


 Cite this: *RSC Adv.*, 2022, 12, 35094

Preparation of high temperature NH₃-SCR catalysts with carbonate as precursors by ball milling method

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High-temperature 10Ce–2La/TiO₂ catalysts for selective catalytic reduction of NO with NH₃ were prepared by the ball milling, impregnation and co-precipitation methods and their catalytic performance was compared. The effects of different starting materials of the ball milling method on the catalytic activity were investigated. The results showed that the 10Ce–2La/TiO₂ catalyst prepared by the ball milling method using carbonates as starting materials exhibited the highest NO conversion, which was more than 80% in the temperature range of 330–550 °C. The as-prepared catalysts were characterized by XRD, TEM, and XPS. Results showed that the ball milling prepared 10Ce–2La/TiO₂ had the advantages of uniform active site distribution, high oxygen storage capacity, and high Ce³⁺ and O_x ratio. The results of NH₃-TPD and H₂-TPR showed that the ball milling method not only improved the redox ability but also increased the quantities and concentration of the acidic sites. The green production and economically viable concept of this process provides a new solution for the production application of industrial catalysts.

 Received 17th October 2022
 Accepted 1st December 2022

DOI: 10.1039/d2ra06552e

rsc.li/rsc-advances

1. Introduction

In modern society, the increase in air pollution due to harmful gases released from fossil energy consumption has become a global problem. These harmful gases mainly include NO_x, SO_x, and CO, and so on. Among them, NO_x mainly originates from the flue gas of stationary sources represented by boilers in coal-fired plants and exhaust from the mobile sources represented by vehicles. The NO_x emissions cause environmental problems such as acid rain, photochemical smog, ozone layer depletion, and greenhouse effect.^{1,2} Therefore, it is required to study a technique to diminish the NO_x emission. Ammonia selective catalytic reduction (NH₃-SCR) technology is currently the most widely used NO removal technology for flue gas. The most used commercial catalysts for NH₃-SCR are vanadium-based catalysts such as V₂O₅–WO₃ (MoO₃)/TiO₂. Although vanadium based catalyst has high NO conversion rate, it also has many disadvantages, such as narrow temperature operation window, high vanadium toxicity and poor high temperature activity.^{3,4} With that regards, non-vanadium-based catalysts

have been explored and studied. Among them, cerium oxides have excellent oxidation properties as well as oxygen storage capacity due to the special electron distribution of cerium.^{5,6} At the same time, because cerium oxide has no biological toxicity, it is currently considered to be a powerful substitute for vanadium based catalysts. In our previous report, we prepared a series of Ce–La/TiO₂ high-temperature NH₃-SCR catalysts by the impregnation method.⁷ The introduction of La₂O₃ improved the catalytic activity and the Ce–La/TiO₂ catalysts had a wide temperature window (355–590 °C) and better catalytic performance than commercial vanadium-based catalysts at high temperature.

The catalytic activity and N₂ selectivity of catalysts are influenced not only by the active components, but also by the preparation method and starting materials.^{8,9} In some cases, although the precursor for the preparation of catalysts does not change the final elemental composition of the catalyst, it can have an impact on the catalytic performance of the catalyst. Xu¹⁰ *et al.* prepared Fe–TiO₂ catalysts *via* a co-precipitation method and found that different TiO₂ precursors (titanium sulfate, titanium tetrachloride, *n*-butyl titanate and commercial TiO₂) had a significant effect on the catalytic activity. Among them, the samples synthesized with titanium sulfate as the precursor showed the highest catalytic activity. As for the preparation methods, Chen¹¹ *et al.* compared the catalytic performance of the Ce–Mn/TiO₂ mixed oxides prepared by inverse co-precipitation, conventional co-precipitation and impregnation methods. Results showed that the catalyst prepared by inverse co-precipitation method had the highest low-temperature

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catalytic activity and the best resistance to water and SO₂. Pan *et al.*¹² prepared a series of catalysts with different mixing ratios by ball milling. The catalysts prepared by the ball milling methods showed NO conversion more than 90%, good N₂ selectivity and high toxicity resistance to SO₂ and H₂O in a wide temperature range (200–400 °C). It is well known that the ball milling method is an easy industrial production method with the advantages of simple operation, low cost, and easy to scale up. In particular, the ball milling method can reduce the discharge of waste water and harmful exhaust gases when compared with the impregnation and co-precipitation methods that often used in the industrial production, thus contributing to environmental protection.^{13,14} Although the Ce–La/TiO₂ catalysts prepared by the impregnation method of our group have excellent high-temperature catalytic performance, the raw materials contain a large amount of nitrates, which will exhaust NO_x during the following calcination. Therefore, if catalysts with comparable performance to that of the impregnation method can be produced by a ball milling method, it will be of great help to save cost and reduce the emission of wastewater and waste gas. To our best knowledge, there are no reports on the preparation of Ce–La/TiO₂ catalysts by ball milling method using carbonates as the starting materials. Also, there is no report on the comparison of the catalytic activity of the Ce–La/TiO₂ catalysts prepared by different methods.

In this work, in order to compare the effects of ball milling, impregnation and co-precipitation on the catalytic activity, and to minimize pollution during the catalyst preparation, Ce–La/TiO₂ catalysts with the same mass ratio were prepared using different methods or precursors (NO₃[−], OH[−], CO₃^{2−}). All catalysts conduct catalytic reaction in the same simulated flue gas environment. In order to analyze the denitration performance of the catalyst from its phase, morphology, specific surface area, acidic sites and redox capacity, a series of characterizations such as XRD, SEM, BET, XPS, H₂-TPR and NH₃-TPD were carried out. The apparent activation energy and turn over frequency (TOF) of NH₃-SCR catalyst were calculated.

2. Experimental

2.1 Materials and reagents

2.1.1. Qualification of reagents. All chemicals and reagents were purchased without further purification. Ce(NO₃)₃·6H₂O, La(NO₃)₃·6H₂O, NH₃·H₂O and citric acid are of analytical grade, and other reagent are of industrial grade.

2.1.2. Synthesis of catalysts. First, cerium carbonate and lanthanum carbonate were weighed and mixed according to Ce_xLa_yTi₈₈, where *x* and *y* were the weight ratio of CeO₂ and La₂O₃ to 88 parts of anatase TiO₂. Then the materials were placed in a nylon jar and ground on a KQM-Z/B planetary ball miller in the presence of appropriate amount of deionized water and zirconia balls. The rotation speed and time were set as 500 rpm and 1 h, respectively. Every 20 min, the rotation direction was changed. After the ball milling, the zirconia balls were separated through a sieve and the slurry was dried at 105 °C for 12 h. Finally, the samples were calcined at 500 °C for 4 h to obtain the catalyst for measurement, denoted as BC-10Ce-2La/

Table 1 List of the starting materials and the ratio of the four different catalysts

Preparation method	Starting materials	Abbreviation
Ball milling	Ce ₂ (CO ₃) ₃ , La ₂ (CO ₃) ₃ , TiO ₂	BC-10Ce-2La/TiO ₂
Ball milling	Ce(OH) ₄ , La(OH) ₃ , TiO ₂	BH-10Ce-2La/TiO ₂
Impregnation	Ce(NO ₃) ₃ ·6H ₂ O, La(NO ₃) ₃ , 6H ₂ O, TiO ₂	IN-10Ce-2La/TiO ₂
Co-precipitation	Ce(NO ₃) ₃ ·6H ₂ O, La(NO ₃) ₃ , 6H ₂ O, TiO ₂	CN-10Ce-2La/TiO ₂

TiO₂. For comparison, 10Ce-2La/TiO₂ catalysts were prepared by different methods (Table 1). The catalyst prepared by the ball milling method using Ce(OH)₄ and La(OH)₃ instead of Ce₂(CO₃)₃ and La₂(CO₃)₃ as raw materials was denoted as BH-10Ce-2La/TiO₂. The catalysts prepared by the impregnation method⁷ and co-precipitation method¹¹ according to the literature were labeled as IN-10Ce-2La/TiO₂ and CN-10Ce-2La/TiO₂, respectively.

2.2 Instrumental measurements

An X-ray diffractometer (Thermo ARL SCINTAG X'TRA) was used to examine the phase composition of the samples. The X-ray source was Cu K_α radiation (wavelength 0.154056 nm) operated at an accelerating voltage of 40 kV and a tube current of 40 mA. The sample was tested by N₂ adsorption automatic pore specific surface area analyzer (Builder SSA-7300). The specific surface area (m² g^{−1}), pore volume and average pore diameter of the catalyst were calculated from the desorption branch of the isotherm in the pressure range of 0.05–0.30 by Brunauer–Emmett–Teller (BET) equation, *t*-plot method and Barrett–Joyner–Halenda (BJH) model, respectively. The morphology of the catalyst was observed on a transmission electron microscope (TEM, Talos F200x, FEI, USA) with a Super-X energy dispersive spectrometer (EDS) for the test of the elemental mappings. Before the observation, the sample was dispersed in anhydrous ethanol and dried. X-ray photoelectron spectroscopy (XPS) was performed on a Thermo Scientific K-Alpha electron spectrometer with an Al K_α (*hν* = 1486.6 eV) radiation source operated at 12 kV with a vacuum pressure of 3 × 10^{−5} Pa. All binding energies were calibrated by the standard C1s peak (284.8 eV). Temperature programmed desorption/reduction (TPD/TPR) experiments were carried out on a chemisorption apparatus (Micromeritics, AutoChem II 2920). First, appropriate amount of sample was weighed and put into a reaction tube, and then heated from room temperature to 350 °C for surface impurities removal. Then, the sample was purged with He gas flow for 1 h and cooled to 50 °C. For NH₃-TPD, 10% NH₃/He mixture was injected for 1 h until the adsorption was saturated, then He gas flow was introduced for 1 h to remove weak physical adsorption of NH₃ on the surface. Finally, the temperature was raised to 700 °C at a heating rate of 10 °C min^{−1} in He flow and a TCD detector was used for the detection of the NH₃ desorption. For H₂-TPR, 10% H₂/Ar mixture was used and the sample was heated to 1000 °C at a heating rate of 5 °C min^{−1} and detected the reducing gas with a TCD.



2.3 Catalytic test

First, the as-prepared catalysts were ground in a KQM-Z/B planetary ball miller and coated to a honeycomb cordierite carrier with size of $\varphi 20 \times L50$. After drying in an oven, the loaded cylinders were placed in a quartz tube furnace to test the catalytic activity. The loading weight of the catalyst was 1 g. The fed gas mixture consisted of 500 ppm NO, 500 ppm NH₃, 5% H₂O, 3% O₂ and the balanced N₂. The total gas flow was 2500 mL min⁻¹, hence the corresponding gas hourly space velocity (GHSV) was calculated to be 150 000 mL g⁻¹ h⁻¹. The outlet concentrations of NO and NO₂ were measured using an ECOM flue gas analyzer (Germany), and the outlet N₂O concentration was detected using a KRM50 infrared analyzer. The temperature control was performed by a computer program. The NO conversion and N₂ selectivity were calculated according to the following equations:¹⁵

$$\text{NO conversion (\%)} = \frac{[\text{NO}]_{\text{in}} - [\text{NO}]_{\text{out}}}{[\text{NO}]_{\text{in}}} \times 100\% \quad (1)$$

$$\text{N}_2 \text{ selectivity (\%)} = \frac{[\text{NO}]_{\text{in}} + [\text{NH}_3]_{\text{in}} - [\text{NO}_2]_{\text{out}} - 2[\text{N}_2\text{O}]_{\text{out}} - [\text{NO}]_{\text{out}} - [\text{NH}_3]_{\text{out}}}{[\text{NO}]_{\text{in}} + [\text{NH}_3]_{\text{in}} - [\text{NO}]_{\text{out}} - [\text{NH}_3]_{\text{out}}} \times 100\% \quad (2)$$

where, []_{in} and []_{out} represent the inlet and outlet concentrations of different gases at steady state, respectively.

At high GHSV, assuming that the NH₃-SCR catalytic reaction is not controlled by diffusion but by the dynamic mode, the normalized SCR reaction rate constant per specific surface area of the catalyst can be calculated according to the following equation:^{16,17}

$$\text{Rate (mol m}^{-2} \text{ s}^{-1}) = \frac{X_{\text{NO}} \times Q \times C_f}{V_m \times W \times S_{\text{BET}}} \quad (3)$$

where X_{NO} is the NO conversion (%) at different temperatures (250–350 °C with an interval of 25 °C), Q is the volumetric flow (2500 mL min⁻¹), C_f is the fed NO concentration (500 ppm), V_m is the molar volume of gas under standard conditions (22.4 L mol⁻¹), W is the weight of the catalyst (g), and S_{BET} is the specific surface area of the catalyst (m² g⁻¹).

The turnover frequency (TOF) values were used to compare the catalytic rates of the different catalysts. To ensure that the SCR reaction was not controlled by diffusion, the NO conversion was controlled below 20% by increasing GHSV and the TOF value of NO at the active center Ce was calculated by the following equation:^{18,19}

$$\text{TOF} = \frac{Pv/RT\alpha}{m_{\text{cat}}\beta_{\text{Ce}}/M_{\text{Ce}}} \quad (4)$$

where P is the standard atmospheric pressure (1.01 × 10⁵ Pa), v is the flow of NO (129 mL min⁻¹), R is the molar gas constant (8.314 J mol⁻¹ K⁻¹), T is the test temperature: 473, 488, 503, 518, 533 and 543 K, α is the NO conversion (%), m_{cat} is the weight of the catalyst (1 g), β_{Ce} is the loading ratio of Ce (%) calculated

using XPS data, and M_{Ce} is the molecular weight of cerium (140.1 g mol⁻¹).

3. Results and discussion

3.1 Characterization of catalysts

Fig. 1 shows the X-ray diffraction patterns of the four catalysts. It can be seen that the main phase of all samples was anatase TiO₂ (JCPDS no. 21-1272). Weak diffraction peaks of ceriumite CeO₂ (JCPDS no. 43-1002) were detected near 28.6°, 33°, etc. Among them, BC-10Ce-2La/TiO₂ has the strongest CeO₂ peak (111 crystal plane), while BH-10Ce-2La/TiO₂ has the weakest diffraction peak, indicating that the precursors can induce CeO₂ crystallization to different degree. The high crystallization of BC-10Ce-2La/TiO₂ catalyst can promote the activation of NH₃,³ which is consistent with its high catalytic activity. No peaks of La₂O₃ species were observed for all samples, which might be related to their low content, poor crystallinity and high dispersion on the catalyst surface.²⁰

Table 2 lists the specific surface area (S_{BET}), pore volume (V_p) and average pore size (D_p) of the catalysts measured by N₂ adsorption and desorption method. As can be seen from the table, except for BH-10Ce-2La/TiO₂, the surface area and pore volume, pore size of other three catalysts showed almost no

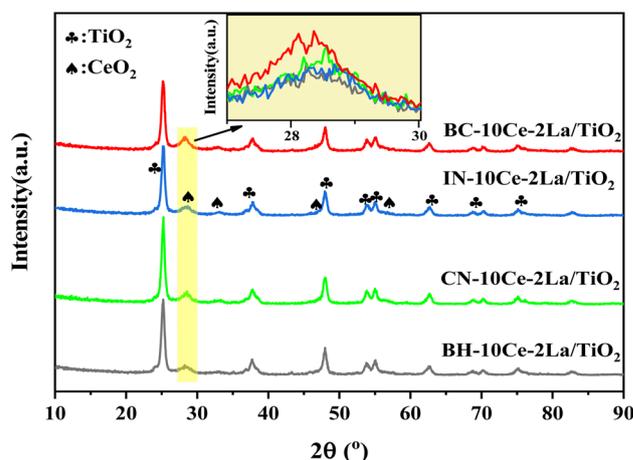


Fig. 1 XRD pattern of BH-10Ce-2La/TiO₂, CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂ and BC-10Ce-2La/TiO₂ catalysts.

Table 2 Specific surface area, pore volume and average pore size of the catalysts

Samples	BET surface area ^a (m ² g ⁻¹)	Pore volume ^b (cm ³ g ⁻¹)	Average pore size ^c (nm)
BC-10Ce-2La/TiO ₂	79	0.043	1.08
IN-10Ce-2La/TiO ₂	80	0.042	1.06
CN-10Ce-2La/TiO ₂	80	0.042	1.05
BH-10Ce-2La/TiO ₂	74	0.040	1.08

^a Calculated by BET method. ^b Calculated by *t*-plot method. ^c Calculated by BJH method.



difference, which might be due to the same content of TiO_2 as the carrier. The results showed that the catalysts prepared by the ball milling method with carbonates as the precursors had comparable temperature windows and catalytic activities with the conventional methods.

Fig. 2 shows the TEM images, HR-TEM images and the elemental mapping of the four catalysts. It can be seen from Fig. 2(a)–(d) that all catalysts have similar morphology and are porous structures formed by the accumulation of nanoparticles of different sizes, which helps to exhibit good catalytic activity.²¹ From the HR-TEM images in Fig. 2(e)–(h), a crystalline spacing of 0.35 nm can be observed in all the catalysts, corresponding to the (101) crystalline plane of anatase TiO_2 .²² The d spacing of 0.31, 0.26 and 0.19 nm correspond to the (111), (200) and (220) crystalline planes of CeO_2 , respectively.²³ It is noteworthy that

no lattice striations of the crystalline lanthanide oxide can be observed for all samples, suggesting that it exists on the catalyst surface in an amorphous structure.²⁴ This is in agreement with the XRD results. Moreover, the elemental mappings of Ce, La and Ti (Fig. 2(i)–(t)) show that Ce, La and Ti elements are uniformly distributed in the catalysts.

XPS was used to detect the electrovalence and the relative proportions of elements on the surface of the catalysts and shown in Fig. 3. Ten peaks of Ce 3d in Fig. 3(a) can be fitted, and the peaks labeled as “V” and “U” represents the $3d_{5/2}$ and $3d_{3/2}$ spin-orbit states of cerium, respectively. The peaks labeled V_1 , V_3 , and V_4 are from $\text{Ce}^{4+} 3d_{5/2}$, while the peaks labeled U_1 , U_3 , and U_4 represent $\text{Ce}^{4+} 3d_{3/2}$. In addition, the peaks of V_0 , V_2 and U_0 , U_2 belong to $\text{Ce}^{3+} 3d_{5/2}$ and $\text{Ce}^{3+} 3d_{3/2}$, respectively. The presence of V_0/U_0 and V_2/U_2 double peaks indicates that the

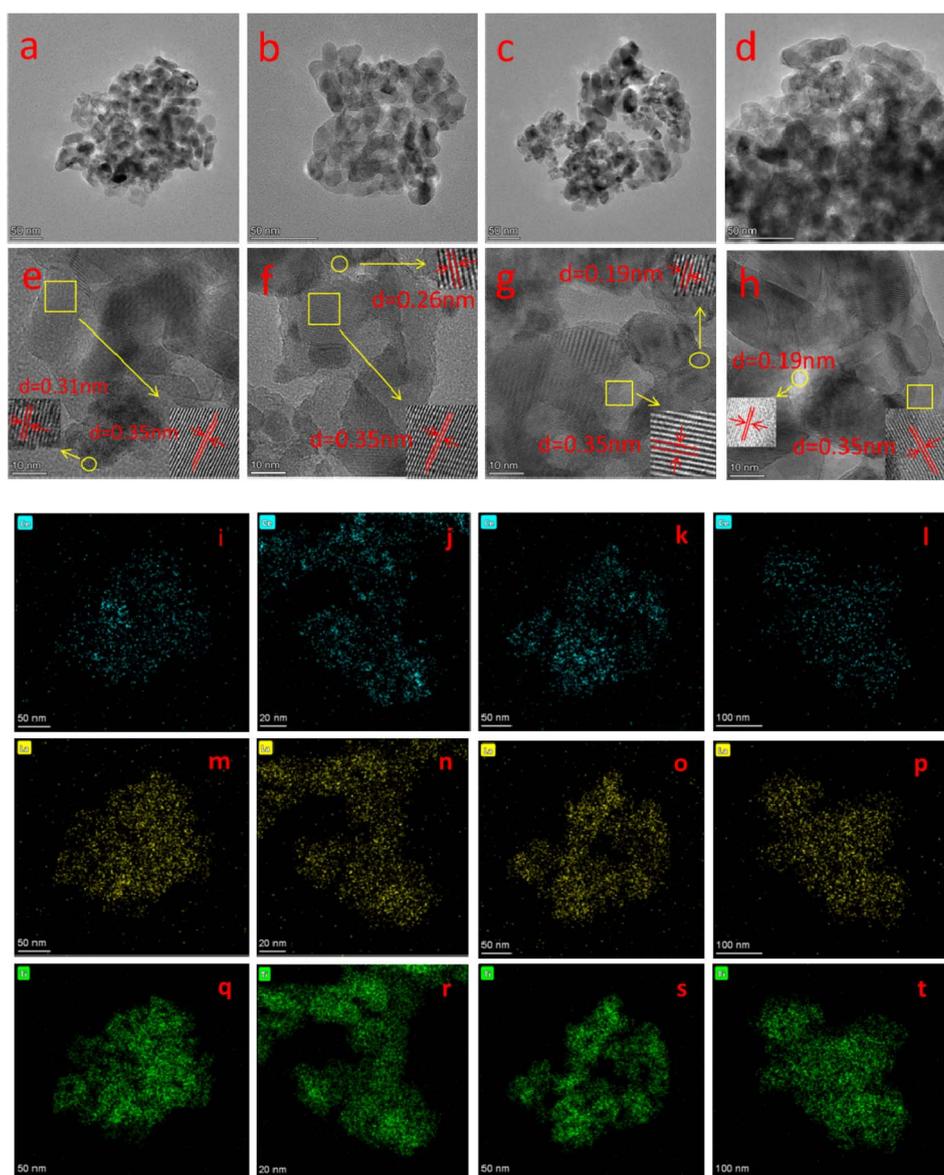


Fig. 2 (a–d) TEM image, (e–h) HR-TEM, and (i–l) Ce, (m–p) La, (q–t) Ti mapping of BH-10Ce-2La/TiO₂, CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂, and BC-10Ce-2La/TiO₂.



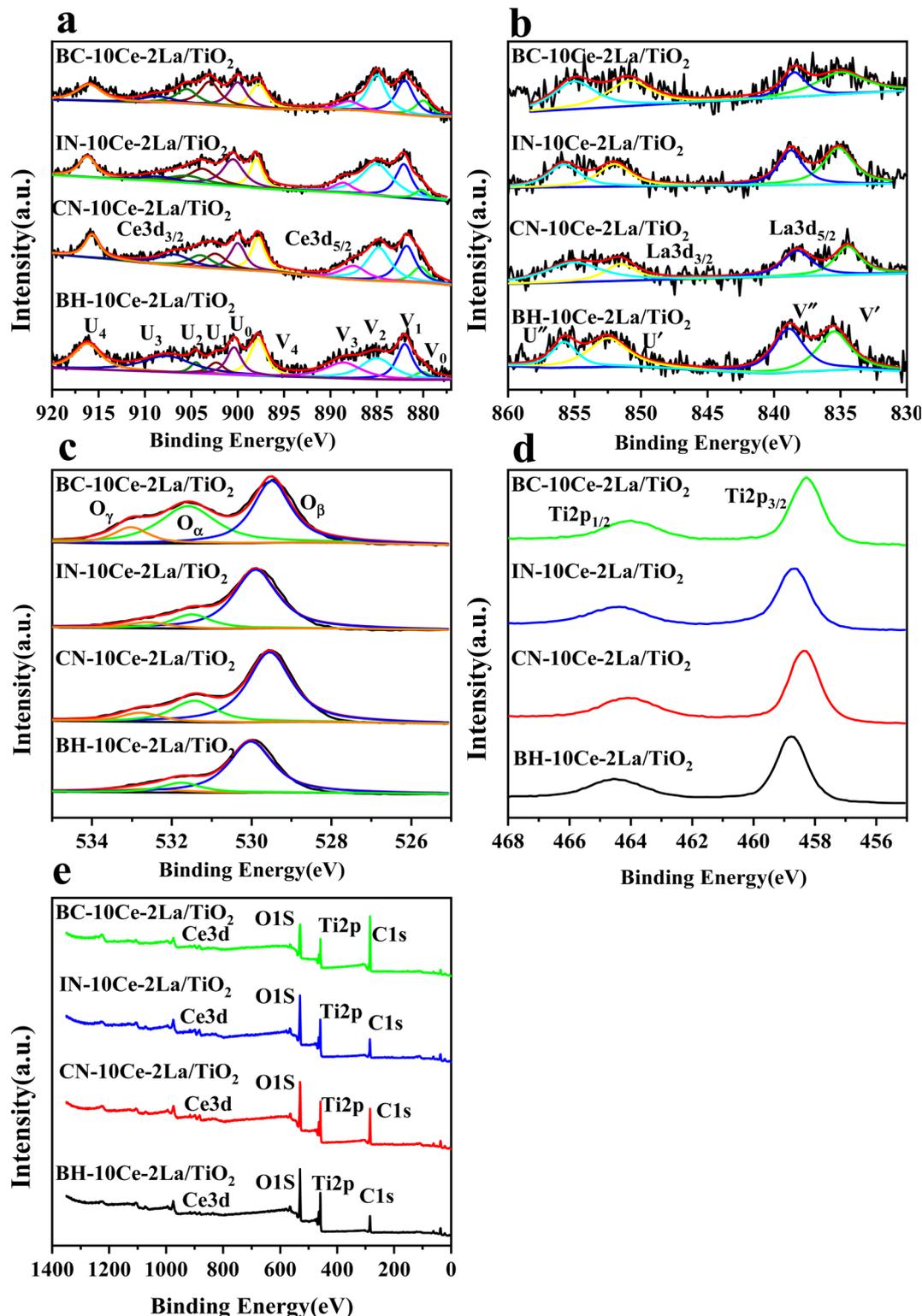


Fig. 3 XPS of BH-10Ce-2La/TiO₂, CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂ and BC-10Ce-2La/TiO₂ catalysts. (a) Ce 3d; (b) La 3d; (c) O 1s; (d) Ti 2p; (e) Survey spectra.

catalyst contains some oxygen vacancies and is in a partially reduced state.²⁵ Table 3 lists the surface element concentrations and the ratios of Ce³⁺ and O₂ for the catalysts calculated by XPS. The relative content of Ce³⁺ in these samples can be calculated

by the following equation for the integral peak area ratio of Ce³⁺ and total Ce:²⁶ Ce³⁺ (%) = $(S_{V_0} + S_{V_2} + S_{U_0} + S_{U_2}) / \sum(S_U + S_V) \times 100\%$ and is presented in Table 3. It can be seen that the highest percentage of Ce³⁺/(Ce³⁺+Ce⁴⁺) on the surface of IN-10Ce-2La/



Table 3 Surface element concentrations and ratios of Ce^{3+} and O_α calculated by XPS

Catalysts	Surface atomic concentration (atom%)				Ce^{3+} $\text{Ce}^{4+} + \text{Ce}^{3+}$	O_α $\text{O}_\alpha + \text{O}_\beta$
	O	Ce	La	Ti		
	BC-10Ce-2La/TiO ₂	76.92	1.99	0.48	20.64	42.52%
IN-10Ce-2La/TiO ₂	69.37	3.05	0.57	26.99	48.87%	17.89%
CN-10Ce-2La/TiO ₂	69.19	2.44	0.46	24.24	41.18%	23.85%
BH-10Ce-2La/TiO ₂	69.19	1.36	0.54	27.30	30.46%	17.72%

TiO₂ catalyst is 48.87%, while those on BC-10Ce-2La/TiO₂, CN-10Ce-2La/TiO₂ and BH-10Ce-2La/TiO₂ are 42.52%, 41.18% and 30.46%, respectively. It is noteworthy that BH-10Ce-2La/TiO₂ exhibits the lower Ce^{3+} and O_α ratios than that of IN-10Ce-2La/TiO₂ and CN-10Ce-2La/TiO₂. The low Ce^{3+} ratio of BH-10Ce-2La/TiO₂ can be attributed to the starting material of $\text{Ce}(\text{OH})_4$. On the other hand, a higher proportion of Ce^{3+} can promote the generation of oxygen vacancies, unsaturated chemical bonds and charge imbalance on the catalyst surface, thus further promoting the NO oxidation reaction.^{27,28}

In Fig. 3(b), both the XPS peaks of La 3d_{5/2} and 3d_{3/2} exhibit double splitting, one is attributed to spin-orbit interactions and the other is electron transfer from the valence band of oxygen to the empty La 4f energy level orbital.²⁹ Compared with BC-10Ce-2La/TiO₂, the peaks of IN-10Ce-2La/TiO₂ and BH-10Ce-2La/TiO₂ shifted toward the high binding energy direction, which indicated that the interaction between Ce and La of BC-10Ce-2La/TiO₂ was enhanced. In Fig. 3(c), the lower binding energy (529.5–530 eV) of O1s is attributed to lattice oxygen, denoted as O_β ; the higher binding energy (531.4–531.8 eV) is attributed to surface unsaturated oxygen, denoted as O_α ; and the highest

peak (532–532.8 eV) corresponds to adsorbed water, denoted as O_γ .^{7,10} Because O_α has a higher mobility than the lattice oxygen O_β , O_α can lead to form more surface oxygen vacancies and subsequently be more highly active in oxidation reactions. As can be seen from Table 3, the O_α concentration (76.92%) and $\text{O}_\alpha/(\text{O}_\alpha + \text{O}_\beta)$ ratio (47.62%) of BC-10Ce-2La/TiO₂ are the highest among all catalysts, which is favorable for the oxidation of NO to NO₂ in the “fast SCR” mechanism.³⁰ BC-10Ce-2La/TiO₂ has the second highest Ce^{3+} and the highest O_α ratio. The catalytic activity of BC-10Ce-2La/TiO₂ is slightly greater than that of IN-10Ce-2La/TiO₂ and CN-10Ce-2La/TiO₂, indicating that both Ce^{3+} and O_α ratio have an effect on the catalytic activity. The reason for the difference in Ce^{3+} and O_α ratio may be due to the difference of the new generated CeO₂ decomposed by $\text{Ce}_2(\text{CO}_3)_3$, $\text{Ce}(\text{NO}_3)_3$, $\text{Ce}(\text{OH})_3$ (for CN-10Ce-2La/TiO₂), and $\text{Ce}(\text{OH})_4$ of the different method. Also, the ball milling method accounts for the difference in Ce^{3+} and O_α ratio, because the mechanical movement is benefit to improve the O_α ratio.³¹ Therefore, the ball milling process can be used to control the dispersion of the active component on the catalyst surface and improve the redox characteristics by increasing the Ce^{3+} and O_α ratio. In the XPS of Ti 2p (Fig. 3(d)), two broad peaks are observed at approximately 458.5 eV and 464.5 eV for all samples, showing Ti presents in the highest oxidation valence Ti⁴⁺.^{30,32} In addition, all the peaks of Ce, La, O, Ti and C can be found in the survey XPS of Fig. 3(e).

The redox properties of the catalysts were studied using H₂-TPR and the results were shown in Fig. 4(a). All samples have reduction peaks at ~550 °C, which can be attributed to the reduction of surface-ligated unsaturated Ce⁴⁺ that plays an important role in the oxidation reaction.³³ In contrast, the smaller reduction peak over 600 °C is the reduction of the bulk phase of Ce⁴⁺ species.³⁴ The hydrogen consumption of the

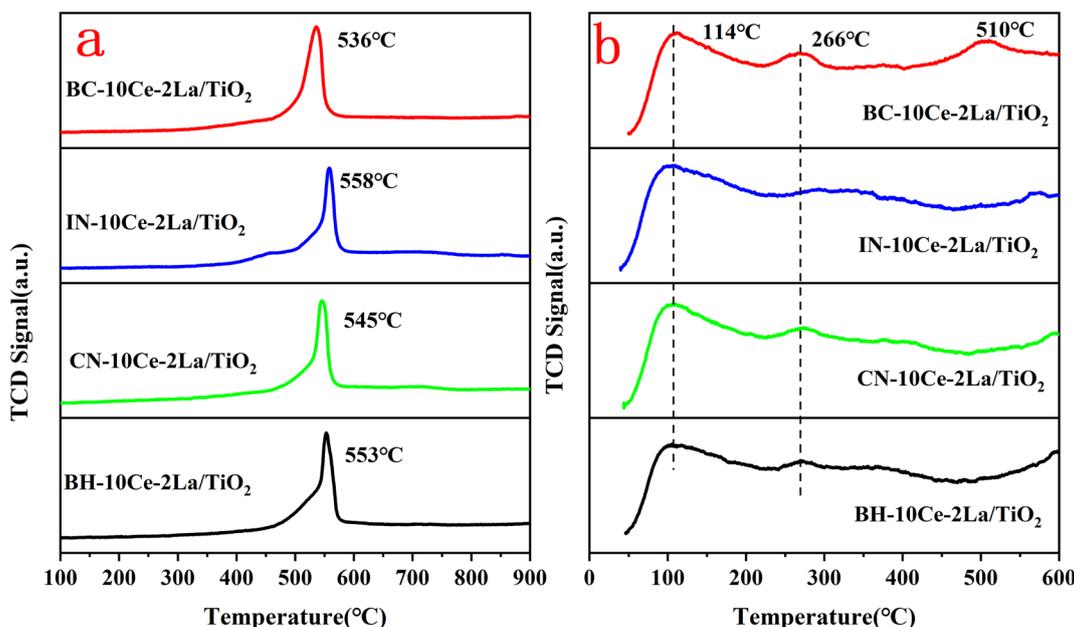


Fig. 4 (a) H₂-TPR and (b) NH₃-TPD curves of BH-10Ce-2La/TiO₂, CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂, and BC-10Ce-2La/TiO₂ catalysts.



Table 4 H₂-TPR peak position and H₂ consumption of the catalysts

Sample	Peak position (°C)	H ₂ consumption (mmol g ⁻¹)
BC-10Ce-2La/TiO ₂	536	1.37
IN-10Ce-2La/TiO ₂	558	1.21
CN-10Ce-2La/TiO ₂	545	1.16
BH-10Ce-2La/TiO ₂	553	0.93

reduction peak between 400 and 600 °C was quantified using CuO as the standard and listed in Table 4. Compared with other three samples, the reduction peak position of BC-10Ce-2La/TiO₂ catalyst was the lowest and the hydrogen consumption (1.37 mmol g⁻¹) was the highest, indicating the strongest redox ability. The results show that the surface active species of the BC-10Ce-2La/TiO₂ are highly dispersed, which not only improves the redox capacity of the catalyst, but also enhances its oxygen storage capacity. The result is consistent with the XPS calculation.

The types and numbers of acidic sites of the catalysts were investigated by NH₃-TPD and the results were shown in Fig. 4(b). The remarkable strong peaks below 200 °C and weak peaks at around 266 °C can be observed for all samples, which can be attributed to NH₃ desorbed from the weak and medium to strong acid sites of the catalysts, respectively.³³ For BC-10Ce-2La/TiO₂, there is also a broad desorption peak at 510 °C which can be attributed to the desorption of ammonia ligated to strong acidic sites.³⁵ Compared with the other three catalysts,

the desorption peak of BC-10Ce-2La/TiO₂ shifts toward higher temperatures and has a larger desorption peak area, implying that the most NH₃ adsorbed on the surface.³⁶ The above results show that the ball milling process can improve the quantity and the concentration of the acid sites on the catalyst, which helps to improve the denitrification efficiency of the catalyst.

3.2 Catalytic properties

3.2.1. Activity of catalysts. Fig. 5 shows the catalytic performance of 10Ce-2La/TiO₂ catalysts prepared by different methods. As shown in Fig. 5(a), for BH-10Ce-2La/TiO₂, with the increasing of the temperature, the NO conversion showed a slowly increasing trend from 250 to 500 °C, and then slowly decreased after reaching the highest NO conversion of 87.8% at 500 °C. The NO conversion of BC-10Ce-2La/TiO₂ was greater than 80% in the temperature range of 330–550 °C and reached a maximum of 97.2% at 380 °C, which was slightly higher than those of IN-10Ce-2La/TiO₂ and CN-10Ce-2La/TiO₂, but much higher than that of BH-10Ce-2La/TiO₂.

In addition to catalytic activity, N₂ selectivity is also an important factor to evaluate the catalyst performance. As shown in Fig. 5(b) and (c), when the reaction temperature was higher than 350 °C, N₂O started to generate, leading to a slow decrease of the N₂ selectivity. In the reaction temperature interval, the N₂ selectivity of all catalysts except CN-10Ce-2La/TiO₂ is higher than 95.4%, which is very favorable for their practical applications. Considering that the preparation process of ball milling method has minimal environmental pollution and the products

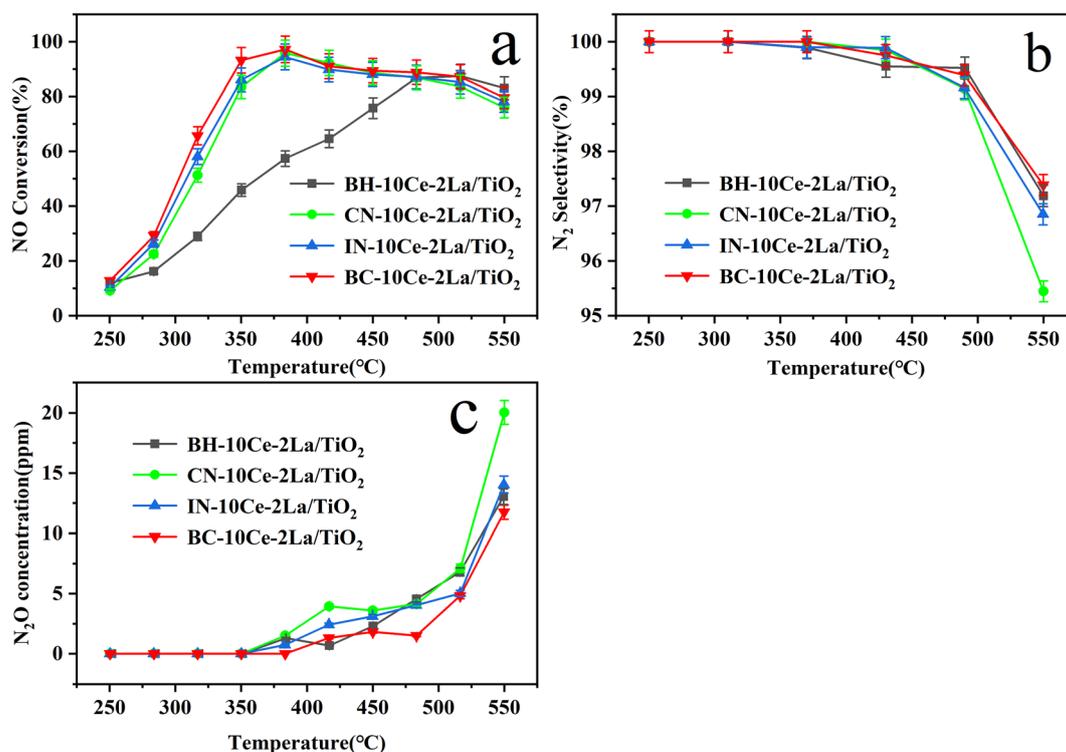


Fig. 5 (a) NO conversion, (b) N₂ selectivity, and (c) N₂O concentration of BH-10Ce-2La/TiO₂, CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂ and BC-10Ce-2La/TiO₂ catalysts.



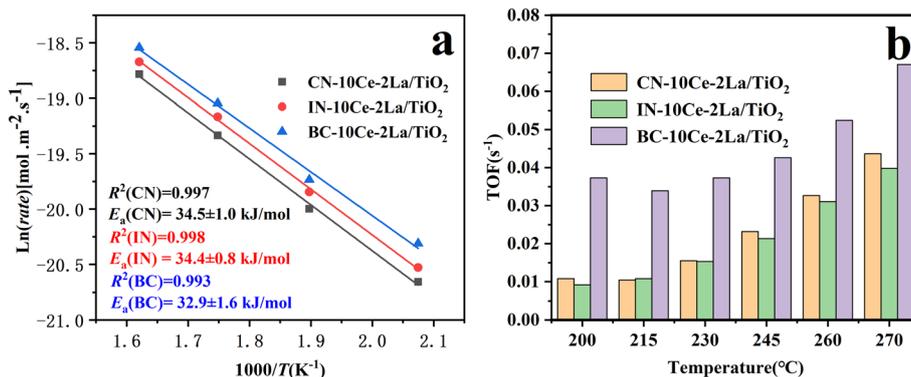


Fig. 6 (a) Arrhenius plot in 250–350 °C, (b) TOF values in 200–270 °C of CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂ and BC-10Ce-2La/TiO₂ catalysts.

have the highest catalytic activity, BC-10Ce-2La/TiO₂ should have a broad application prospect.

3.2.2. Kinetic of reaction in the presence of catalysts. For a catalytic reaction, activation energy is usually considered as a key factor to measure whether the reaction is easy to occur or not.¹⁹ The reaction rate of NO conversion per square meter of the catalysts in the temperature window of 250–350 °C was calculated according to eqn (3). By plotting $\ln(\text{rate})$ against $1/T$, the activation energy of SCR reaction performance is determined *via* the slope of the line. Fig. 6 shows the Arrhenius plot in 250–350 °C and the TOF values in 200–270 °C of the CN-10Ce-2La/TiO₂, IN-10Ce-2La/TiO₂ and BC-10Ce-2La/TiO₂ catalysts. As shown in Fig. 6(a), the activation energy of BC-10Ce-2La/TiO₂ is 32.9 kJ mol⁻¹, which is slightly lower than that of CN-10Ce-2La/TiO₂ (34.5 kJ mol⁻¹) and IN-10Ce-2La/TiO₂ (34.4 kJ mol⁻¹). The reason might be that for catalysts prepared by different methods, not all surface cerium ions are involved as active sites for NO_x reduction.³⁷ The lower activation energy of BC-10Ce-2La/TiO₂ also indicates that this catalyst requires less energy and is more likely to undergo catalytic reactions.^{16,17} To further understand the catalytic rate of different catalysts, the TOF value per Ce atom was calculated in the range of 200–270 °C. In the experiments, the maximum conversion of NO_x is controlled below 20% in the whole temperature range to eliminate the influence of diffusion. It is clear that the BC-10Ce-2La/TiO₂ catalyst exhibits higher TOF values at each temperature than the other two catalysts, indicating that the BC-10Ce-2La/TiO₂ has greater catalytic efficiency and higher intrinsic activity. According to the previous results, the reason may be owing to the synergistic effect between Ce and La catalysts, as well as more acidic sites and strength on the surface.^{18,38}

3.3 Effect of preparation methods on the activity of Ce-La/TiO₂ catalysts

Compared with impregnation method and co-precipitation method, the ball milling prepared catalyst shows excellent Ce³⁺ and O₂ Ratio, which not only benefits from the carbonate raw materials, making the active components on the catalyst surface more dispersed, but also benefits from the physical treatment process of ball milling. The high-energy ball milling process can not only enhance the interaction between Ce oxide and other

oxides, but also increase the fragmentation, extrusion and structural defects of the sample, which induces the transformation of Ce⁴⁺ to Ce³⁺ to a certain extent. Uniform active components will further improve the redox ability of the catalyst and improve the number and concentration of acid sites of the catalyst. Obviously, these advantages make BC-10Ce-2La/TiO₂ have better catalytic performance and higher TOF value than other catalysts.

4. Conclusion

In conclusion, different preparation methods and precursors have an impact on the catalytic activity of high temperature catalysts. Compared with the catalysts prepared by conventional impregnation and co-precipitation methods, the ball milling method using carbonate instead of nitrate as raw material has uniform active sites, optimal redox properties and good acidic sites. Carbonate not only can induce CeO₂ crystallization to a certain extent, but also avoid the secondary pollution problem caused by the release of NO_x during calcination with nitrate as raw material. In addition, the ball milling process has the advantages of simple operation, low grinding cost, no dust flying, and sustainable intermittent production. The less use of chemicals in the preparation process makes the environmental burden of the method relatively small, which is more in line with the requirements of green production and sustainable development, and provides a new idea for the preparation and production of denitrification catalysts.

Author contributions

Na Wang: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, writing – review & editing. **Lei Wang:** writing – original draft, data curation, formal analysis, investigation, methodology. **Huidong Xie:** investigation, methodology, project administration, supervision. **Yang Liu:** investigation, methodology. **Yepeng Sun:** data curation, formal analysis. **Chang Yang:** data curation, formal analysis. **Chengmin Ge:** conceptualization, funding acquisition, supervision, validation.



Conflicts of 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.

Acknowledgements

The work was supported by the National Natural Science Foundation of China under grant No. 51708447 and Major Scientific and Technological Innovation Projects of Shandong Province under grant No. 2019JZZY010343. The project is also supported by the Science and Technology Planning Project of Yulin City, Shaanxi Province under grant CXY-2021-135.

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