystal Ball at MAMI. The code includes a detailed description of the Crystal Ball detector as well as the TAPS forward wall, and the liquid hydrogen target. The analysis of the Monte Carlo data is performed with the Analyzer software package initially developed for the Crystal Ball AGS experiments. The

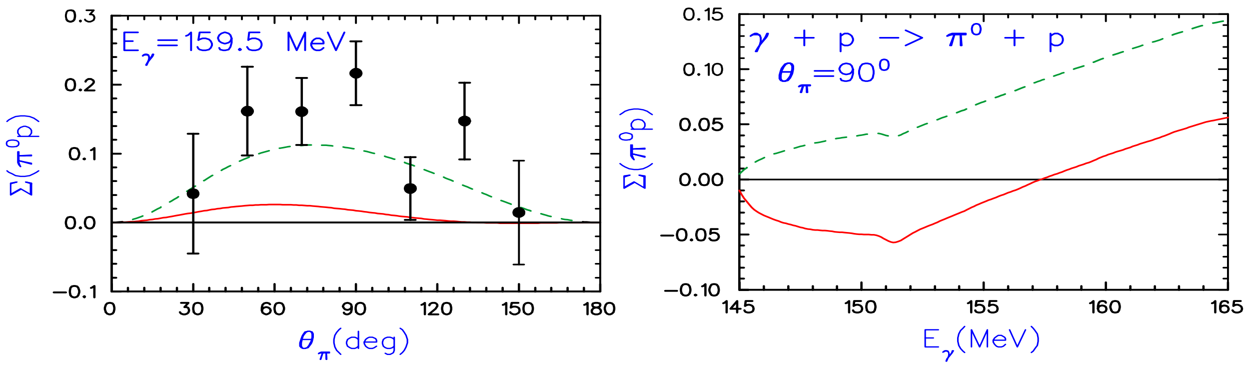

Figure 2: Results for the photon asymmetry from [14] compared to a dynamical-model calculation [13]. Due to poor statistics, there is only one bin in incident photon energy from 144–166 MeV with an average of 159.5 MeV. The solid curve is with standard parameters, and the dashed curve is the same but with the M_{1-} multipole decreased by 15%. The right frame shows the predicted strong energy dependence of Σ.

Analyzer modified for the MAMI experiments includes a TAPS cluster recognition routine. The acceptance is shown for events in which both photons are detected.

3 Event Rates

The parameters entering the count-rate estimate and resulting beam-time request are:

- Incoming electron beam energy: $E_0 = 380$ MeV.
- Tagged photon energy range: $E_\gamma = 120 - 350$ MeV.
- Average electron count rate over the region of interest (140–170 MeV): $\dot{N}_e = 0.6 \times 10^6 \, \frac{1}{s} \, \frac{1}{MeV}$.
- Tagging efficiency: $\varepsilon_{tag} \approx 50\%$.
- Number of protons in a 5 cm long LH$_2$ target: $t = 2.1 \times 10^{23} \, \frac{1}{cm^2}$.
- Data acquisition system live time: $\varepsilon_{DA} \approx 70\%$.

where the estimates have been done with tagger channels having photon energy lower than 120 MeV switched off.
The resulting number of events expected per hour per MeV of the incident photon energy is then given by:

$$\dot{N}_{\pi^0} = \varepsilon_{tag} \dot{N}_e \, \frac{d\sigma}{d\Omega} \, t \, \varepsilon_{\pi^0} \, \Delta\Omega \, \varepsilon_{DA}, \tag{5}$$

and the results for an incident photon energy bin $E_\gamma = 150 \pm 1$ MeV are given in Table 2.
The beam time requested for the data taking is 200 hours; 100 for each $d\sigma^\perp/d\Omega$ and $d\sigma^\parallel/d\Omega$. Although it is not necessary to measure both parallel and perpendicular due to the complete ϕ-coverage of the set-up, it will help to understand systematic errors. No set-up time will

	Schmidt [14]	Fuchs [7]	Bergstrom [8]	ChPT [10, 11]	DR [12]
$E_{0+}(E_{thr}^{p\pi^0})$	-1.23 ± 0.09	-1.31 ± 0.2	-1.32 ± 0.05	-1.16	-1.22
$E_{0+}(E_{thr}^{n\pi^+})$	-0.45 ± 0.07	-0.34 ± 0.03	-0.52 ± 0.04	-0.43	-0.56
β	2.43 ± 1.0	2.82 ± 0.32	3.0–3.8	2.78	3.6
P_1	9.46 ± 0.28	9.08 ± 0.14	9.3 ± 0.09	9.14 ± 0.5	9.55
P_2	-9.5 ± 0.28			-9.7 ± 0.5	-10.37
P_3	11.32 ± 0.36			10.36	9.27
P_{23}	10.45 ± 0.07	10.37 ± 0.08	10.53 ± 0.07	11.07	9.84

Table 1: Summary of the experimental results for $\Re\{E_{0+}\}$ at the π^0– and π^+–threshold (unit: $10^{-3}/m_{\pi^+}$), for the parameter β of $\Im\{E_{0+}\}$ (unit: $10^{-3}/m_{\pi^+}^2$) and for the three P–wave amplitudes (unit: $q \cdot 10^{-3}/m_{\pi^+}^2$, where q is the outgoing pion momentum) compared with theoretical predictions.

be needed as this experiment will use the set-up identical to that of the magnetic moment of the delta measurement, and 24 hours are required for test with the beam on.
For the $E_\gamma = 150 \pm 1$ MeV bin, this will provide better than 2% error in the differential cross section for middle bins and 5% for the extreme-θ_π bins. It is important to note that the cross section increases rapidly with energy so that bins at higher energy will have better than 2% statistics.
The photon asymmetry Σ will be measured with the coherent peak set at about 160 MeV. The linearly polarized photons cover the range between 135–165 MeV with a mean polarization $P_\gamma \approx 30\%$ (see the left frame of Figure 3). The polarization for $E_\gamma = 150$ MeV is about 30%. The number of events expected in the 200 hours is roughly 2500 per bin of ± 1 MeV incident photon energy and ± 10 deg in θ_π at $E_\gamma = 150$ MeV. Assuming the number of counts for the parallel and perpendicular cross sections are roughly the same, namely N_{π^0}, then the expected accuracy in the photon asymmetry for this MeV bin is then

$$\delta\Sigma = \frac{1}{p_\gamma}\,\frac{1}{\sqrt{2N_{\pi^0}}} \approx 0.05. \tag{6}$$

Again, the error in the asymmetry will rapidly decrease as the incident photon energy increases. For the $E_\gamma = 160 \pm 1$ MeV bin, the expected accuracy for the asymmetry at 90 deg is $\delta\Sigma = 0.01$, a gain of about a factor of five.
This will be a vast improvement over the previous measurement, which has one incident photon energy bin spanning 145–166 MeV and errors in the asymmetry ranging from 20–50%. In addition, the energy dependence in the P–waves will also allow a more accurate determination of β and thus the imaginary part of the E_{0+}. Moreover, the full azimuthal coverage of the CB-TAPS set-up will also significantly reduce the systematic uncertainty over the previous measurements, further improving the total errors in the S– and P–wave amplitudes.

To summarize, the total beam time requested is:

224 hours

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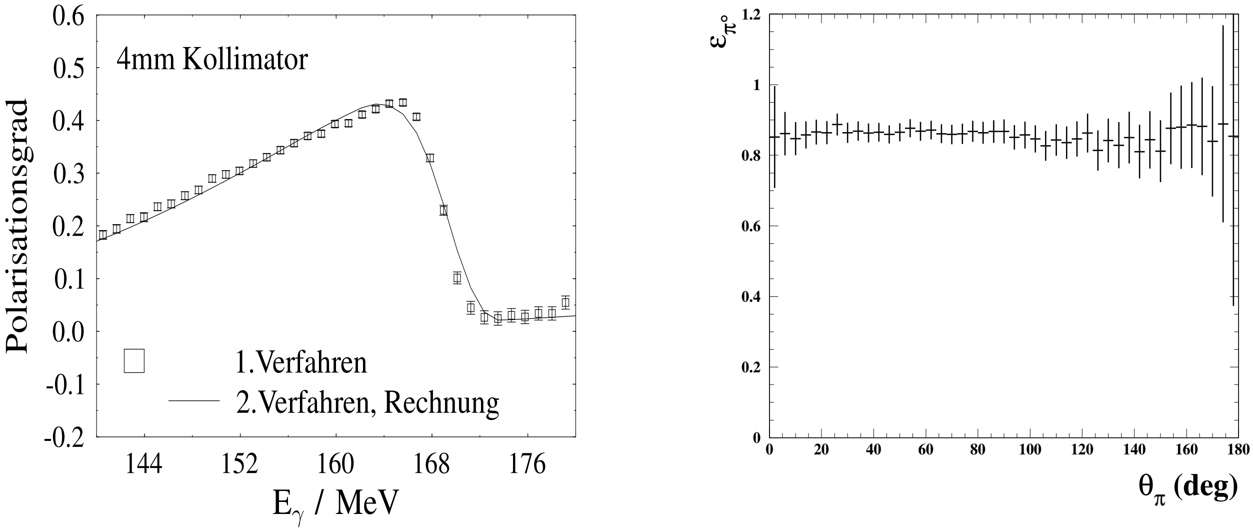

Figure 3: The degree of polarization for coherent bremsstrahlung from [14] (left frame) along with a Monte Carlo simulation of the π^0 detection efficiency of the CB-TAPS experimental apparatus as a function of the pion emission angle [15] (right frame). The efficiency is shown for the reaction $\gamma p \to \pi^0 p$ for an incident photon energy of 150 MeV and for events in which both photons are detected.

Table 2: Rate estimates as a function of pion emission angle for $E_\gamma = 150 \pm 1$ MeV. Data are from [14]. Other parameters are $\varepsilon_{tag} = 0.50$, $t = 2.1 \times 10^{23}$ 1/cm^2, $\varepsilon_{DA} = 0.70$, and $\dot{N}_e = 0.6 \times 10^6$ 1/s. Note that the bins in θ_π cover 20 degrees each, the azimuthal pion angle is integrated over, and the rates are given per 2 MeV of incident photon energy.

θ_π (deg)	$\Delta\Omega$ (sr)	ε_{π^0}	$d\sigma/d\Omega$ (μb/sr)	$\dot{N}_{\pi^0}$ (1/h/2 MeV)	Time needed for 2% (h)
10	0.4	0.87	0.012 ± 0.003	1.3	1957
30	1.1	0.86	0.014 ± 0.002	4.3	582
50	1.7	0.86	0.023 ± 0.002	10.5	237
70	2.1	0.86	0.027 ± 0.002	15.1	165
90	2.2	0.85	0.030 ± 0.003	17.9	139
110	2.1	0.85	0.035 ± 0.003	19.4	129
130	1.7	0.85	0.046 ± 0.004	20.9	119
150	1.1	0.85	0.045 ± 0.004	13.3	187
170	0.4	0.85	0.047 ± 0.006	4.8	524

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