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Recoil polarimetry with the Crystal Ball at MAMI

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Abstract The spectrum and properties of the excited states of the nucleon are still poorly established despite decades of study. These proceedings describe new measurements of pseudo-scalar meson photoproduction at the Crystal Ball at MAMI, employing a new large acceptance nucleon recoil polarimeter. The double- and single-polarisation observables obtained will provide valuable and unique data to be used as part of the world effort to improve our knowledge of this fundamental spectrum.

Key words photoproduction reactrons

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1 Introduction

The excitation spectrum of the nucleon is a fundamental observable which is sensitive to the dynamics of the constituents of the nucleon. Despite its importance this spectrum is not well established by experiment, many resonances have large uncertainties in their mass, width and electromagnetic couplings. Even the existence of many resonances is uncertain as they give inconsistent signals in different partial wave analyses of the world data set[1].

This situation is particularly disappointing given the expected progress in the theoretical description of the spectrum currently ongoing and expected in the near future. Most existing predictions are based on constituent quark models in which the degrees of freedom of the nucleon are taken to be quarks with large effective masses. Different assumptions employed in these quark models, such as assuming symmetric or di-quark dynamics, result in different predictions for the spectrum. However these are not discernible given the present experimental uncertainties. These phenomenological constituent quark approaches are being complemented in recent years by continuously improving predictions of the excitation spectrum from Lattice QCD[2], being carried out at progressively more realistic light quark masses as computing power increases. Recent developments of holographic dual theories[3] are also promising and calculations based on a Dyson-Shwinger approach[4] could be achievable in the near future.

There is a current world effort to improve the quality of experimental information on the excitation spectrum of the nucleon through measurements of meson photoproduction from the nucleon. This is being carried out at facilities including Jefferson Lab, ELSA, MAMI, GRAAL and LEPS. The photon probe is ideal for such studies having the benefit of being polarisable and having a well understood interaction (Quantum Electrodynamics). The main process under study in these reactions is the photoproduction of pseudo-scalar mesons from the nucleon. This process can be described by 4 complex reaction amplitudes which lead to 16 experimental observables. These comprise the cross section, 3 single polarisation observables corresponding to polarisation of the photon beam (Σ), nucleon target (T) or measurement of recoil nucleon polarisation (P) and three quartets of double-polarisation observables corresponding to simultaneous determination of the polarisation of beam and target, beam and recoil or target and recoil.

Given the long standing uncertainties in resonance properties, largely arising because of the different results between the different partial wave analyses of the existing world data, it is highly desirable to move as close as possible to what is referred to as a "complete measurement" of observables. This represents the measurement of sufficient experimental quantities to fully constrain the 4 basic reaction amplitudes, enabling a model independent extraction. This can be

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achieved with a minimum of eight measurements[5], which necessarily involve at least 4 measurements of double-polarisation observables. There has already been tremendous efforts to develop circularly and linearly polarised photon beams at the major laboratories. In more recent years there has been great progress in the setup of frozen spin polarised targets at the major facilities, which allow polarised nucleon targets without significantly limiting the detector acceptance due to restrictive amounts of holding magnet infrastructure.

The large acceptance recoil polarimeter developed for the Crystal Ball at MAMI by the Edinburgh group enables measurements from the crucial beam-recoil group of observables to be obtained for non strange pseudo-scalar meson photoproduction. This new data will be a valuable and unique contribution to this world programme. In the following sections the data analysis procedures and preliminary results from the recoil nucleon polarimeter from the Crystal Ball at MAMI will be presented.

2 The Crystal Ball recoil polarimeter at MAMI

2.1 Pseudo scalar meson photoproduction

The spin degrees of freedom in the photoproduction of pseudoscalar mesons from a nucleon target lead to 16 possible experimental observables, the differential cross section, 3 single polarization observables with recoil polarization P, target polarization T , beam asymmetry Σ and a further 12 double polarization observables. In discussing the results we can obtain with the recoil polarimeter we will focus on the subset of observables that can be measured with a polarized photon beam and determination of recoil nucleon polarization. The differential cross section for such measurements can be written as[6].

$$\begin{aligned}\rho_{\rm f}\frac{{\rm d}\sigma}{{\rm d}\Omega} = \frac{1}{2}\frac{{\rm d}\sigma}{{\rm d}\Omega}_{\rm un}\Big\{&1-P_\gamma^{\rm T}\Sigma\cos 2\phi-\\ &\sigma_{x'}\left(P_\gamma^{\rm T}O_x\sin 2\phi+P_\gamma^{\rm C}C_x\right)+\\ &\sigma_{y'}\left(P-P_\gamma^{\rm T}T\cos 2\phi\right)-\\ &\sigma_{z'}\left(P_\gamma^{\rm T}O_z\sin 2\phi+P_\gamma^{\rm C}C_z\right)\Big\},\end{aligned}$$

where O_x, C_x, O_z and C_z are the relevant double polarization observables with $P_\gamma^{\rm T}$ and $P_\gamma^{\rm C}$ the beam linear and circular polarization respectively. The matrices $\sigma_{i'}$ refer to the hadron quantisation axis of Fig. 1 and $\rho_{\rm f}$ represents its density matrix. To determine the longitudinal polarization, or z-components, a magnetic field is required to precess the longitudinal component into the transverse direction where it can be measured by a polarimeter. This will not be possible for our proposed polarimeter, however the 4 observables O_x, C_x, P and T will, together with previous and ongoing measurements of $\frac{{\rm d}\sigma}{{\rm d}\Omega}$, Σ, and the beam-target observables G and E, enable the first measurement of a complete set of observables in π and η photoproduction.

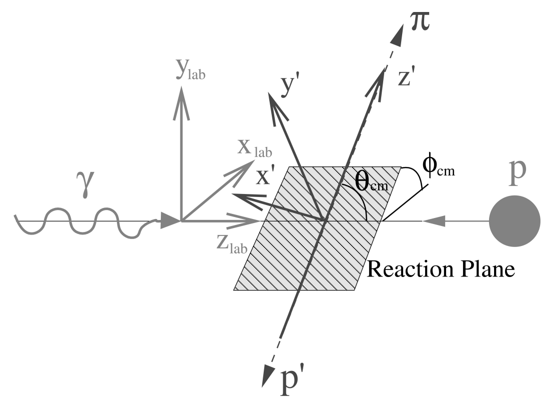

Fig. 1. Outline of coordinate frame.

2.2 Basics of nucleon polarimetery

Nucleon polarimeters in the sub-GeV regime typically employ nucleon-nucleus scattering. In such processes the spin-orbit potential in the interaction results in an azimuthal modulation in the yield of scattered nucleons, the amplitude of which is proportional to the degree of transverse polarisation of the incident nucleons. As the polarimeter only measures transverse polarisation components in the lab frame this naturally leads to a new reference frame with the z-axis along the nucleon momentum direction in the lab (z'), the y-axis as for the primed frame in Fig. 1. (y^l) and the x-axis is defined by $x^l = y^l \times z^l$. The azimuthal scattering distribution is then given by,

$$n(\phi_{\rm sc}) = n_{\rm o}(1+A[P_y''\cos\phi_{\rm sc} - P_x''\sin\phi_{\rm sc}]), \quad (1)$$

where $\phi_{\rm sc}$ is the azimuthal scattering angle and A the analysing power. The polarisation components can be determined from a fit to the distribution, given the knowledge of the analysing power for p-^{12}C scattering from previous data. Evaluating equation 1 determines the polarization of the recoiling nucleon in terms of the photoproduction observables. In the case of a circularly polarised beam:

$$P_x = -P_\gamma^{\rm C}C_x^l,$$

$$P_y = P,$$

$$P_z = -P_\gamma^{\rm C}C_z^l.$$

In the case of a linearly polarised beam the components can be written as:

$$P_x = \frac{-P_\gamma^{\mathrm{T}} O_x^{\mathrm{l}} \sin 2\phi}{\left(1 - P_\gamma^{\mathrm{T}} \Sigma \cos 2\phi\right)},$$

$$P_y = \frac{P - P_\gamma^{\mathrm{T}} T \cos 2\phi}{\left(1 - P_\gamma^{\mathrm{T}} \Sigma \cos 2\phi\right)},$$

$$P_z = \frac{-P_\gamma^{\mathrm{T}} O_z^{\mathrm{l}} \sin 2\phi}{\left(1 - P_\gamma^{\mathrm{T}} \Sigma \cos 2\phi\right)}.$$

The l superscript on the double polarisation observables represents the fact that experimentally it is the polarisations transverse to the nucleon direction in the lab frame are measured by the polarimeter.

2.3 The Crystal Ball Polarimeter

This section will outline the operation of the polarimeter developed for the Crystal Ball. First the relevant properties and capabilities of the Crystal Ball and TAPS detectors will be described. The phase-I design for use with proton targets and preliminary results are outlined in Sec 2.5. Sec 2.6 describes the plans for a phase-II polarimeter for use with deuterium targets.

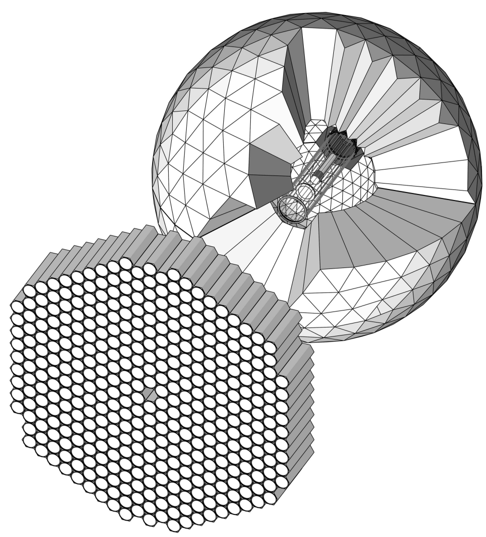

Fig. 2. Schematic diagram of the Crystal Ball and TAPS detectors. A rection of the Crystal Ball has been removed for clarity.

2.4 The Crystal Ball detector

The Crystal Ball[7] was conceived in the mid 1970s at SLAC and has been involved in experiments at SPEAR, DORIS and Brookhaven National Laboratory before arriving at MAMI. The Crystal Ball is a 672 element NaI detector covering 94% of 4π. Each element is shaped like a a truncated pyramid ∼41 cm long (Fig. 3). Photons incident on the ball produce an electromagnetic shower which generally deposits energy in a number of crystals (98% of the deposited energy of each photon is contained in a cluster of 13 crystals). From analysing the centre of gravity of the shower angular resolutions for the photon of 2°—3° in theta and $2°/\sin(\theta)$ in phi are achieved. The high light output of NaI also permits a good determination of the photon energy ($\sigma/E_\gamma \sim 1.7\%/E_\gamma(\mathrm{GeV})^{0.4}$).

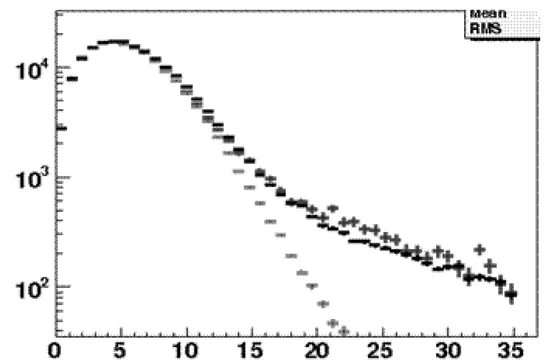

Fig. 3. The reconstructed scatter angle in the polarimeter. The data (points) is compared with G4 simulations with and without nuclear scatter processes included in the simulation.

The photon calorimetry capabilities of the Crystal Ball have been well established. The detector has had a more limited history in use for hadron calorimetry, but the low energy final state particles produced in many reactions at the Mainz beam energies makes development of this capability extremely desirable. The length of the counters corresponds to the stopping range of 233 MeV for π, 341 MeV for K and 425 MeV for protons.

A 4 mm thick segmented plastic scintillator barrel forms the particle identification detector (PID)[8], which gives a Δ-E signal with which to distinguish various charged particle types in the ball. Each scintillator element is 500 mm long with one side angled at 15 degrees so that the 24 scintillators can be formed into a barrel with minimal gaps between the scintillator edges. The scintillators are read out at one end by 9 mm diameter photomultiplier tubes.

The TAPS detector system[9] covers the forward angle region for 0° which is not covered by the Crystal Ball. This is an important part of the phase space for fixed target experiments with high beam momenta. TAPS consists of 376 hexagonally shaped BaF2 detectors each 25 cm long corresponding to 12 radiation lengths.

2.5 The Crystal Ball polarimeter

The mode of operation and preliminary results for the phase-I polarimeter, designed for use with liquid hydrogen targets in p(γ, meson)p reactions is described below.

The operation of the phase-I polarimeter requires observation of the azimuthal modulation in the yield of scattered protons following proton-^{12}C scattering of recoil nucleons. The analysing material for the polarimeter is chosen as ^{12}C because of the well established analysing power for the reaction. The analysing material comprises a tube of graphite which is placed around the hydrogen target and an additional disc of graphite at forward angles shadowing TAPS, as shown in Fig. 4.

The direction of the proton into the graphite of the polarimeter following a p(γ,meson)p reaction is calculated kinematically, from the incident (tagged) photon 4-vector and the detected meson. An associated hit in a PID element within $\pm 12°$ of the calculated phi angle is also required. The protons incident on the polarimeter typically have ~2%—3% probability of undergoing a nuclear scatter in the graphite and to then be detected in the CB or TAPS. For these events the scatter angle in the graphite can be reconstructed.

This reconstructed scatter angle is compared with simulation in Fig. 4. Results from the simulation are presented for the full simulation and also where nucleon nucleus scattering events are turned off in the simulation. It is clear that selecting scatter angles greater than ~14 degrees provides a good sample of nuclear scattered events. For these nuclear scatter events the azimuthal modulation of the scattered proton yield can be analysed to extract the polarisation. More details of the analysis procedure for the polarimeter are given in the proceedings of M. Sikora in this volume.

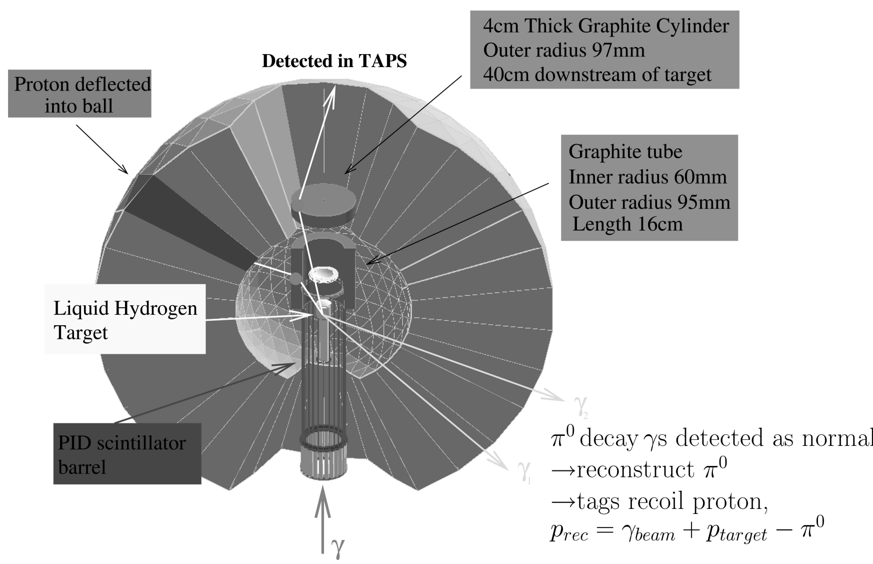

Fig. 4. GEANT4 visualisation of the phase-I polarimeter.

The beam-recoil double polarisation observable C_x^l can be extracted from the beam helicity asymmetry of the azimuthal distribution of scattered nucleons. Very preliminary results for the p(γ,π^0)p reaction are shown in Fig. 5, obtained from the 2 weeks of production beamtime obtained at MAMI to date. Reasonable agreement with the previous experimental measurement of the observable [11] from Hall A of Jefferson Lab is seen. The preliminary C_x^l data are compared to two partial wave analysis solutions from MAID and SAID. Although the preliminary nature of the data do not allow physics conclusions to be drawn at present it is clear the fully analysed data will be valuable for PWA, particularly in regions where the partial wave analyses give different expectations such as in the $E_\gamma = 500$—800 MeV region. Further preliminary analysis of C_x in the η photoproduction channel is presented in Fig. 6 where the utility of double-polarisation measurements to give valuable new constraints on the PWA is clearly seen.

Future analysis will obtain beam-recoil observables in 2π and $\pi\eta$ photoproduction. The formalism for the observables accessible in multiple scalar meson photoproduction is outlined in Ref. [12].

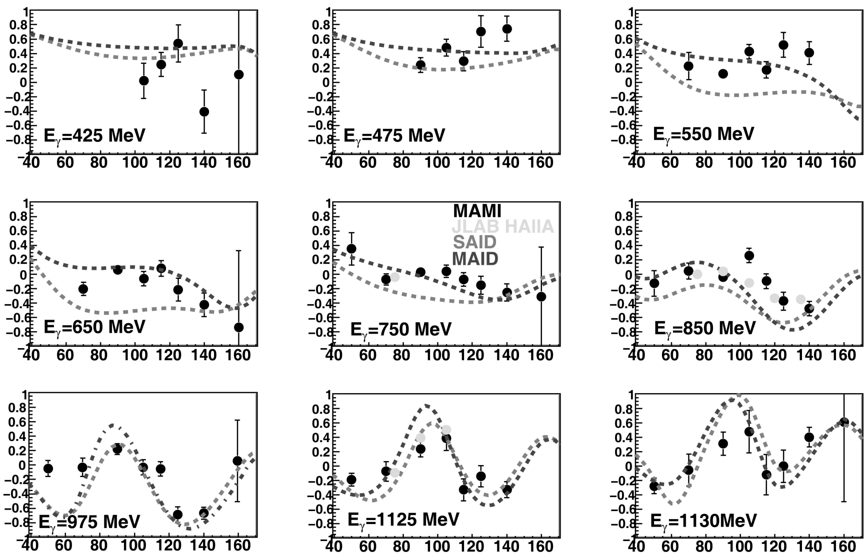

Fig. 5. Very preliminary results for the C_x observable in the p$(\gamma,p)\pi^0$ reaction, presented as a function of π^0 angle in the centre of mass for the E_γ bins shown in the figure. Black filled circles - Crystal Ball data; Green filled circles - Jefferson Lab data; red dashed line - SAID PWA; blue dashed line - MAID PWA.

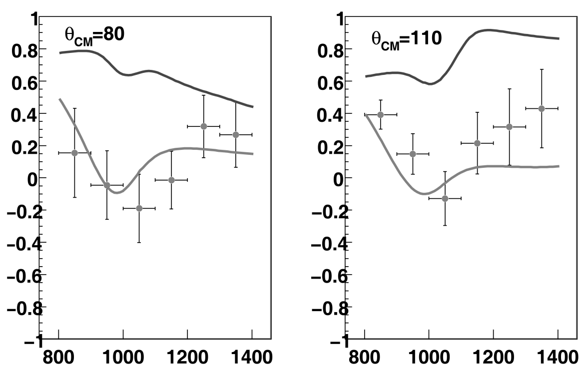

Fig. 6. Very preliminary results for C_x in the p$(\gamma,p)\eta$ reaction. The data are presented as a function of incident photon energy (MeV) and for two angular bins for the η in the centre of mass. The blue line shows results from MAID and the red line shows results from SAID PWA.

2.6 Phase-II polarimeter

The current design of the polarimeter gives information on proton targets and for polarimetry of recoiling protons. Of course it would be extremely valuable to have beam-recoil data on both neutron and proton targets to better constrain the excitation spectrum, in particular the isospin dependence of the electromagnetic couplings for the resonances. To enable this requires modification of the design of the polarimeter to work with deuterium targets, where Fermi motion plays a role, and with final state neutrons.

A new design for the polarimeter is currently under development. The schematic of the proposed design is shown in Fig. 7. The design will exploit the cylindrical multiwire proportional chamber (MWPC) constructed for the Crystal Ball by the Pavia group. The analysing graphite will be placed inside the MWPC so that scattered nucleon tracks can be characterised. A new segmented scintillator barrel (of smaller radius than the current device) will be placed inside the graphite cylinder. The design has been simulated using GEANT4 and some of the results are presented in Fig. 8. For the operation of the polarimeter the incident nucleon track is obtained from a vector joining the centre of the target to the reconstructed scatter point in the graphite (because of the Fermi motion of the target nucleon the kinematic tracking exploited in the phase-I design cannot be used effectively). The scattered nucleon vector will be measured with an accuracy of 2° by the MWPC.

The simulation assumes an analysing power of 1, 100% polarised beam and a value of C_x=1. This then allows the effect of any dilution of the analysing power arising from angular resolution in the scatter determination to be assessed. From the results it is clear that the combined effects producing uncertainty in the scatter angle reconstruction and nuclear scatter event sample in the polarimeter only dilute the analysing power at the level of ~20%. This can be simulated and corrected easily in the final data analysis. The present analysis of the simulation data employs rather simple analysis cuts. Further refinements in the analysis should be able to reduce this dilution.

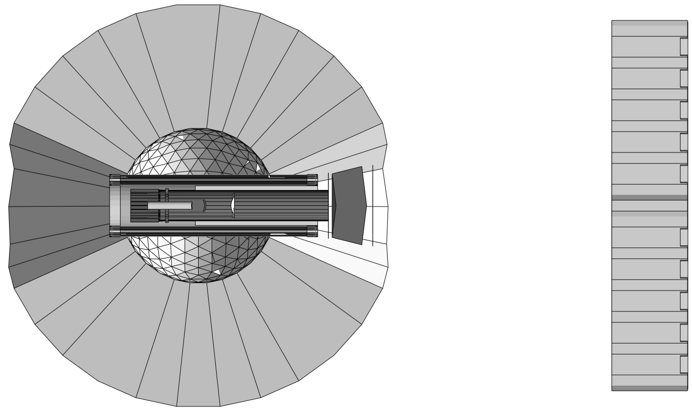

Fig. 7. GEANT4 visualisation of the phase-II polarimeter. The target is shown shaded red. Surrounding the target is the new segmented scintillator barrel (strips), followed by the graphite cylinder and the two chambers of the MWPC. A plug of plastic scintillator at the downstream exit of the CB is also shown.

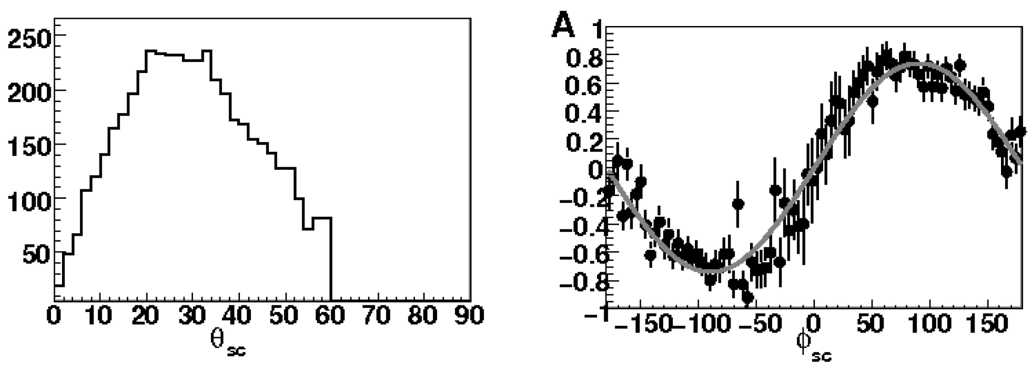

Fig. 8. GEANT4 simulation of the phase-II polarimeter for the n($\gamma, n\pi^0$) reaction. The simulation data has been analysed using realistic experimental conditions for track determination. Fermi motion of the target neutron in the deuterium is included in the generated events. Left plot shows the reconstructed nucleon scatter angle in the polarimeter. Right plot shows the reconstructed beam helicity asymmetry in the azimuthal distribution for the scattered nucleons. The simulation assumes $C_x = A = P_\gamma = 1$.

3 Summary

A large acceptance recoil nucleon polarimeter has been commissioned with the Crystal Ball at MAMI. The first block of production data on the proton has been obtained, and preliminary results for double polarisation beam-recoil observables in meson photoproduction have been extracted. The data from the polarimeter programme will provide new constraints on partial wave analyses of meson photoproduction and will therefore be an important part of the world programme to better establish the nucleon excitation spectrum.

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