



Letter

Charge radii of $^{11-16}\text{C}$, $^{13-17}\text{N}$ and $^{15-18}\text{O}$ determined from their charge-changing cross-sections and the mirror-difference charge radii

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ABSTRACT

Charge-changing cross-sections (CCCSs) of $^{11-16}\text{C}$, $^{13-17}\text{N}$ and $^{15-18}\text{O}$ on a carbon target have been determined at energies around 300 MeV/nucleon. A nucleon separation energy-dependent correction factor has been introduced to the Glauber model calculation for extracting the nuclear charge radii from the experimental CCCSs. The charge radii of ^{11}C , $^{13,16}\text{N}$ and ^{15}O thus were determined for the first time. With the new radii, we studied the experimental mirror-difference charge radii ($\Delta R_{\text{ch}}^{\text{mirror}}$) of ^{11}B - ^{11}C , ^{13}C - ^{13}N , ^{15}N - ^{15}O , ^{17}N - ^{17}Ne pairs for the first time. We find that the $\Delta R_{\text{ch}}^{\text{mirror}}$ values of ^{13}C - ^{13}N and ^{15}N - ^{15}O pairs follow well the empirical relation to the isospin asymmetry predicted by the *ab initio* calculations, while $\Delta R_{\text{ch}}^{\text{mirror}}$ of ^{11}B - ^{11}C and ^{17}N - ^{17}Ne pairs deviate from such relation by more than two standard deviations.

1. Introduction

The nuclear charge distribution is one of the fundamental quantities for understanding nuclear structure and essential to study the neutron skin thickness of heavy nuclei together with the neutron density distribution, which provides insights into the equation of state for the nucleonic matter [1]. Mirror nuclei comprise the same total number of protons and neutrons, but the number of protons in one equals the number of neutrons in the other. Properties of mirror nuclei provide access to the charge symmetry of the nuclear force and the nuclear isospin symmetry. For instance, precise charge radii data of mirror nuclei are extremely valuable for studying isospin effects in nuclei and model developments [2]. The mirror-difference charge radii, $\Delta R_{\text{ch}}^{\text{mirror}}(^A Y/X) = R_{\text{ch}}(^A Y_Z) - R_{\text{ch}}(^A X_N)$ with N (Z) being the neutron (proton) num-

ber of the proton-rich mirror partner, for the mirror nuclei with mass number $6 \leq A \leq 56$ are predicted to have a linear relation to the isospin asymmetry ($I \equiv (N - Z)/A$) using the *ab initio* coupled cluster (CC) and auxiliary field diffusion Monte Carlo (AFDMC) methods [3]. As an analog of the neutron skin, $\Delta R_{\text{ch}}^{\text{mirror}}$ has also been suggested to constrain the slope of the symmetry energy at saturation density [4]. Test of this hypothesis has been made with different theories and sparse data [2,4–11]. However, the proper treatment of theoretical parameters (e.g., pairing correlations [9,12], deformation [13] and shell effects [14], etc.) still needs to be verified with experimental data of both bound and weakly bound nuclei over a broad range of isospin asymmetry.

When extending from stable to short-lived exotic nuclei, the electron scattering method has been precluded by the difficulty in preparing the target material, but the recent internal target-forming technique opens

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the possibility for electron scattering off short-lived unstable nuclei in the near future [15–17]. The isotope shift method has been booming in recent years [18]. It relies on theoretical calculations to disentangle the nuclear size-related field shift from the mass shift and can hardly access nuclei in the region containing carbon and oxygen isotopes [19]. Both methods use electromagnetic probes. From the hadronic probe side, the nuclear matter distribution has been extensively studied by measuring the interaction cross sections. Analogously, the charge-changing cross section (CCCS), describing the probability of an incident nucleus losing its proton(s) by interacting with the target, is considered as an alternative method to investigate the proton distributions in nuclei [20]. Such a method can in principle be applied to any isotope in the nuclear chart.

Investigations have been done to correlate CCCSs of nuclei to their root-mean-square (*rms*) point-proton distribution radii (R_p) within the framework of the Glauber model [21,22]. Only the collision of projectile protons with the target nucleus is considered in such models, while the projectile neutrons are treated as spectators in the charge-changing reaction. Recently, progress has been made in further understanding the charge-changing reaction mechanism. It is pointed out that the projectile neutrons also contribute to the CCCS. Such contribution has been taken into account by considering the charged-particle evaporation process (CPEP) induced by the projectile neutron removal [23,24]. The CPEP contribution to the CCCS exhibits an isospin dependence and closely correlates with the neutron-to-proton separation energy [24]. This also justifies the newly developed empirical method of deducing R_p from the CCCSs [25], where the authors found the ratios of experimental data to the Glauber model calculations follow excellent linearity with the nucleon separation energies of the nuclide of interest. This then allows them to develop a novel approach to extract R_p from CCCSs measured at around 900 MeV/nucleon on both hydrogen and carbon targets. However, a remaining question is whether such an approach is fragile with the reaction energy. One of the primary goals of this work is to answer this question.

The present paper reports CCCSs of $^{12-16}\text{C}$, $^{14-17}\text{N}$ and ^{16}O on carbon measured at energies around 230 MeV/nucleon. The experiment was performed at the External Target Facility (ETF), located alongside the third focus (F3) of the second Radioactive Ion Beam Line (RIBLL2) at HIRFL-CSR [26]. Secondary beams were produced by the fragmentation of ^{18}O projectiles at 280 MeV/nucleon interacting with a beryllium target. Fragments were separated in flight by the first half (F0-F2) of RIBLL2 and then delivered to ETF. Nuclei of interest were identified event-by-event by using the magnetic rigidity ($B\rho$), time-of-flight (TOF), and energy loss (ΔE) information. A 2.77 g/cm² thick carbon plate was used as the reaction target at ETF. The CCCSs were measured with the transmission method, where we counted the numbers of the incident and reaction particles without losing protons (*i.e.*, Z -unchanged particles). To account for reactions in materials other than the target, such as detectors, we measured without the target using the same setup. The CCCS is then calculated using the equation $\sigma_{\text{cc}}^{\text{exp}} = -(1/t)\ln(\gamma/\gamma_0)$, where γ and γ_0 are the ratios of Z -unchanged particles for the cases with and without the carbon reaction target, respectively. t is the number of target nuclei per unit area. More experimental and data analysis details can be found in previous papers [24,27,28].

Combining these new data with the CCCSs at around 300 MeV/nucleon measured with the same setup [24], we have identified an empirical correlation between the ratios of experimental cross sections to the theoretical ones and nucleon separation energies. This allowed us to determine the charge radii of ^{11}C , $^{13,16}\text{N}$, ^{15}O for the first time and investigate the mirror-difference charge radii of ^{11}B – ^{11}C , ^{13}C – ^{13}N , ^{15}N – ^{15}O , ^{17}N – ^{17}Ne and ^{18}O – ^{18}Ne pairs.

2. Results and discussions

CCCSs of $^{11-16}\text{C}$, $^{13-17}\text{N}$ and $^{15-18}\text{O}$ measured in this work and published in Ref. [24] are summarized in Table 1. CCCSs of $^{14-16}\text{C}$ and $^{16-18}\text{O}$ measured at a similar energy region [20] are listed as well for

Table 1

R_{ch} and R_p of $^{11-16}\text{C}$, $^{13-17}\text{N}$ and $^{15-18}\text{O}$ extracted from their experimental CCCSs, which include the ones measured in the present work (*i.e.*, CCCSs of $^{12-16}\text{C}$, $^{14-17}\text{N}$ and ^{16}O), published in our previous paper [24] and Ref. [20].

	Energy (MeV/u)	CCCS (mb)	R_p (fm)	R_{ch} (fm)
^{11}C	319 (38)	716 (20) ^a	2.18 (12)	2.32 (11)
^{12}C	228 (9)	723 (23)	2.41 (24)	2.54 (22)
	294 (5)	731 (52) ^a	2.40 (26)	2.53 (25)
^{13}C	231 (8)	720 (25)	2.28 (21)	2.41 (20)
	322 (30)	729 (22) ^a	2.30 (13)	2.42 (13)
^{14}C	234 (7)	707 (13)	2.33 (21)	2.45 (20)
	339 (12)	732 (22) ^a	2.38 (13)	2.50 (13)
	287	731 (5) ^b	2.36 (10)	2.48 (9)
^{15}C	236 (7)	749 (19)	2.44 (21)	2.56 (20)
	327 (16)	758 (56) ^a	2.44 (28)	2.56 (27)
	285	743 (6) ^b	2.36 (9)	2.47 (8)
^{16}C	237 (6)	738 (17)	2.46 (22)	2.57 (21)
	284	726 (6) ^b	2.33 (10)	2.44 (10)
^{13}N	310 (29)	752 (35) ^a	2.23 (17)	2.37 (16)
^{14}N	223 (7)	843 (32)	2.47 (19)	2.59 (18)
	289 (4)	878 (77) ^a	2.62 (31)	2.74 (30)
^{15}N	226 (6)	808 (15)	2.46 (17)	2.58 (16)
	315 (21)	815 (11) ^a	2.47 (9)	2.59 (9)
^{16}N	227 (3)	860 (21)	2.56 (16)	2.67 (15)
	322 (18)	813 (9) ^a	2.38 (7)	2.50 (7)
^{17}N	236 (3)	809 (17)	2.46 (17)	2.57 (16)
	328 (13)	790 (11) ^a	2.35 (9)	2.47 (9)
^{15}O	301 (24)	880 (18) ^a	2.57 (10)	2.69 (9)
^{16}O	219 (5)	862 (17)	2.61 (20)	2.73 (19)
	288	852 (17) ^b	2.54 (11)	2.66 (10)
^{17}O	308 (12)	866 (11) ^a	2.51 (8)	2.62 (8)
	294	896 (9) ^b	2.61 (8)	2.72 (7)
^{18}O	368 (2)	887 (39) ^a	2.66 (17)	2.76 (17)
	299	891 (10) ^b	2.67 (9)	2.78 (9)

^a Data measured with the same setup, already published in Ref. [24].

^b Data from Ref. [20].

comparison. Our results are in good agreement with the ones from the previous experiment [20].

Following the empirical method developed in Ref. [25], we have examined the ratios of experimental CCCSs to the theoretical ones as a function of the separation energy, *i.e.*, $S_1(^A_Z X_N) \equiv S_n(^A_Z X_N) + S_p(^{A-1}_Z Y_{N-1})$, for $^{12-14}\text{C}$, $^{14-15}\text{N}$ and $^{16-18}\text{O}$. Here, $S_n(^A_Z X_N)$ is the one-neutron separation energy of the nucleus $^A_Z X_N$ and $S_p(^{A-1}_Z Y_{N-1})$ is the one-proton separation energy of the one-neutron removed pre-fragment $^{A-1}_Z Y_{N-1}$. Ratios of the experimental CCCSs ($\sigma_{\text{cc}}^{\text{exp}}$) to the zero-range optical-limit approximation Glauber model calculations (ZRG) ($\sigma_{\text{cc}}^{\text{ZRG}}$), can be well described by $\sigma_{\text{cc}}^{\text{exp}}/\sigma_{\text{cc}}^{\text{ZRG}} = -0.005(1) \times S_1 + 1.28(3)$ as shown in Fig. 1. The slope and intercept parameters are almost identical to those for the 900 MeV/nucleon data [25]. This can be attributed to the fact that the incident energy can be well-considered in the ZRG. Such consistent results indicate that the correlation between $\sigma_{\text{cc}}^{\text{exp}}/\sigma_{\text{cc}}^{\text{ZRG}}$ and S_1 is robust for the p -shell nuclei. The incident energy independent feature of this correlation strengthens its application in determining the charge radius from the charge-changing reaction studies. As pointed out in Refs. [23,24], the discrepancy of the Glauber model prediction from the experimental CCCS can be resolved by considering the CPEP induced by the projectile neutron removal. The projectile neutrons are removed in the first step by interacting with the target nucleons in such considerations. If the pre-fragment is highly excited, it can decay by emitting charged particles in the second step. Such CPEP will contribute to the experimental CCCS. In the first step, single neutron removal is dominant, and the probability closely relates to the one neutron separation energy (*i.e.*, $S_n(^A_Z X_N)$). In the second step, single proton emission is often dominant, and the probability closely relates to the one proton separation energy of the pre-fragment (*i.e.*, $S_p(^{A-1}_Z Y_{N-1})$). If both separation ener-

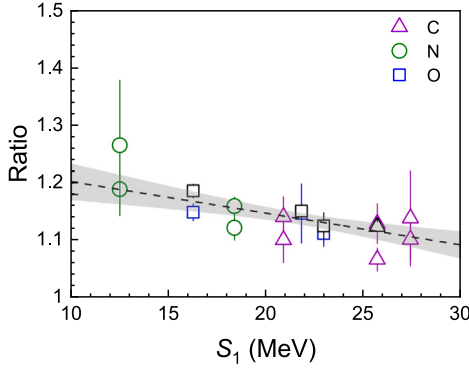


Fig. 1. Ratios of experimental charge-changing cross sections to the theoretical ones, as a function of the separation energy (i.e., $S_1(^A_Z X_N) \equiv S_n(^A_Z X_N) + S_p(^{A-1}_{Z-1} Y_{N-1})$) for $^{12-14}\text{C}$, $^{14-15}\text{N}$ and $^{16-18}\text{O}$. Data are from the present work (colored markers) and Ref. [20] (black markers). The dashed line with a slope of -0.005 and an intercept of 1.28, represents the best linear fit to the data. The gray band shows the 95% confidence level.

gies are high, the CPEP will be suppressed. Thus, the $\sigma_{cc}^{\text{exp}}/\sigma_{cc}^{\text{ZRGm}}$ ratio dependence on the $S_1(^A_Z X_N)$ can be qualitatively understood [25].

Introducing the above correction factor to the ZRGM allows us to determine R_p of nuclei with unknown radii from the experimental CCCSs. The point-proton density distribution of p -shell nuclei is assumed in the harmonic oscillator type. Table 1 summarizes the determined R_p of $^{11-16}\text{C}$, $^{13-17}\text{N}$ and $^{15-18}\text{O}$. The error bars of R_p include both the systematic uncertainty from the scaling method and the statistical uncertainty. In the cases where CCCS statistical errors are more than 2%, they account for more than 60% of the uncertainties of the final R_p . Only in the cases where CCCS statistical errors are smaller than 1%, the scaling method starts to dominate the uncertainties of R_p .

In Fig. 2, we plot R_p of $^{11-16}\text{C}$, $^{13-17}\text{N}$ and $^{15-18}\text{O}$ determined in this work, the ones from the electron scattering method [29] and previous CCCS measurements whenever available [20,30,37–39]. The predictions from deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) [32–36] and from the *ab initio* no-core shell-model [31] are shown for comparisons. Within the present uncertainties, the new data of ^{15}O indicates a smooth R_p transition over the doubly magic ^{16}O . While the smaller R_p of ^{13}N than that of ^{14}N may indicate an appearance of a local minimum at $N = 6$ in the nitrogen isotopic chain. Both cases agree with the DRHBc predictions. The *ab initio* no-core shell-model theory and the DRHBc predict a decreasing trend of the R_p from ^{11}C to ^{12}C , but the R_p of ^{11}C hints differently. It is worth noting that ^{11}C shows the smallest root-mean-square matter radius among that of ^{9-20}C [40].

As listed in Tabel 1, we computed the charge radii (R_{ch}) from the R_p using the formula, $R_{\text{ch}}^2 = R_p^2 + \langle r_p^2 \rangle + (N/Z)\langle r_n^2 \rangle + \langle r_{\text{DF}}^2 \rangle$. Here, the $\langle r_p^2 \rangle = (0.8409(4))^2 \text{ fm}^2$ is the charge radius squared of the proton [41], the $\langle r_n^2 \rangle = -0.1155(17) \text{ fm}^2$ is the mean-square charge radius of the neutron [41], and the Darwin-Foldy term $\langle r_{\text{DF}}^2 \rangle = 0.033 \text{ fm}^2$ [42].

Together with the known charge radii of ^{11}B , $^{17,18}\text{Ne}$ from Ref. [29], we deduce the $\Delta R_{\text{ch}}^{\text{mirror}}$ of $^{11}\text{B}-^{11}\text{C}$, $^{13}\text{C}-^{13}\text{N}$, $^{15}\text{N}-^{15}\text{O}$, $^{17}\text{N}-^{17}\text{Ne}$ and $^{18}\text{O}-^{18}\text{Ne}$ pairs. $\Delta R_{\text{ch}}^{\text{mirror}}$ is obtained by subtracting R_{ch} of the proton-rich mirror partner from the neutron-rich one, e.g., $\Delta R_{\text{ch}}^{\text{mirror}}(^{17}\text{N}-^{17}\text{Ne}) = R_{\text{ch}}(^{17}\text{N}) - R_{\text{ch}}(^{17}\text{Ne})$. Fig. 3 plots these results from this work and $\Delta R_{\text{ch}}^{\text{mirror}}$ of other 18 mirror nuclei pairs as a function of the isospin asymmetry, I . Charge radii of ^3H , ^3He , ^7Li , ^7Be , ^{18}O , ^{19}F , $^{18,19,21,22}\text{Ne}$, $^{21,23}\text{Na}$, $^{34,36}\text{S}$, $^{35,37}\text{Cl}$, $^{32,34,35,37,38}\text{Ar}$, ^{39}K , ^{39}Ca , ^{54}Fe from Ref. [29] and charge radii of $^{22,23}\text{Mg}$ from Ref. [43], ^{32}Si from Ref. [44], ^{37}K from Ref. [45], $^{36,37,38}\text{Ca}$ from Ref. [46], ^{54}Ni from Ref. [47] are used for calculating the relevant $\Delta R_{\text{ch}}^{\text{mirror}}$. $\Delta R_{\text{ch}}^{\text{mirror}}(^{18}\text{O}-^{18}\text{Ne})$ determined in this work is consistent with the value deduced from the precisely known R_{ch} [29].

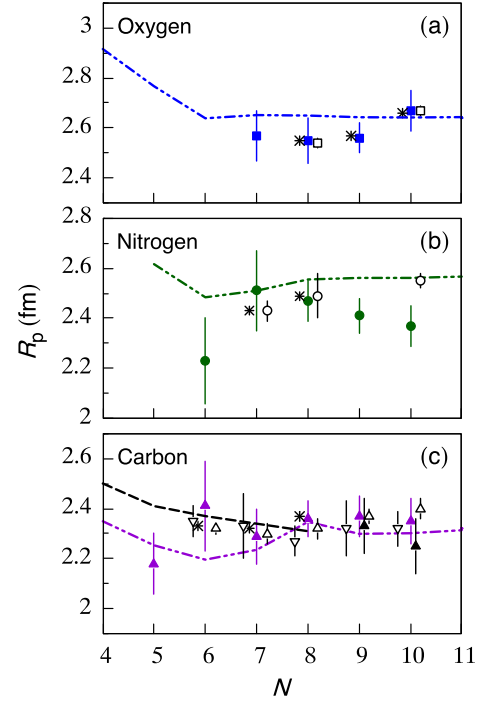


Fig. 2. R_p determined from the present work (colored solid markers), Ref. [20] (black solid markers), Refs. [30,37–39] (open markers) in comparison with the ones (shown by *) from the electron scattering method. The data points are partially shifted in the x-axis to avoid overlapping. The dash-double-dotted lines represent predictions from the DRHBc theory [32–36]. The dashed line shows predictions from the *ab initio* no-core shell-model theory for $^{10-14}\text{C}$ [31].

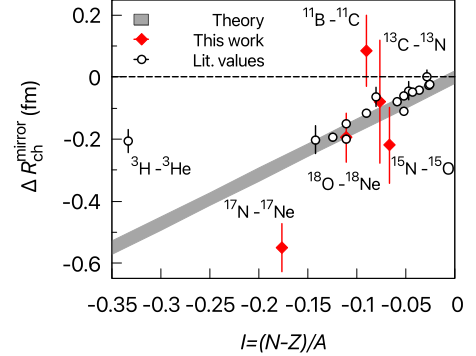


Fig. 3. Mirror-difference charge radii plotted against the isospin asymmetry. Experimental results from this work (filled diamonds) are compared with the ones from literature (open circles) and the gray band representing $\Delta R_{\text{ch}}^{\text{mirror}} = 1.574 \cdot I \pm 0.021$.

As shown in Fig. 3, R_{ch} of the proton-rich mirror partner is always larger than that of the neutron-rich one, except for $^{11}\text{B}-^{11}\text{C}$. In general, $\Delta R_{\text{ch}}^{\text{mirror}}$ exhibits a linear correlation to the isospin asymmetry I as the one (i.e., $R_{\text{ch}}^{\text{mirror}} = 1.574 \cdot I \pm 0.021$) identified in the *ab initio* calculation [3], where the experimental charge radii of individual mirror nuclei are reproduced within a few percent. A deviation of $\Delta R_{\text{ch}}^{\text{mirror}}$ from such correlation implies an anomaly in the nuclear structure contributing to the isospin symmetry breaking within the mirror pairs. For instance, the deviation of $\Delta R_{\text{ch}}^{\text{mirror}}(^{17}\text{N}-^{17}\text{Ne})$ is probably due to the proton halo character of ^{17}Ne [48,49]. The more extreme case of $\Delta R_{\text{ch}}^{\text{mirror}}(^3\text{H}-^3\text{He})$ is not surprising since the structure effects (e.g., pairing correlation, short-range-correlation [50]) are more pronounced for such light nuclei with large isospin asymmetry. $\Delta R_{\text{ch}}^{\text{mirror}}(^{11}\text{B}-^{11}\text{C})$ slightly deviates from that linear correlation. However, a recent laser spectroscopic study

on $^{10,11}\text{B}$ [51] has pointed out that the nuclear charge radius of ^{11}B from Ref. [29] suffers from large uncertainties. As shown in Fig. 3, we have extended the experimental $\Delta R_{\text{ch}}^{\text{mirror}}$ down to the isospin asymmetry of -0.176 . Our experimental data, including both the bound (e.g., ^{15}N) and weakly bound proton-rich mirror partners, provide ideal test cases for the treatment of shell effects and pairing correlation in the nuclear theories [2].

3. Summary

In the present study, we reported the charge radii of $^{11-16}\text{C}$, $^{13-17}\text{N}$, and $^{15-18}\text{O}$ determined from the relevant CCCSs on a carbon target at around 300 MeV/nucleon. For the first time, we have identified a robust correlation of the experimental cross section relative to the models for p -shell nuclei at this energy range. The correction factor is almost identical to those found at 900 MeV/nucleon data indicating that the reaction energy dependence has been eliminated by taking the ratio of the experimental CCCS to the Glauber model prediction. This method opens a new vista of determining nuclear charge radii from the charge-changing reaction studies. With the R_p of ^{11}C , $^{13,16}\text{N}$, and ^{15}O measured for the first time, we show the R_p of oxygen isotopes show a smooth transition over the magic neutron number $N = 8$ and suggest a local minimum at $N = 6$ in the nitrogen isotopes. The smaller proton radius of ^{11}C than that of ^{12}C tends to differ from the predictions of the *ab initio* no-core shell model and the DRHBc theories.

These new data allow us to deduce the experimental mirror-difference charge radii $\Delta R_{\text{ch}}^{\text{mirror}}$ of ^{11}B - ^{11}C , ^{13}C - ^{13}N , ^{15}N - ^{15}O , ^{17}N - ^{17}Ne pairs for the first time. $\Delta R_{\text{ch}}^{\text{mirror}}$ of ^{13}C - ^{13}N and ^{15}N - ^{15}O pairs are consistent with the *ab initio* theoretical predictions. The deviation of $\Delta R_{\text{ch}}^{\text{mirror}}$ of ^{17}N - ^{17}Ne coincides with the proton halo structure of ^{17}Ne . The slight deviation of $\Delta R_{\text{ch}}^{\text{mirror}}$ of ^{11}B - ^{11}C implies the uncertainty in the present knowledge on the charge radius of ^{11}B . Although present data do not have high precision, an improved statistic in the CCCS experiment will help to quantify such linearity better. Experimental $\Delta R_{\text{ch}}^{\text{mirror}}$ will also be valuable in revealing distinct nuclear (e.g., structure) effects contributing to the isospin symmetry breaking and testing the treatment of shell effects and pairing correlation in the nuclear theories.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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