Study of ^{14}N by the Reaction ^{13}C(^{3}He,d)^{14}N†

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A thin carbon foil enriched to 91% in ^{13}C was bombarded with 15-MeV ^{3}He ions from a tandem electrostatic accelerator. Angular distributions of deuterons corresponding to the bound states of ^{14}N were measured with a single-gap magnetic spectrograph. Distorted-wave calculations were performed and spectroscopic factors were extracted. Agreement with the predictions of intermediate-coupling theory is very good, indicating that this theory provides a good description of states arising from p-shell configurations.

INTRODUCTION

THE considerable data on transition probabilities and multipolarities of gamma rays emitted in the decay of ^{14}N have been analyzed and reviewed by Warburton and Pinkston.[1] Their work has been supplemented by further studies of ^{14}N based chiefly on the analysis of decay γ rays[2–5] and at the present time the spins and parities of most of the levels up to 10-MeV excitation are established.

The existence of detailed experimental information has made ^{14}N a particularly convenient nucleus for theoretical study.[6–11] True[12] has analyzed states arising from the p^{-2}, $p^{-3}(2s,1d)$, and $p^{-4}(2s,1d)^2$ configurations. In order to do this he treats ^{14}N as two nucleons outside a closed ^{12}C core ($p_{3/2}{}^8$). As True notes, such a simplification means that states thought to arise from excitation of the $p_{3/2}{}^8$ core, such as those at 3.945-MeV and 7.03-MeV excitation, will not be predicted by this model.

Kurath and others have calculated the wave functions of the positive-parity states arising from the p-shell configurations using the intermediate-coupling model. This model accounts for the well known fact that ^{12}C does not have a closed $p_{3/2}$ subshell.[1,9,10] The calculations predict the existence of states with configurations containing a hole in the $p_{3/2}$ orbital which True could not predict.

More recently, Sebe[13] has used the approach of Lane[14] to calculate wave functions for the negative-parity states of ^{14}N. He treats ^{14}N as a single nucleon in a shell-model orbital plus the ground or second excited state of ^{13}C (the first excited state of ^{13}C is of positive parity and, hence, is not used). This technique successfully accounts for the energies and other properties of many of these states.

Although a great deal has been learned by analysis of γ-ray studies, until recently the lack of suitable bombarding particles of appropriate energies has made it difficult to study ^{14}N by nuclear reactions. However, because of recent technical advances, ^{14}N can now be studied conveniently by reactions such as ^{13}C(^{3}He,d)^{14}N, ^{12}C(^{3}He,p)^{14}N, and ^{15}N(^{3}He,α)^{14}N at energies at which the reactions are expected to proceed directly.

Of the three reactions mentioned, ^{13}C(^{3}He,d)^{14}N is expected to be especially useful. It proceeds by transfer of a single nucleon under kinematic conditions which are expected to make it easy to identify l values and to extract spectroscopic factors by distorted-wave Born-approximation (DWBA) analysis. For these reasons a study of the ^{13}C(^{3}He,d) reaction has been made and the results are reported in the present paper.

EXPERIMENT AND RESULTS

The target was a self-supporting foil of carbon, enriched to 91% in ^{13}C, made by cracking methyl iodide onto a thin nickel foil and then dissolving away the nickel. The target was determined to be 40 ± 10 μg/cm^2 by direct weighing.

The target was bombarded with 15-MeV ^{3}He ions from a tandem accelerator. The emitted deuterons were magnetically analyzed in a 65-cm-radius Browne-Buechner broad-range spectrograph and recorded on Ilford K2 nuclear emulsion plates. Exposures were made at 15 emission angles in the range 5° to 85°. The incident beam was collected in a Faraday cup and the total charge per exposure (100 μC at the small angles and 250 μC at the larger ones) was measured.

A typical deuteron spectrum is shown in Fig. 1. The deuteron groups are labeled with the excitation energies corresponding to the states in ^{14}N beginning with the first excited state. In this exposure the magnetic field was such that the deuterons corresponding to the ground state did not strike the nuclear emulsions. Peaks arising from impurities are labeled with the chemical symbol of the corresponding residual nucleus with a subscript indicating the excited state.

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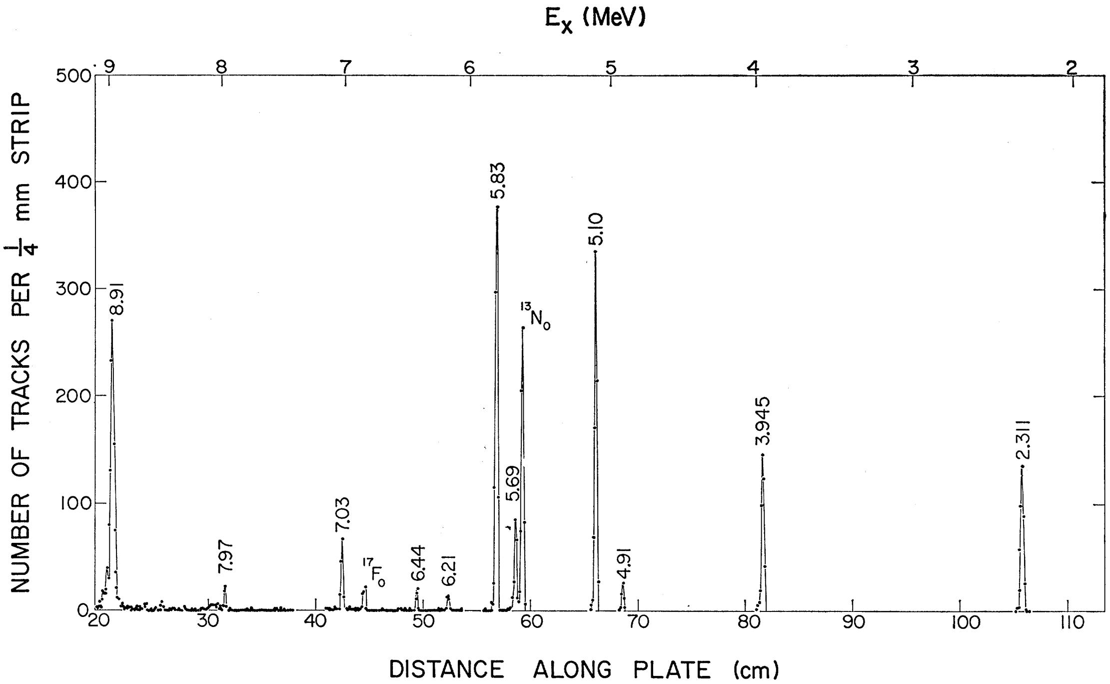

FIG. 1. A deuteron spectrum from the $^{13}C(^3He,d)^{14}N$ reaction taken at an incident energy of 15 MeV and at an angle of 15° relative to the incident beam. The groups are labeled with the corresponding excitation energy in ^{14}N. The ground state is not shown. Two groups arising from ^{16}O and ^{12}C contaminants are labeled $^{17}F_0$ and $^{13}N_0$ to indicate they correspond to the ground states of these nuclei.

Angular distributions of deuterons leading to most of the bound states of ^{14}N are shown in Fig. 2. In order to make comparison easier the angular distributions have been grouped according to the l value best characterizing them. The points are experimental data while the solid lines are angular distributions calculated by the DWBA method using the code JULIE.

The optical-model potential used in the fits is the one described by Kellogg.[15] The symbols, names and values of the various parameters used in this potential are given in Table I. The parameters of the entrance channel were obtained from Kellogg and Zurmühle's[15] optical-model fits to their data on the elastic scattering of 15-MeV ^3He on ^{13}C. For the exit channel the parameters used were those obtained by Satchler *et al.*[16] from studies of the elastic scattering of 15-MeV deuterons on ^{18}O.

The spectroscopic factors were extracted from the DWBA fits using the relation

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{expt}} = \frac{2J_f+1}{2J_i+1} NC^2\sigma_J(l,\Theta,Q)S,$$

where S is the spectroscopic factor, σ_J is the cross section obtained from JULIE, C^2 is a factor taking into account isotopic spin and the symmetry of the wave function. It equals $\frac{1}{2}$ for all ^{14}N states except those which arise from j^2 configurations. The constant N, which was taken equal to 4.0, represents the overlap of the ^3He and deuteron wave functions in the nucleus; J_i and J_f are the spins of the target and residual nuclei, respectively; $(d\sigma/d\Omega)_{\text{expt}}$ is the measured value of the differential cross section.

TABLE I. Optical-model parameters used in the DWBA analysis of the $^{13}C(^3He,d)^{14}N$ reaction.

Parameter	Particle energy E_0 (MeV)	Real well V (MeV)	Imaginary well W (MeV)	Real well radius $\times A^{-1/3}$ r_0 (F)	Diffusivity a (F)	Imaginary radius $\times A^{-1/3}$ r_g (F)	Imaginary well diffusivity b (F)	Coulomb radius $\times A^{-1/3}$ r_c (F)	Spin-orbit potential V_{so} (MeV)	Surface absorption well $4W_d$ (MeV)
Values for He^3 (ingoing)	15	158	6.75	0.93	0.81	2.25	0.65	1.4	6	···
Values for d (outgoing)	18	86.3	···	1.105	0.9385	1.608	0.598	1.3	···	39.7

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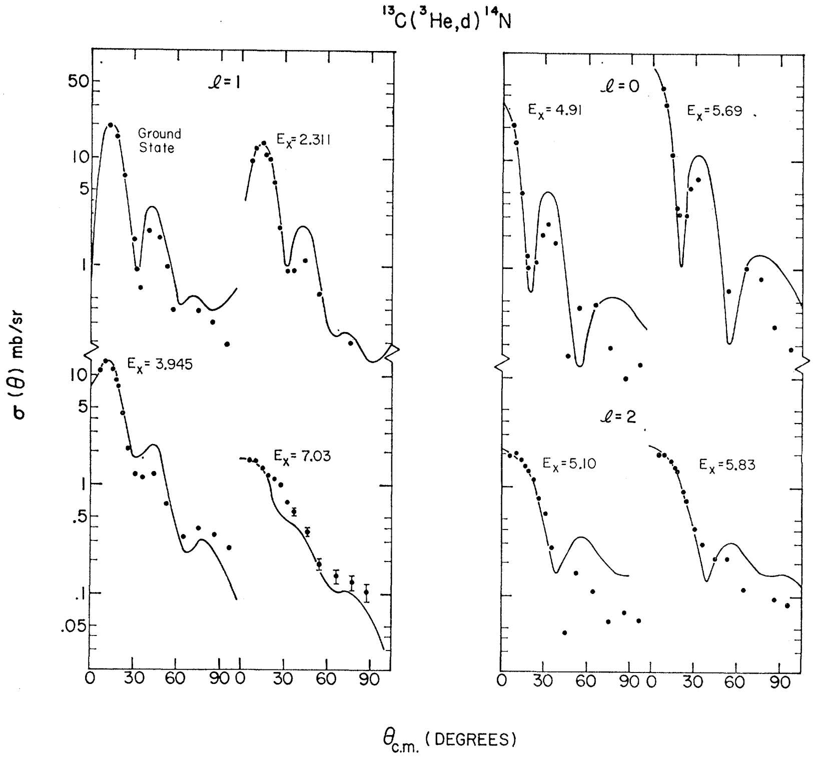

FIG. 2. Angular distributions of groups corresponding to all the bound states of ^{14}N except the 6.21- and 6.44-MeV states. The points are experimental data; the solid lines are calculated from distorted-wave theory using the code JULIE.

The spectroscopic factors obtained from the present data have been normalized to a value of $S=1$ for the transition to the 4.91-MeV state. This choice was suggested by the relatively simple configuration of the state. It has been assumed to have spin and parity of 0^- and seems to be formed by the coupling of an $s_{1/2}$ proton to the ^{13}C, $\frac{1}{2}^-$ ground state. Consequently, one expects complete overlap between the target and final nucleus implying $S=1$. This simple physical argument is supported by the calculations of True[12] and Sebe[13] which also predict $S=1$. The normalized spectroscopic factors have an uncertainty of $\pm10\%$ arising from uncertainties in the fitting procedures.

Spectroscopic factors were also calculated directly from the absolute cross sections without any normalization. However, these values are not accurate to better than $\pm25\%$ because of uncertainties in target thickness. Nevertheless, it is gratifying to note that the unnormalized spectroscopic factors were only 25% higher than the normalized ones listed in Table II.

TABLE II. Spectroscopic characteristics of the bound states of ^{14}N.

E_x (MeV)	J^π	Configuration	l	Θ_{max} c.m., (degrees)	$(d\sigma/d\Omega)_{max}$ (mb/sr)	S_{expt}	S_{theor}
0	1^+	$p_{1/2}^{-2}$	1	10	19	1.07	1.39[a]
2.331	0^+	$p_{1/2}^{-2}$	1	10	14	1.64	1.73[a]
3.945	1^+	$p_{3/2}^{-1}p_{1/2}^{-1}$	1	10	14	0.42	0.40[a]
4.91	0^-	$p_{1/2}s_{1/2}$	0	0	12[b]	1.00	0.99[c]
5.10	2^-	$p_{1/2}d_{5/2}$	2	0	20[b]	0.83	0.94[c]
5.69	1^-	$p_{1/2}s_{1/2}$	0	0	24[b]	0.91	0.8[c]
5.83	3^-	$p_{1/2}d_{5/2}$	2	0	20[b]	0.55	0.8[c]
6.21	1^+	$s_{1/2}^2+d_{5/2}^2$	1	0	0.4[b]	$\sim$0.03	...
6.44	3^+	$d_{5/2}^2+s_{1/2}d_{5/2}$	1	0	0.6[b]	$\sim$0.04	...
7.03	2^+	$p_{3/2}^{-1}p_{1/2}^{-1}$	1	0	2.5[b]	0.13	0.13[a]

[a] Kurath, Ref. 9. [b] Cross section at 10° c.m. [c] Sebe, Ref. 13.

Table II presents the excitation energies, l values of transitions, peak differential cross sections and the normalized spectroscopic factors. Previously determined spins and parities, principal shell-model configurations, and theoretically calculated spectroscopic factors are also given.

DISCUSSION

Ground state. In terms of the simple shell model the 1^+ ground state arises in large part from the coupling of a $p_{1/2}$ neutron with a $p_{1/2}$ proton outside a ^{12}C core. In the same way ^{13}C can be thought of as a $p_{1/2}$ neutron outside the same core. Consequently, transition to the ground state of ^{14}N by proton stripping should proceed by $l=1$. It is apparent from the excellent fit of the ground-state data by the DWBA curve that this is an $l=1$ transition.

If the configuration of the ^{14}N ground state were pure $p_{1/2}^{-2}$ and that of the ^{13}C ground state were pure $p_{1/2}$, the spectroscopic factor for this transition would be $S=2$. However, the experimental value is $S=1.07$ in severe disagreement with the simple shell model picture. The disagreement is not surprising since the intermediate-coupling calculations of Kurath and the experimental data discussed by Warburton clearly indicate that neither ^{13}C nor ^{14}N can be represented by pure shell-model configurations. Kurath's calculations introduce into ^{14}N components of the configuration $p_{3/2}^{-1}p_{1/2}^{-1}$ and $p_{3/2}^{-2}$. For such a wave function, Kurath[9] predicts $S=1.39$ which is in somewhat better agreement with experiment.

2.311-MeV state. The first excited state of ^{14}N has J^π equal to 0^+. This also is to be expected on the basis of a simple shell-model picture. The $p_{1/2}^{-2}$ configuration mentioned in the discussion of the 1^+ ground state should also give rise to a 0^+ state. The $l=1$ transition shown in Fig. 2 supports this view. As before, $S=2$ is predicted from the pure jj shell model, but Kurath predicts $S=1.73$ for transitions to this state. The measured value of $S=1.64$ is in satisfactory agreement with this prediction.

3.945-MeV state. The presence of components of different configurations in the ground state of ^{14}N implies the existence of an additional 1^+ state orthogonal to the ground state. It is expected to contain a large component of $p_{3/2}^{-1}p_{1/2}^{-1}$ and a smaller component of $p_{1/2}^{-2}$. The 3.945-MeV state has the proper spin and parity and exhibits an enhanced γ-ray transition probability implying it contains some core excitation.[1] This state is not predicted by True's pure shell-model calculation,[12] and therefore, he also attributes it to core excitation.

If the state does arise from a mixture of $p_{3/2}^{-1}p_{1/2}^{-1}$, $p_{3/2}^{-2}$ and $p_{1/2}^{-2}$ configurations, it is expected to be excited by an $l=1$ transition. Figure 2 shows that this is the case. In addition it is expected that the spectroscopic factor for this state should be somewhat less than for the ground state. The measured S is 0.42, in excellent agreement with Kurath's predicted value of 0.40.

4.91-MeV state. This level has been described by True[12] as arising from the $p_{1/2}s_{1/2}$ shell-model configuration. This configuration is consistent with the suggested spin[1] and parity of 0^-. To reach this level from ^{13}C by stripping requires only the addition of a proton to the $2s$ orbital, an $l=0$ transition. In fact, this is the l value assigned to the transition on the basis of the fit shown in Fig. 2 so that the configuration assignment seems substantially confirmed. The consistency among the spectroscopic values also strongly supports the J^π assignment of 0^- to this state.

5.10-MeV state. The 2^- spin and parity of this state indicate it may well arise from a $p_{1/2}d_{5/2}$ configuration. The $l=2$ angular distribution measured for this state and shown in Fig. 2 strongly supports this assignment. Again the spectroscopic factors expected on the basis of Sebe's calculations ($S=0.94$) and True's calculations ($S=0.97$) are almost the same. The experimentally measured spectroscopic factor $S=0.83$ agrees satisfactorily with both theoretical values.

5.69-MeV state. The configuration $p_{1/2}s_{1/2}$ should give rise to a 1^- state as well as the 0^- state seen at 4.91 MeV. The level at 5.69-MeV excitation has been assigned J^π equal to 1^- on the basis of γ-ray studies,[1] and in the present study the transition was found to proceed by $l=0$ as can be seen in Fig. 2. Therefore, there is little doubt that in terms of the simple shell model this state has a configuration $p_{1/2}s_{1/2}$. This view seems to be supported by comparison of the experimentally measured spectroscopic factor with that calculated from True's shell-model wave functions. Theoretically, he predicts $S=0.98$ and experimentally S is found to be 0.91. Sebe's calculation predicts S to be 0.8. However, in view of the 10% uncertainty in the values of S, it is impossible to choose between the two theoretical values on experimental grounds.

5.83-MeV state. Like the $p_{1/2}s_{1/2}$ configuration the $p_{1/2}d_{5/2}$ configuration should give rise to two states. The 2^- state has already been determined to be the 5.10-MeV state; the other state should be 3^- and should lie nearby in energy. Gamma-ray studies have led to a reliable assignment of 3^- to the 5.83-MeV state and, as Fig. 2 shows, the state is excited by an $l=2$ transition in the ^{13}C(^{3}He,d)^{14}N reaction. Thus it seems certain this state arises from the addition of a $d_{5/2}$ proton to the $p_{1/2}$ ground state of ^{13}C.

In Sebe's calculations of the wave function of this state he finds that, in addition to the ^{13}C ground state, there is an appreciable component of the 3.68-MeV state of ^{13}C coupling with a $d_{5/2}$ proton. Consequently, the parentage of the 5.83-MeV state is not pure and the spectroscopic factor is $S=0.8$. On the other hand, True's calculation makes no such distinction and on the basis of his approach to the problem S is expected to be 1. The experimental value $S=0.55$ is in closer agreement with Sebe's results and indicates the presence of a substantial admixture of the 3.68-MeV state of ^{13}C in the 5.83-MeV state of ^{14}N.

6.21- and 6.44-MeV levels. These states are well known to have positive parity and spins of 1 and 3, respectively.[3,4] They are weakly excited in the ^{13}C(^{3}He,d)^{14}N reaction, but are very strongly excited in the ^{12}C(^{3}He,p)^{14}N reaction[17] indicating that these states arise from two particle excitations outside the ^{12}C core. The configurations are probably $s_{1/2}^2$ and $d_{5/2}^2+s_{1/2}d_{5/2}$ for the 1^+ and 3^+ states, respectively. The calculations of True[12] and analysis of other data by Warburton and Pinkston[1] support these assumptions.

Because the transitions are weak in intensity and the angular distributions rather lacking in structure, DWBA fits are ambiguous. However, the positive parity of these states requires an odd l transition, and the distributions are not inconsistent with $l=1$ transitions. The fact that these states are excited, even though weakly, implies that the ground state of ^{13}C contains small components of configurations with two particles in the s-d shell.

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Using the angular distribution calculated by the DWBA for the 7.03-MeV level, approximate values for the spectroscopic factors of transitions to the 6.21 and 6.44-MeV states have been obtained. They are $S=0.03$ and $S=0.04$, respectively. The smallness of these values indicates that the overlap of these states with the ^{13}C ground state is slight. Since other evidence indicates that the configurations are $s_{1/2}{}^2$ and $d_{5/2}{}^2$, the small overlap is not surprising.

Evidence for the existence of components of the form $p_{3/2}{}^{-1}s_{1/2}{}^2$ and $p_{3/2}{}^{-1}d_{5/2}{}^2$ in the ground state of ^{13}C is relevant to the problem of the unexpectedly long lifetime[1] for β-decay of ^{14}C. The long lifetime of ^{14}C is thought to arise from an accidental cancellation of a matrix element. This cancellation could occur if suitable admixtures of p^8s^2 and especially p^8d^2 were present in the ground state of ^{14}C. Warburton and Pinkston[1] suggest such a component is present on the basis of an analysis of the strength of the γ transition from 8.63 MeV to the ground state in ^{14}N. The results of the ^{14}C$(d,t)^{13}$C experiment of Baranger and Meshkov[18] also indicate that such admixtures are present. The presence of similar components in the ^{13}C ground state further supports these arguments.

7.03-MeV level. The 3.945-MeV state is believed to have a configuration $p_{3/2}{}^{-1}p_{1/2}{}^{-1}$ coupled to 1^+. Such a configuration should also give rise to a 2^+ state lying higher in energy. Such a state is expected to be excited by an $l=1$ transition in the ^{13}C(^{3}He,d)^{14}N reaction. Previous studies have assigned a spin and parity of 2^+ to the 7.03-MeV state and Fig. 2 indicates that the transition does proceed by $l=1$. It seems likely that the 7.03-MeV state is the 2^+ state with the $p_{3/2}{}^{-1}p_{1/2}{}^{-1}$ configuration. This assignment is further supported by the close agreement of the experimental spectroscopic factor $S=0.13$ for this transition with the value $S=0.13$ calculated by Kurath[9] from his intermediate-coupling wave functions.

Other levels. Above 7.55-MeV excitation ^{14}N becomes unbound to proton emission and DWBA analysis of the angular distributions with the JULIE code is no longer convenient. Furthermore, near and above the proton emission threshold the angular distributions lack structure (cf. the 7.03-MeV state distribution in Fig. 2) and it becomes difficult to distinguish which l value best characterizes a given angular distribution. Consequently, no attempt has been made to analyze angular distributions of deuterons leading to states above the proton emission threshold.

[18] E. Baranger and S. Meshkov, Phys. Rev. Letters **1**, 30 (1958).

CONCLUSIONS

The bound states of ^{14}N now seem to be well understood both experimentally and theoretically. Kurath's wave functions of the positive parity states arising from p-shell configurations are confirmed by the data presented here and the wave functions calculated by Sebe for the negative-parity states receive some support. The over-all good agreement of theory and experiment also supports the 0^- assignment to the 4.91-MeV state upon which normalization of the spectroscopic factors was based.

The principal questions remaining concern the higher excited states and these can be more effectively studied using other reactions. The detailed results of studies of the ^{12}C(^{3}He,p)^{14}N and ^{15}N(^{3}He,α)^{14}N reactions will be published later; some results have already been published elsewhere.[17,19]

It should also be noted that even though ^{14}N is a very light nucleus the DWBA method appears to give quite accurate results. The absolute values of the spectroscopic factors obtained from the foregoing data are within 25% of the normalized values. In view of the uncertainties associated with the selection of appropriate optical-model parameters and evaluation of the overlap of the ^{3}He nucleus with the deuteron the agreement of theory and experiment is excellent. Subject to qualifications of the sort discussed by Siemssen *et al.*,[20] these results are further evidence that DWBA analysis can be used to obtain reliable spectroscopic information about light nuclei.

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