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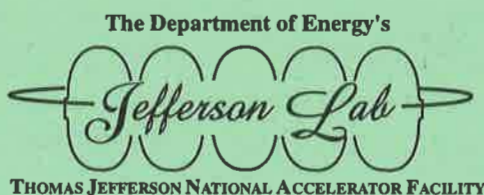
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Proceedings of the GW/JLab Workshop on N^* Physics

Edited by H. Haberzettl, C. Bennhold, and W. J. Briscoe

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October 30 – November 1, 1997



Program of the GW/JLab Workshop on N* Physics

Organizers: C. Bennhold, W. J. Briscoe, and L. Elouadrhiri

Thursday, 30 October, 1997

- 8:55 am C. Bennhold (GW)
Opening Remarks
- 9:00 am H. Haberzettl (GW)
Dynamical Resonance Formation
- 9:40 am P. Siegel (CSPU)
Dynamical Formation of the $S_{11}(1535)$ and the $\Lambda(1405)$
- 10:20 am Coffee
- 10:40 am T. Feuster (Giessen)
Photon and Meson Scattering on the Nucleon in a Coupled Channels Model
- 11:20 am S. Dytman (Pittsburgh)
Recent Progress in the Coupled Channels Cutkosky Analysis
- Noon Lunch
- 1:30 pm S. Krewald (Jülich)
The Jülich πN and (γ, π) Models
- 2:10 pm R. Workman (VPI)
Review of (γ, π) and the Delta $E2/M1$ Ratio
- 2:50 pm Coffee
- 3:10 pm J. Price (RPI)
New $p(e, e'p)\pi$ Results from JLab
- 3:25 pm C. Vellidis (ASU)
New $(e, e'\pi)$ Results from Bates
- 3:40 pm R. Davidson (RPI)
A Relativistic, Unitary Model for $(e, e'\pi)$
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- 4:40 pm Working groups meet

Friday, 31 October 1997

- 9:00 am E. Hourany (GRAAL)
New Results and Future Plans at GRAAL
- 9:30 am J. Price (RPI)
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- 10:00 am Coffee
- 10:30 am L. Tiator (Mainz)
Eta Photoproduction
- 11:00 am M. Benmerrouche (SAL)
Eta Electroproduction

Dynamical Formation of the $N^*(1535)$ and $\Lambda(1405)$

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Abstract

The octet-meson octet-baryon interaction is represented by a potential, which is iterated in a Lippman-Schwinger equation to obtain a multi-channel S matrix for two-body final states in the $l = 0$ partial wave. It is shown that a potential which has $SU(3)$ symmetry is able to explain a large amount of hadronic and photoproduction data, including the properties of the $\Lambda(1405)$ and $N^*(1535)$ resonances. In this picture, these resonances are a result of an attractive meson-baryon interaction and coupled-channel dynamics.

INTRODUCTION

In this talk, we discuss the interaction between the pseudo-scalar meson octet and the baryon octet. Our focus will be on the general features of the interaction, and the coupled-channel potential model approach. Although we summarize the results of using the effective chiral Lagrangian to obtain a potential for the interaction, the main points we want to emphasize are: a) the necessity for using a coupled-channel approach, b) the success of using approximate $SU(3)$ symmetry for the potential, and c) the fact that $SU(3)$ symmetric potentials produce at least two dynamically generated $l = 0$ resonances, the $\Lambda(1405)$ and the $N^*(1535)$. We first discuss the coupled-channel potential model approach, then the $SU(3)$ symmetry properties of the interaction, and conclude with an analysis of the experimental data. Our discussion here is restricted to the $l = 0$ partial wave.

COUPLED CHANNEL POTENTIAL MODEL CALCULATIONS

In a coupled channel potential model calculation, a potential is constructed to represent the interaction between the particles. We will be focusing our analysis on two-body initial and final states where the degrees of freedom are the meson-baryon states. The general form for such a potential is $V_{ijj'}(\sqrt{s}, k, k')$, where i and j correspond to the initial meson and baryon, and i' and j' represent the meson and baryon in the final state. The three momenta k and k' are the center of mass momentum of the initial and final states respectively, and \sqrt{s} is the total center-of-mass energy of the interaction. We abbreviate this potential as $V_{mm'}(\sqrt{s}, k, k')$, where m and m' represent the initial meson-baryon and final meson-baryon states.

The coupled channel potential $V_{mm'}$ which connects all possible initial meson-baryon states to all possible final meson-baryon states is inserted into a Lippman-Schwinger equation to solve for the T matrix for the partial wave $l = 0$:

$$T_{mm'}(\sqrt{s}, k, k') = V_{mm'}(\sqrt{s}, k, k') + \sum_n \int_0^\infty V_{mn}(\sqrt{s}, k, q) G_0(\sqrt{s}, q) T_{nm'}(\sqrt{s}, q, k') q^2 dq \quad (1)$$

Here, n represents an intermediate meson-baryon state, and the sum is over all such possible channels. For the propagator, G_0 , we choose $2\mu_n/(k_n^2 - q^2 + i\epsilon)$, where k_n is the on-shell momentum and μ_n is the reduced energy of the intermediate meson-baryon channel n . We find that if the energy range of the analysis is small, the results are not particularly sensitive to the choice of propagator.

One can include photoproduction or radiative capture processes to the calculation by adding a baryon-photon channel, and a potential which connects the baryon-gamma to the

meson-baryon channels. To a very good approximation one can neglect the rescattering of the photon with the baryon. This is the same approximation used in deriving “Watson’s Theorem”, and amounts to setting the propagator $G_{0(B\gamma)}$ in the baryon-gamma channels to zero. Another consequence of this approximation is that only the off-shell dependence of the hadronic side of $V_{n \rightarrow B\gamma}$ enters into the calculation.

It was shown in Ref. [1] that the amplitude for radiative capture is given by the sum over charged hadronic channels of the product of a complex number times the Born amplitude for that channel:

$$F_{K^-p \rightarrow \Lambda\gamma(\Sigma\gamma)} = \sum_n A_n(\sqrt{s}) f_{n \rightarrow \Lambda\gamma(\Sigma\gamma)}^{Born} \quad (2)$$

The sum n is over all possible intermediate meson-baryon channels. All the initial state interactions are subsumed into the complex numbers $A_n(\sqrt{s})$. In analyzing the radiative capture of K^-p , it was found [1] that the initial state hadronic interactions of the various channels was very important. This result emphasizes the importance of a coupled channels approach to radiative capture and photoproduction processes.

There are some positive (+) and negative (−) aspects in using the coupled channel potential approach described above:

- (+) One obtains a coupled-channel S matrix which is unitary. Since transitions to 3-body final states are small, using only two-body final states is a good approximation. So unitarity is satisfied to a very good degree.
- (−) Complete four-dimensional loop integrals are not done in the iteration process. Only three dimensional iterations over the center of mass momentum are carried out via the Lippman-Schwinger equation. That is, only ladder graphs are included in the multiple scattering. Even though the potential can have crossing symmetry, after iteration, the S-matrix will not.
- (+) However, if the energy range of the coupled channel potential analysis is small, the energy dependence of the S-matrix will be approximated well. Also, if a resonance dominates the interaction, the main energy dependence comes from the pole, and the deficiencies mentioned in b) above are minimal. We note that for the low energy K^-p interaction, potentials which satisfy $SU(3)$ symmetry give very similar results even though different off-shell forms and propagators were used.

WHAT IS DYNAMICAL RESONANCE FORMATION

Dynamical resonance formation means that the resonance is formed as a quasi-bound state due to the attractive nature of the interaction. In other words, there is no pole in the potential $V_{mm'}(\sqrt{s}, k, k')$, but the multiple scattering produces a pole in the T or S matrix of the coupled-channel system. This is to be differentiated from an “s-channel” resonance in which there is a pole in the potential V itself. In this case the pole in the potential V produces a pole, which is shifted in energy, in the S-matrix.

One would like to determine if a resonance is dynamically generated, or is a result of a pole in the potential matrix, directly from the data in a model independent manner. This is not easy, if possible at all, so we look at the physics of the interaction in the next section to help us determine the nature of various s-wave resonances.

THE PHYSICS OF THE POTENTIAL

One of the first coupled-channels calculation involving the pseudo-scalar mesons and baryons dates back to the late 1960's by Dalitz, Wong and Rajasekaran [2]. Here, a vector-meson exchange potential with $SU(3)$ universal coupling is applied to the strangeness -1 sector. Using known coupling strengths, a resonance ($\Lambda(1405)$) is produced just below the K^-p threshold. The potential was taken to be a Yukawa form:

$$V_{mm'} = C_{mm'} \frac{e^{-\mu r}}{r} \quad (3)$$

where the $C_{mm'} = C_{ii' \rightarrow jj'} = \sum f_{ijk} f_{ki'j'}$, and f_{ijk} are the $SU(3)$ structure constants.

In a more recent calculation, chiral $SU(3)_L \times SU(3)_R$ symmetry was incorporated in the Lagrangian of the cloudy bag model [3], which was applied to the low energy K^-p system. Excellent fits to the low energy K^-p scattering data and the $\Lambda(1405)$ resonance were obtained. The successes of $SU(3)$ symmetry in the meson-baryon potential led us [4] to investigate to what extent all the low energy K^-p data, including the threshold branching ratios, could be fit. The threshold branching ratios of the K^-p atom decay are precise data and put constraints on any potential model. We found that all the low energy K^-p data could be fit with only a 30 percent variation of the relative coupling strengths from their $SU(3)$ values. It was also shown [5-7] that all the low energy hadronic K^-p data as well as $\pi\eta$ production and some photoproduction data can be fit from a potential derived from an effective chiral Lagrangian, which has approximate $SU(3)$ symmetry. In a recent preprint [8] it was found that all the low energy hadronic K^-p data, including the threshold branching ratios, could be fit without any $SU(3)$ symmetry breaking if one included the $\eta\Lambda$ and $\eta\Sigma^0$ channels.

Good fits were obtained in the above calculations even though different off-shell potential forms and different propagators were used: *the critical ingredient in fitting the low energy K^-p data is to have approximate $SU(3)$ relative coupling strengths in the potentials.* This same result holds in low energy πN scattering, where the leading order, Weinberg-Tomozawa, term in a chiral perturbation expansion has this same symmetry. Therefore, **there is substantial evidence to believe that $SU(3)$ relative coupling strengths hold to a good approximation for the whole meson-baryon octet.**

Let's examine the sectors of the meson-baryon interaction where the $SU(3)$ relative coupling strengths might be sufficiently attractive to form a dynamical resonance:

- **Strangeness = -1:** There is a strong attraction for isospin $I=0$. The constants $C_{mm'}$ are

	$\pi\Sigma$	$\bar{K}N$	$\eta\Lambda$
$\pi\Sigma$	-2	$-\sqrt{6}/4$	$-3\sqrt{2}/4$
$\bar{K}N$	$-\sqrt{6}/4$	-3/2	0
$\eta\Lambda$	$-3\sqrt{2}/4$	0	0

The attraction is in both the $\pi\Sigma$ and $\bar{K}N$ channels. Using expected strengths and ranges for the potential a resonance is formed just below the $\bar{K}N$ threshold [5]. This resonance has all the properties of the $\Lambda(1405)$!

- **Strangeness = 0:** For isospin $I=1/2$ there is an attractive interaction for both $\pi N \rightarrow \pi N$ and $K\Sigma \rightarrow K\Sigma$ scattering. The $C_{mm'}$ are:

	πN	ηN	$K\Lambda$	$K\Sigma$
πN	-1	0	3/4	-1/4
ηN	0	0	3/4	3/4
$K\Lambda$	3/4	3/4	0	0
$K\Sigma$	-1/4	3/4	0	-1

There are several important features to note. The interaction between the kaon and the sigma is strongly attractive. This attraction can be enhanced due to the large mass of the kaon. Although there is a no direct interaction between the ηN and the πN channels, there is a strong coupling of both the ηN and the πN channels to the $K\Sigma$ channel. For expected strengths and ranges, *a quasi-bound $K^+\Sigma$ resonance is formed, and it strongly connects the πN and ηN channels via multiple scattering.* The properties of this resonance are very similar to the $N^*(1535)$!

• **Strangeness = -2:** In the isospin 1/2 sector, there is attraction between the Ξ and π as well as the \bar{K} and Sigma. The $C_{mm'}$ are given by:

	$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$
$\pi\Xi$	-1	$\sqrt{3}/8$	-5/4	0
$\bar{K}\Lambda$	$\sqrt{3}/8$	0	0	3/4
$\bar{K}\Sigma$	-5/4	0	-1	$\sqrt{3}/4$
$\eta\Xi$	0	3/4	$\sqrt{3}/4$	0

The attraction between the Ξ and π and the Σ and \bar{K} might be strong enough to form a dynamical resonance. There are two candidates for this resonance, the $\Xi(1609)$ and the $\Xi(1690)$. We are at present examining the properties this system in order to determine whether a resonance is dynamically formed, and if so, which Ξ resonance fits its properties best.

COMPARISON WITH AVAILABLE DATA

The most extensive data to check the baryon-meson coupled channel approach is in the $S = -1$ sector near the K^-p threshold. Here there is a *wealth of data in a small energy range*: the K^-p reaction can scatter into six final states: K^-p , $\bar{K}^0 n$, $\pi^+\Sigma^-$, $\pi^0\Sigma^0$, $\pi^-\Sigma^+$, and $\pi^0\Lambda$. Data have been taken for all scattering final states for K^- laboratory momenta from 60 to 200 MeV/c. At threshold, there are very precise branching ratio data of the K^- proton atomic decay to the three hadronic final state as well as the two radiative capture transitions. In addition, there is a resonance, the $\Lambda(1405)$ just below the K^-p threshold for which there are $\Sigma - \pi$ spectrum measurements. These data have two important features: they contain information about the relative coupling to the various channels, and they are in a narrow energy range $1400 < \sqrt{s} < 1460$. The first feature places stringent tests on any model describing the octet meson-baryon interaction. The second feature reduces the model dependence of the analysis.

Effective Chiral Lagrangian Approach

Next, we summarize the results of a coupled channel potential derived from the $SU(3)$ effective chiral Lagrangian. Details of the work are described in Refs. [5-7]. The potential (or pseudo-potential) is constructed such that in the Born approximation it has the same s-wave scattering amplitude as the effective chiral Lagrangian, at order q^2 .

The motivation for using this approach are two-fold. First, $SU(3)_L \times SU(3)_R$ chiral symmetry is believed to be approximately valid for meson-baryon interactions. To leading order in

meson momenta “ q ” the potential has the $SU(3)$ relative coupling strengths, $C_{mm'}$. There is slight breaking however, since the mass of the meson enters in the numerator. Second, $SU(3)$ symmetry breaking can be treated systematically. At next order in the expansion scheme, q^2 , there are a finite number of new terms allowed by chiral symmetry [9]. Once these terms are fixed, the relative coupling strengths for the whole octet-meson octet-baryon interaction is determined. This allows one to use “physics” to guide the $SU(3)$ symmetry breaking.

Our initial approach was to use the low energy K^-p data to determine the unknown coefficients in the “ q^2 ” terms of the effective chiral Lagrangian. Once this was done, all the Lagrangian parameters (i.e. potential strengths for all channels) are fixed. We then examined other sectors, where the data was not as precise, to determine if resonances are formed and if so, their properties.

There are no free Lagrangian parameters for the order “ q ” terms, and six free parameters for the order “ q^2 ” terms. Using data from the πN , K^+N scattering lengths, and the $\sigma_{\pi N}$ term reduces the number of free Lagrangian parameters to 3. In addition to the Lagrangian (potential strengths) parameters, a limited number of off-shell range parameters enter the calculation as well. We found that a satisfactory fit for all the low energy K^-p hadronic data was obtained by using a local potential with one common off-shell range for all the channels. This is not a trivial exercise, since the data have a diverse $SU(3)$ structure and the threshold branching ratios are accurately measured.

There are two interesting results of the analysis. The first is that a fit for the local potential was found using a Yukawa potential with only one common “exchange mass” of 412 MeV for all channels. This value lies between the mass of a vector meson and that of two pions. Since such t-channel exchanges are believed to dominate the interaction, this mass is in line with the physics of the process. The second is that we also found a fit using a separable potential, and the Lagrangian parameters for this fit were very similar to those using the local potential. As mentioned above, this is probably because the energy range of the data is small.

Using the same potential parameters as determined from the K^-p analysis, we examined πN scattering near the ηN threshold [6]. As discussed in Ref. [6], excellent agreement was obtained in describing the $\pi N \rightarrow \eta N$ total cross section, and the resonance properties of the $N^*(1535)$.

Recently [7], this analysis was extended to include the photoproduction reactions $\gamma p \rightarrow \eta p$, $\gamma n \rightarrow \eta n$, $\gamma p \rightarrow K^+\Lambda$, $\gamma p \rightarrow K^+\Sigma^0$, and $\gamma p \rightarrow K^0\Sigma^+$. Also, the analysis was extended up in energy to compare with $\pi^-p \rightarrow K^0\Lambda$, $\pi^-p \rightarrow K^0\Sigma^0$, $\pi^-p \rightarrow K^+\Sigma^-$ and $\pi^+p \rightarrow K^+\Sigma^+$ total cross section data. No new potential parameters are needed for the photoproduction channels, since the Born terms, and hence the potential strengths are determined from the effective chiral Lagrangian. *The agreement with the data is remarkable!!*

DETERMINING RESONANCE PARAMETERS FROM THE DATA

There has been some discussion at this workshop regarding the extraction of the mass of a resonance, its width, and the decay branching ratios from the scattering data. Problems arise due to the relatively large width of the resonance compared to its mass. Complications can also occur if the resonance is close to a threshold as in the $N^*(1535)$ case. Often Breit-Wigner forms are used in the parameterization of the data, with the hope that the parameters used in this Breit-Wigner piece correspond to the parameters of the resonance. However, the treatment of the non-resonant background can influence these parameters, and the analysis becomes model dependent.

A possible way to overcome these difficulties is to consider the energy dependence of the full coupled-channel S-matrix on the real axis. The eigenvalues of the S-matrix have modulus 1, and can be expressed in terms of eigenphases δ as $e^{2i\delta}$. Near a resonance, one of the eigenphases, δ_{res} , passes through 90 degrees. For a finite energy range near the resonance, the energy dependence of this eigenphase will follow a Breit-Wigner form:

$$\tan(\delta_{res}) = \frac{\Gamma(\sqrt{s})}{2(M^* - \sqrt{s})}. \quad (4)$$

By fitting the eigenphase to this form, the appropriate resonance parameters can be determined. This is a procedure that can be carried out for any analysis for which a coupled-channel S-matrix can be computed, and is an unambiguous method to compare resonance parameters. In particular, for the $N^*(1535)$ this procedure works well.

Consider the $N^*(1535)$ resonance, where there are two main hadronic channels and consequently two eigenphases. In our analysis the resonant eigenphase has a Breit-Wigner energy dependence $\tan(\delta_{res}) = (k_1\gamma_1 + k_2\gamma_2)/(2(M^* - \sqrt{s}))$ over an energy range of 100 MeV. In Fig. 1 we plot the two eigenphases, resonant and non-resonant, as a function of energy from Ref. [6]. The curve is the best fit Breit-Wigner shape to the resonant eigenphase with parameters $\gamma_1 = 0.26$, $\gamma_2 = 0.25$, and $M^* = 1557$ MeV. We note that even though in our case the resonance was formed dynamically, without an explicit s-channel resonance in the potential, a pole is produced in the S-matrix with the energy dependence of a typical Breit-Wigner resonance.

Fig. 1 shows that the eigenphase passes through 90 degrees at $\sqrt{s} = 1557$ MeV. However, as the energy is increased, the phase shift increases to around 120 degrees at the $K\Lambda$ threshold, and then starts to decrease [7]. For a “clean” resonance, the phase shift should continue through 180 degrees, as is the case for the $\Lambda(1405)$. So, although resonance parameters can be extracted from the eigenphase, the true status of this resonance might need to be re-examined.

Fig. 1 also shows that the background eigenphase makes up a small but significant part of the interaction. The effect of the background can be quantified in a fairly model independent way. Consider the ratio

$$R = \frac{k_1\gamma_1\sigma_{12}}{k_2\gamma_2\sigma_{11}}. \quad (5)$$

For a pure Breit-Wigner resonance this ratio is exactly one, and any deviation from unity is due to the background. The momentum in the center of mass of channel 1 and 2 are k_1 and k_2 , and the other parameters are determined from the scattering data. σ_{11} is obtained from a phase-shift analysis of πN scattering, and is the isospin $I = 1/2$, $l = 0$ cross section for $\pi N \rightarrow \pi N$. σ_{12} can be obtained directly from the $\pi N \rightarrow \eta N$ total cross section, since this cross section is predominantly $l = 0$. The partial widths γ_1 and γ_2 are determined from the resonant eigenphase. In Fig. 2 we plot R , where the triangles are for the phase shift analysis of Ref. [10] and the circles for the phase shift analysis of Ref. [11]. The solid line is R_{BW} from our analysis [6]. These results suggest that there is a significant background for the $N^*(1535)$ resonance.

In conclusion we see that due to the strong interaction of the meson-baryon system, a coupled-channel analysis is necessary in any quantitative analysis. We also discussed different potential models that have been applied to the K^-p interaction at low energy. Although these potential models used different off-shell extensions or cut-off procedures, and used different propagators, the results were similar. The similarity is due to the use of SU(3) symmetry

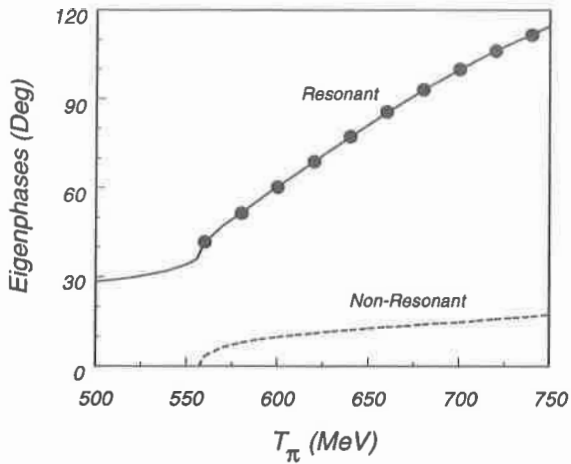


Figure 1. A plot of both the resonant and non-resonant eigenphases for πN , ηN coupled channel system as a function of pion laboratory kinetic energy. There are two other channels included in the calculation, $K\Lambda$ and $K\Sigma$, but they are virtual since the energy is below their threshold. The solid line is a fit to a pure Breit-Wigner form.

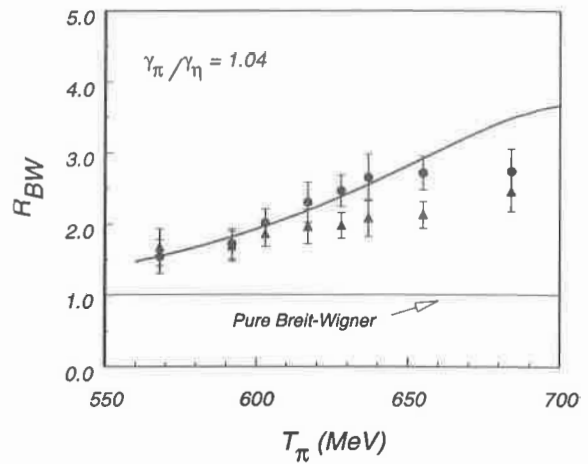


Figure 2. The parameter R_{BW} as defined in Eq. 5 is plotted vs. pion laboratory kinetic energy. The circles (triangles) correspond to using the phase shift analysis of Ref. [11] (Ref. [10]) for the $\pi N \rightarrow \pi N$ $l = 0$ cross section.

in the potentials. It was also shown that potentials based on $SU(3)$ symmetry reproduce the hadronic properties of the $\Lambda(1405)$ and $N^*(1535)$ as well as various photoproduction and hadronic data. Thus we conclude that $SU(3)$ symmetry is a good approximation for the potentials representing the interaction between the octet mesons and baryons. These facts strongly suggest that the $\Lambda(1405)$ and the $N^*(1535)$ are dynamically generated resonances.

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