COSY Proposal and Beam Time Request

Investigation of the η^3H final state in deuteron-neutron collisions at ANKE

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Abstract

Measurements of η-meson production close to threshold are of great interest with respect to the still open questions concerning the strong and attractive η-nucleon and η-nucleus final state interactions (FSI) and hence the possible existence of quasi-bound η-nucleus states. Data on the $dp \to {}^3\mathrm{He}\,\eta$ reaction from ANKE and COSY-11 have shown that the η^3He system is quasi-bound by less than 1 MeV. This value is much smaller than what one might expect from charge symmetry breaking effects and so we propose to study the mirror "nucleus", *viz.* η^3H.

In order to investigate the FSI in this system we want to determine the not-yet-measured cross section for the reaction $dn \to {}^3\mathrm{H}\,\eta$ ($nd \to {}^3\mathrm{H}\,\eta$) near threshold by studying the reaction $dd \to {}^3\mathrm{H}\,\eta\, p_{\mathrm{sp}}$ in deuterium in a region of quasi-free kinematics, where p_{sp} is a "spectator" proton. There are two kinematic branches, with a slow and fast spectator, and both situations can be measured with the ANKE detector. The triton will be registered in both cases in the forward detector system, as will be the fast spectator proton. Slow spectator protons will be measured with the silicon tracking telescopes over an angular range of $\vartheta \approx 45 - 90^\circ$. The measurement of the momenta of the ^{3}H and p_{sp} allows the η-meson to be identified *via* the missing-mass technique. In both cases a wide range of excitation energies from threshold up to 50 MeV can be covered by determining the excess energy on an event-by-event basis with the help of the spectator information.

For the reaction $dd \to {}^3\mathrm{H}\,\eta\, p_{\mathrm{sp}}$ measured at a deuteron beam momentum of 3.16 GeV/c with a deuterium cluster-jet target **four weeks** of beam time are requested.

Contents

1 Introduction and Motivation

For over twenty years the η interaction with nucleons and nuclei has attracted much attention both experimentally and theoretically. One reason for this excitement is the possibility of the formation of η-nucleus bound states. The existence of so-called η-mesic nuclei was first predicted by Haider and Liu [1], based on the observation that the elementary ηN interaction is attractive and moderately strong for both protons and neutrons [2]. Therefore, with increasing nuclear mass number, the attraction should eventually lead to a bound state. However, because such a state could decay *via* pion emission, it would at best be quasi-bound. Owing to the uncertainty of the η-nucleon scattering length, it is still unclear for which mass number binding might start. In the literature one can find speculations that even the ηd system might form such a bound state [3], though this is disputed by other investigators [4]. More conservative workers consider the η^4He system to be the lightest possible candidate [5, 6, 7]. The COSY measurements [8, 9, 10] and their interpretation [11] have shown that a bound state might also be formed by the η^3He system. Evidence for this also comes from the MAMI data on $\gamma\,^3\mathrm{He}\to\eta^3\mathrm{He}$, which seem to show a similarly strong η^3He final state interaction [12].

Heavier nuclei were studied theoretically, *e.g.* in Ref. [13], where it was concluded that, although there should be bound states, their widths could be of the order of their binding energies, making direct observations of these states very difficult, especially when these widths are greater than the nuclear level spacing.

The direct search for η-mesons bound in a nucleus is very difficult because, by definition, the meson can then not escape and any signal is hidden in the very large hadronic background. However, the occurrence of a bound state near a reaction threshold will also be reflected in the corresponding η-nucleus scattering length a [14]. In such a case the real part of the scattering length should be relatively large and negative whereas its imaginary part should be small. Studies of the η-nucleus interaction near threshold, as a final-state interaction (FSI) in a production reaction, can be used to determine the η-nucleus scattering length [15]. In principle, this might permit conclusions to be drawn on the existence of such η-nucleus bound states.

The η^3He interaction has been successfully investigated at the ANKE facility through the measurement of the $dp\to{}^3\mathrm{He}\,\eta$ reaction over a wide excess energy (Q) range [16, 17]. After taking the momentum smearing of the beam into account, it is seen that the total cross section, shown in Fig. 1, rises to its maximum of 400 nb within an excess energy of 0.5 MeV from threshold and is then stable up to 60 MeV [8, 10]. Taking the WASA/PROMICE data [18] into account pushes this up to $\approx$ 120 MeV. This anomalous energy dependence

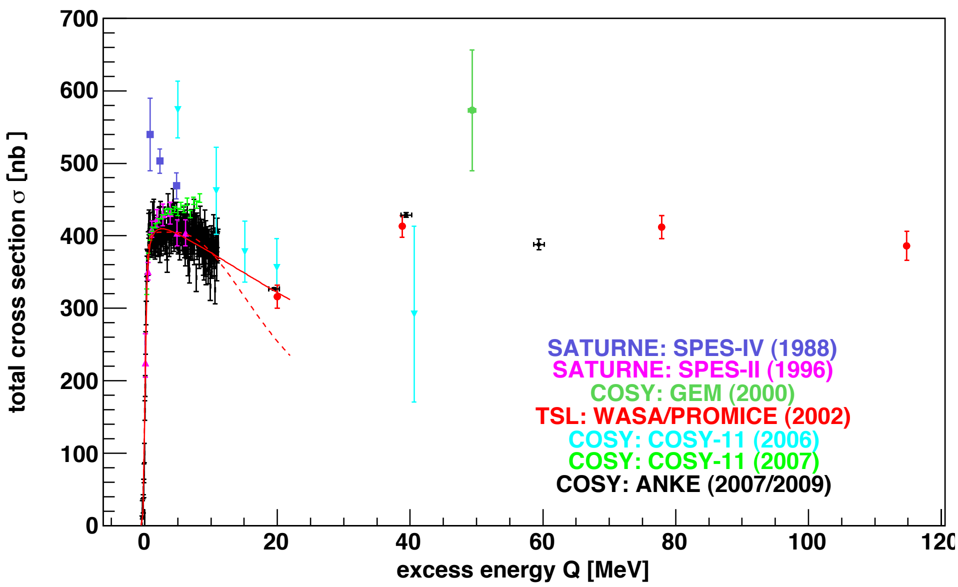

Figure 1: Total cross section for the excess energy range of $Q = 0 - 120$ MeV of the reaction $dp \to {}^3\mathrm{He}\,\eta$ [8, 10, 18].

differs completely from phase space and suggests that there is a very strong η^3He final state interaction which might be a signal for the formation of a new state of matter in the form of a quasi-bound η-nucleus state [15, 11] for a nucleus much lighter than originally proposed [2]. The pole of this state in the complex Q-plane is almost at the threshold, *viz.* $|Q| < 1$ MeV [8].

If the FSI interpretation is correct, the enhancement of the cross section in the first MeV of excess energy should be largely independent of the production process and of the characteristics of the entrance channel and, as remarked above, this has been borne out by the $\gamma\,{}^3\mathrm{He} \to \eta^3\mathrm{He}$ measurements [12].

By charge symmetry, the cross sections for the $dp \to {}^3\mathrm{He}\,\eta$ and $dn \to {}^3\mathrm{H}\,\eta$ reactions should be equal but one might expect breakings of this rule to be larger than the 1 MeV that characterises the "binding" of the η to the ^{3}He. In order to study this we want to measure the $dn \to {}^3\mathrm{H}\,\eta$ cross section over a similar range of excess energies to what we achieved for the $dp \to {}^3\mathrm{He}\,\eta$ reaction. As described in the next section, we propose to do this through the study of η production in deuteron-deuteron scattering under quasi-free conditions, where there is a spectator proton.

2 The reaction $dn \to {}^3\text{H}\,\eta$ ($nd \to {}^3\text{H}\,\eta$) at ANKE

Since we cannot use a free neutron target, the $dn \to {}^3\text{H}\,\eta$ reaction must be studied in the $dd \to {}^3\text{H}\,\eta\, p_{\text{sp}}$ reaction using a deuterium target in a region of quasi-free kinematics where, it is hoped, the spectator proton does not influence the deuteron-neutron interaction. As target we will use the Münster cluster-jet target [19] in the deuterium mode, which gives a maximum target density of the order of 10^{14} particles/cm^2.

In deuteron-deuteron collisions there are two possibilities for a quasi-free neutron deuteron collision. In the first case the target deuteron contains the neutron target and the spectator proton escapes with small Fermi momentum. When the neutron in the beam interacts with the target deuteron to form the triton, the spectator proton escapes with approximately half the beam momentum.

Monte-Carlo simulations have been undertaken for both the $dn \to {}^3\text{H}\,\eta$ and $nd \to {}^3\text{H}\,\eta$ scenarios at different beam momenta. Simulated trajectories of tritons and spectator protons are shown in Fig. 2, generated at a beam momentum of $p_d = 3.16\,\text{GeV/c}$, *i.e.* a beam energy of $T_d = 1.799\,\text{GeV}$, a deflection angle of the circulating COSY beam of $\alpha = 6.5°$ at the ANKE installation and an ANKE-D2 field of 1.57 T.

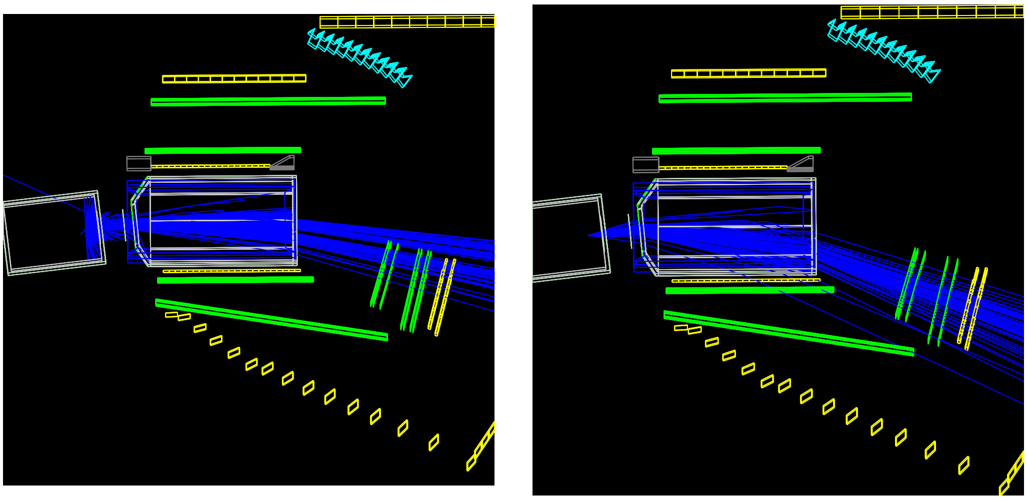

Figure 2: (Left panel) Reaction $dn \to {}^3\text{H}\,\eta$ with a low energetic spectator proton of the target deuteron. (Right panel) Reaction $nd \to {}^3\text{H}\,\eta$ with a fast spectator proton of the beam deuteron.

The reaction threshold is located at $p_d = 3.136\,\mathrm{GeV/c}$. Assuming a stationary neutron target, the beam momentum of 3.160 GeV/c corresponds to an excess energy of 5.7 MeV. In both cases the tritons are produced close to the forward direction and will be registered in the forward detector system. The same is true for the fast spectator proton of the beam. The slow spectator proton of the target will be measured using the solid state counters of the silicon tracking telescopes (STT).

In order to ensure quasi-free conditions, only events with proton momenta in the deuteron rest frame below about 130 MeV/c will be taken into account in the following estimations. The momenta and the kinetic energies of the spectator protons are shown in Fig. 3. The filled red area in Fig. 3 represents

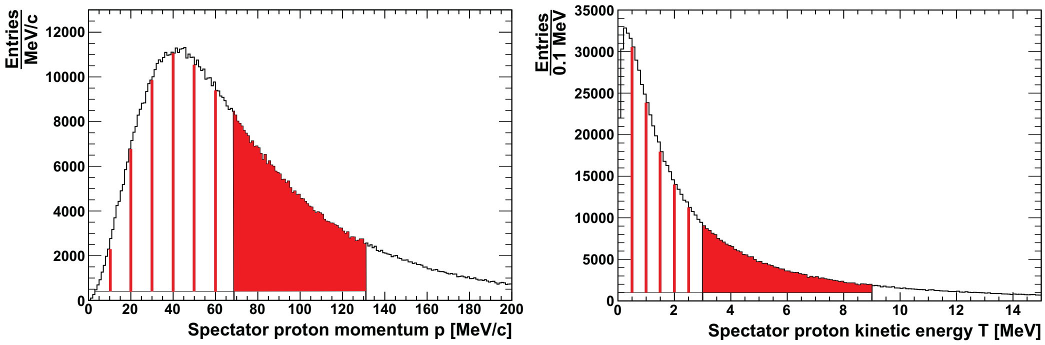

Figure 3: Momentum and kinetic energy of the generated spectator protons in the $dd \to {}^3\mathrm{H}\,\eta\,p_{\mathrm{sp}}$ reaction. The red filled area represents the spectator protons detected in the STT. The upper cut in the kinetic energy at 9 MeV is imposed to ensure the validity of the spectator picture, whereas the lower cut at 2.5 MeV is dictated by the design of the STT. The sum of red dashed and filled area represents the fast spectator protons which will be registered in the forward detector system.

the slow spectator protons detected in the STT from the $dn \to {}^3\mathrm{H}\,\eta$ reaction. The dashed red area added to the filled red area shows the fast spectator protons from the $nd \to {}^3\mathrm{H}\,\eta$ reaction detected in the forward system.

In the following two sections the two different situations will be discussed in more detail.

2.1 The $dn \to {}^3\mathrm{H}\,\eta$ reaction with slow spectator protons

The fusion of the beam deuteron and target neutron results in a fast triton and a slow spectator proton. The triton will have a momentum of about 2.5 GeV/c and will be registered in the ANKE forward detector system, consisting of one drift chamber, two multiwire proportional chambers, and three scintillation walls. The slow spectator proton will be measured at angles between $\vartheta \approx 45 - 90^\circ$ in the STT. By demanding a two-particle trigger, with two coincidence hits, one in the forward detector system and the other in the STT, the background can be suppressed dramatically.

The extraction of quasi-free η^3H production from the $dn \to {}^3\mathrm{H}\,\eta$ reaction requires, not only the identification of the low energetic spectator proton emitted from the deuterium target, but also the reconstruction of its three-momentum. This can be achieved if the particle is detected in two position sensitive detectors with sufficient energy resolution. As the spectator proton momentum distribution has a maximum in the vicinity of 50 MeV/c, the thickness of the first detector, which the protons have to pass through, should be chosen as small as possible. Each of the STT which will be used in this experiment consists of three double-sided segmented detectors.

- 1^{st} layer: 69 μm thick, 66x52 mm^2 active area, 151x121 number of strips with 400 μm strip pitch.
- 2^{nd} layer: 300 μm thick, identical geometry to 1^{st} layer.
- 3^{rd} layer: 5000 μm thick, 64x64 mm^2 active area, 96x96 number of strips with 666 μm strip pitch.

The STT planes will be located at 3, 5 and 6.4 cm from the target position and, by putting the STT so close to the target, an angular acceptance of up to 1 sr will be obtained. The orientation relative to the target can be adjusted such that different angular ranges for the detection of spectator protons are accessible, according to the experimental requirements.

Using the $\Delta E/E$-method for particle identification, the energy range of the setup is naturally divided into two subsets. The first is where particles penetrate through the 69 μm thick first layer and are stopped in the 300 μm thick second layer. This corresponds to proton kinetic energies of 2.5-6 MeV (see Fig. 3). Protons passing through the 300 μm second layer and being stopped in the 5 mm thick detector cover an energy range of 6.5-30 MeV. Figure 4 shows the energy loss in the first layer versus the energy loss in the second, under experimental conditions where only protons could be detected. The

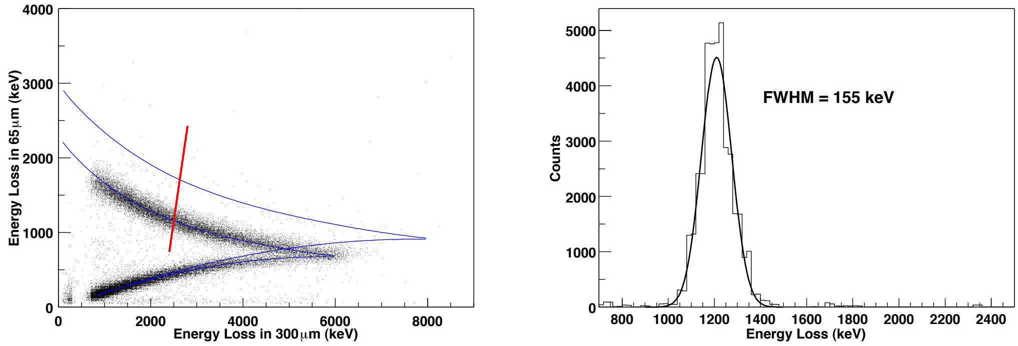

Figure 4: (Left panel) The energy loss in the first layer versus the energy loss in the second layer shows only the proton band. In addition to the experimental data, SRIM calculations for the energy losses of protons and deuterons are drawn. (Right panel) The projection on the indicated slice results in an energy resolution of about 160 keV FWHM [20].

energy resolution along the slice indicated in Fig. 4a is for this case about 160 keV FWHM, as shown in Fig. 4b). This means that the proton and deuteron bands are expected to be separated by about 10σ.

For the determination of the total cross section near threshold, the accepted excess energy ranges of the STT and forward detector system for the $dn \to {}^3\mathrm{H}\,\eta$ reaction is important. Monte-Carlo simulations with two coincidence hits, the spectator proton in the STT and the triton in the forward detector, show that a wide Q-region is covered. This is shown in Fig. 5a, where the acceptance is almost constant for Q in the range 0-50 MeV but

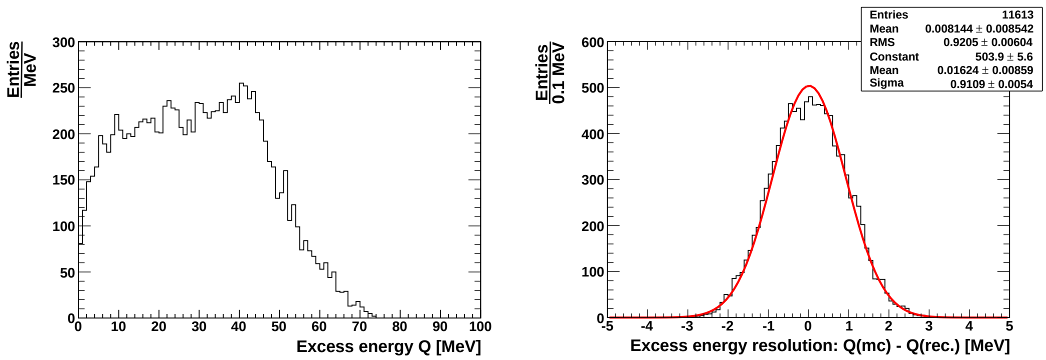

Figure 5: (Left panel) Excess energy range for accepted $dn \to {}^3\mathrm{H}\,\eta$ events, with a low energy spectator proton detected in the STT. (Right panel) The Q-value resolution given by the reconstruction of the four-momentum vector of the spectator proton detected in the STT.

then decreases up to 70 MeV. The uncertainty in the event-by-event excess energy determination depends on the four-momentum reconstruction of the spectator protons detected in the STT. Figure 5b shows the difference between the Monte-Carlo simulated Q-value and the reconstructed one. From this it is seen that an excess energy resolution of better than 1 MeV (σ) will be achievable. Depending on the statistics the measured excitation function could then be determined in bins of $\Delta Q = 1$ MeV. With this setup the whole triton angular range will be covered, so that also differential cross section studies are possible.

2.2 The $nd \to {}^3\mathrm{H}\,\eta$ reaction with fast spectator protons

In this case, both the triton and proton fly close to the forward direction with momenta around 1.5 GeV/c and are registered in the forward detector system. With this setup the whole triton angular range will also be covered. This reaction can be measured with a two-particle trigger, *i.e.* two coincident hits in each of the three scintillation walls. The accepted excess energy range, shown in Fig. 6a, has it maximum at roughly 0-2 MeV and decreases exponentially so that at $Q = 12$ MeV the acceptance has decreased by 50%. In contrast to the slow spectator situation, the excess energy resolution is much worse because of the lower precision of the four-momentum reconstruction at a momentum of 1.5-1.6 GeV/c. Figure 6b shows the difference between the Monte-Carlo simulated Q-value and the reconstructed one. From this it is clear that an excess energy resolution of 6.5 MeV (σ) could be achieved. With a kinematic fit this resolution could be improved further.

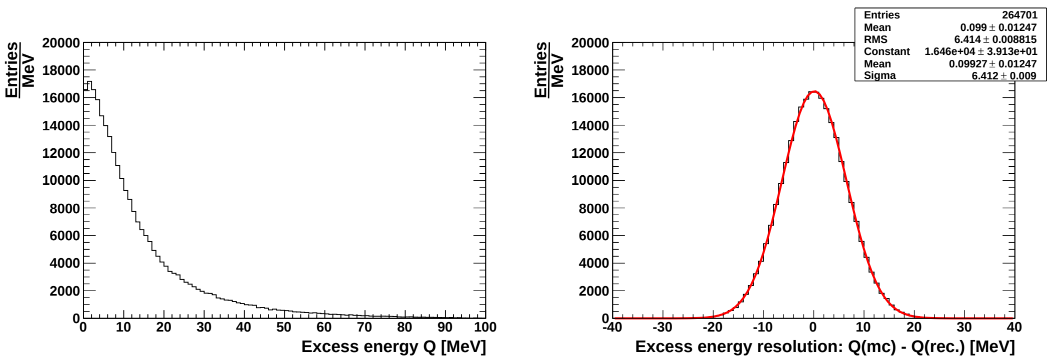

Figure 6: (Left panel) Excess energy range for accepted $nd \to {}^3\mathrm{H}\,\eta$ events with a fast spectator proton detected in the forward detector system. (Right panel) The resulting Q-value resolution.

3 Data normalization

In order to study the FSI, only knowledge of the relative behaviour of the total cross section near threshold is required. Naturally the total cross section is also of great interest and for that normalization is needed. However using the $dd \to {}^3\mathrm{H}\,\eta\,p_{\mathrm{sp}}$ reaction, *i.e.* using spectator physics, data over the whole excess energy range would be taken at same time and with the same luminosity. Therefore the normalization has no effect on the relative behaviour of the excitation function.

To determine absolute numbers for the total cross section, further reactions, such as

- quasi-free dp elastic scattering,
- dd elastic scattering,
- quasi-free $pp \to d\pi^+$,S

will be recorded.

4 Counting rate estimation and beam time request

We propose to study the reaction $dn \to {}^3\mathrm{H}\,\eta$ ($nd \to {}^3\mathrm{H}\,\eta$) near threshold at ANKE-COSY in order to complete our studies on the η-nucleus production and η-nucleus final state interaction. The focus of interest will be detailed studies on the close-to-threshold behaviour of the excitation function in order to extract precise information on the η^3H final state interaction. Therefore we want to study the reaction $dd \to {}^3\mathrm{H}\,\eta\,p_{\mathrm{sp}}$ at a deuteron beam momentum of 3.16 GeV/c to determine the total cross section in an excess energy range of 0-50 MeV.

The counting rate estimations were done by referring to experience from the earlier beam time used for the determination of the η-mass in the $dp \to {}^3\mathrm{He}\,\eta$ reaction at ANKE. Using a hydrogen cluster-jet target with a density of 10^{15} particles/cm^2 and a circulating deuteron beam with an intensity of 2×10^{10} particles, a luminosity of roughly 2.8×10^{31} cm^{-2}s^{-1} was reached. Under these conditions an effective counting rate of 80K η-events/day was obtained. By charge symmetry, the η^3H cross section should be the same as the η^3He cross section of 400 nb. However, for the $dd \to {}^3\mathrm{H}\,\eta\,p_{\mathrm{sp}}$ reaction a reduced cluster-jet target has to be considered, due to the operation with deuterium.

On the basis of these assumptions, and taking into account the results of the Monte-Carlo simulations, we expect for an excess energy range of 0-50 MeV for the $dn \rightarrow {}^3\mathrm{H}\,\eta$ reaction with slow spectator protons, a counting rate of 250 events/day. For the reaction $nd \rightarrow {}^3\mathrm{H}\,\eta$ with fast spectator protons, a counting rate of 4500 events/day should be achievable. In four weeks of beam time, 26 days of data-taking will allow us to collect in total roughly 123,500 η^3H events of which ∼6,500 events would be in the low spectator case and ∼117,000 events in the fast spectator case.

In total we ask for **four weeks** of beam time, including two days for beam preparation, installation of the STT and trigger adjustment.

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