A Safer, Greener and Faster Synthesis Process of Sodium Azide by Simply Altering the Alcohol Reactant

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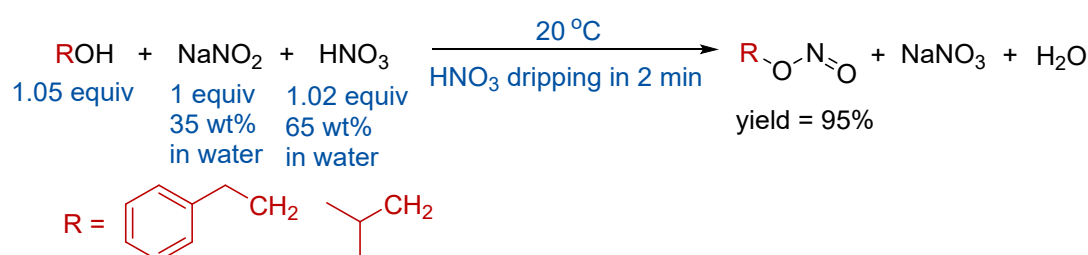## Supporting Information

1. Synthesis of nitrite ester

Figure S1. The synthesis method of nitrite ester.

The benzyl nitrite (BN) and isopropyl nitrite (IPN) used in the experiment were both synthesized in the laboratory by the method shown in **Figure S1**. After mixing 35 wt% $NaNO_2$ aqueous solution with alcohol in a three-necked flask according to the molar ratio shown in Figure S1, a 65 wt% nitric acid solution was added dropwise to the flask with stirring speed of 1000 rpm and temperature of 20 °C. After 2 min of dripping and 3 min for further aging process, the reaction was completed. After phase separation, a nitrite solution with a purity of 90 wt% was obtained in the upper organic phase, and the remaining component was the excess alcohol reactant. The lower

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aqueous phase was NaNO$_3$ generated by the reaction. The conversion rate of reactant NaNO$_2$ could

reach 100%, and the yield of product nitrite ester was 95%. The prepared nitrite ester could be stored

at 4~8 °C for 12 hours.

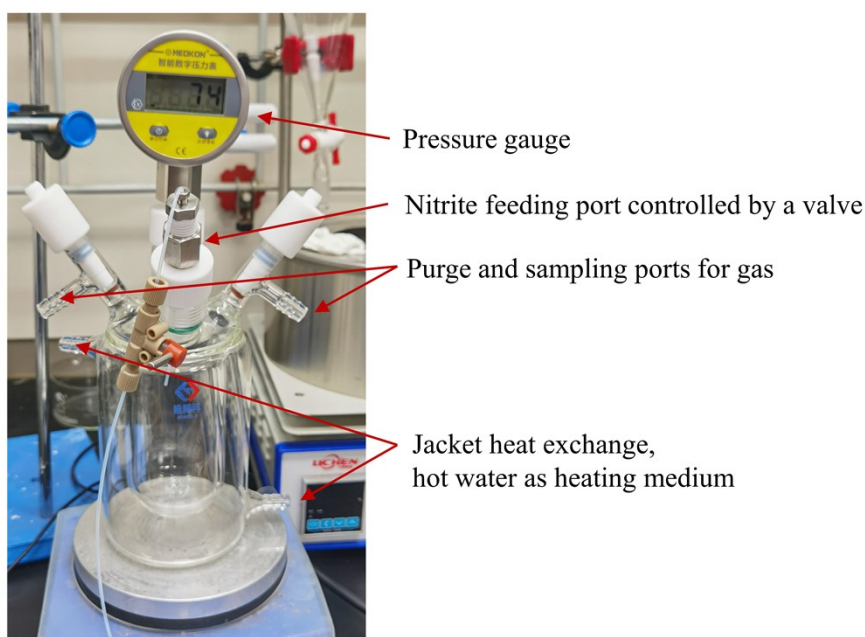## 2. Closed glass reactor

Figure S2. Closed glass reactor (gage pressure < 0.3 MPa) for the reduction reaction of nitrite ester

and hydrazine hydrate

The reactor shown in **Figure S2** allows for the monitoring of pressure changes during the

reduction reaction, as well as the collection of gaseous samples for subsequent analysis. Initially,

NaOH solution and hydrazine hydrate were mixed in the reactor, followed by the introduction of a

specific quantity of reactant alcohol. Since nitrogen was generated during the reaction, it is necessary

to replace the air in the reactor with helium or argon prior to initiating the reaction in order to avoid

interference from nitrogen in the ambient air. The mixture was heated via a jacket heat exchange and

stirred magnetically. Nitrite ester was subsequently delivered into the reactor through the feeding

port by an injection pump. The pressure change was monitored by a pressure gauge. Upon completion of the reaction, the gaseous product was introduced into an aluminum foil air bag by the positive pressure in the reactor. An airtight injection needle was subsequently used to extract samples from the air bag for analysis via gas chromatography and mass spectrometry.

3. Gas chromatography method and standard curves

Table S1 shows the gas chromatography (GC) method for the analysis of benzyl alcohol (BA) and the product benzyl nitrite (BN) in the organic phase. The standard curves with paraxylene as the internal standard substance are shown in **Figure S3**.

Table S1. GC testing method for organic phase analysis

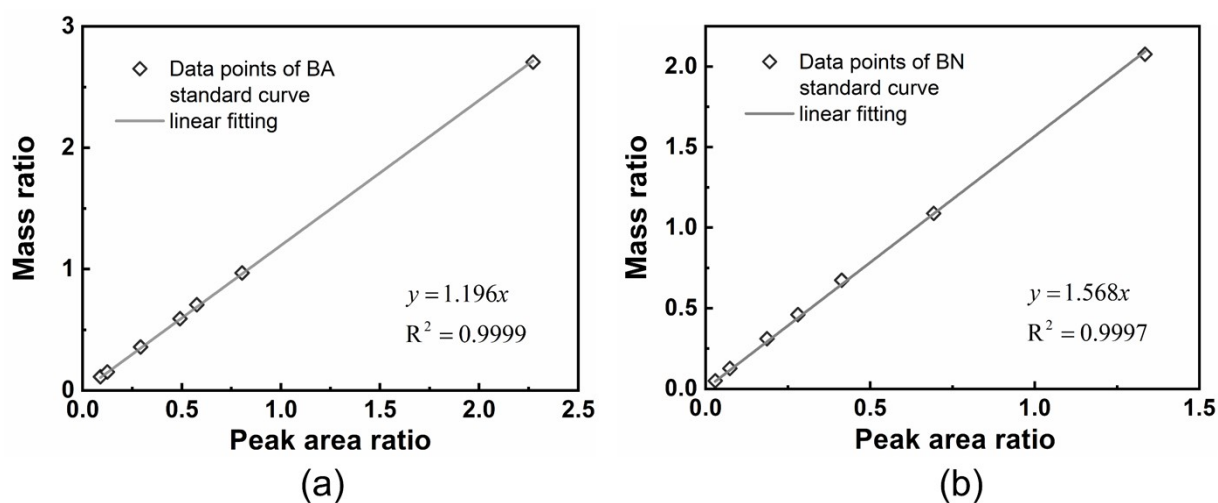|	
Device: Agilent GC-7890A	Injection temperature: 150 °C
Column: DB-17MS / 30 m × 0.25 mm × 0.25 μm	Detection temperature: 250 °C
Carrier gas: N_2, 1 mL/min; Split ratio: 30:1	Sample: 1 μL
Column temperature: start at 60 °C; 10 °C/min to 160 °C; 20 °C/min to 250 °C; maintain for 3 min	Quantitative method: internal standard
	Internal standard substance: paraxylene
Detector: FID	

Figure S3. GC standard curves of BA (a) and BN (b).

4. Ion chromatography method and standard curves

Table S2 shows the ion chromatography (IC) method for the analysis of main product NaN_3 and the side product $NaNO_2$ in the aqueous phase. The standard curves with NaCl as the internal standard substance are shown in **Figure S4**.

Table S2. IC testing conditions of the aqueous phase

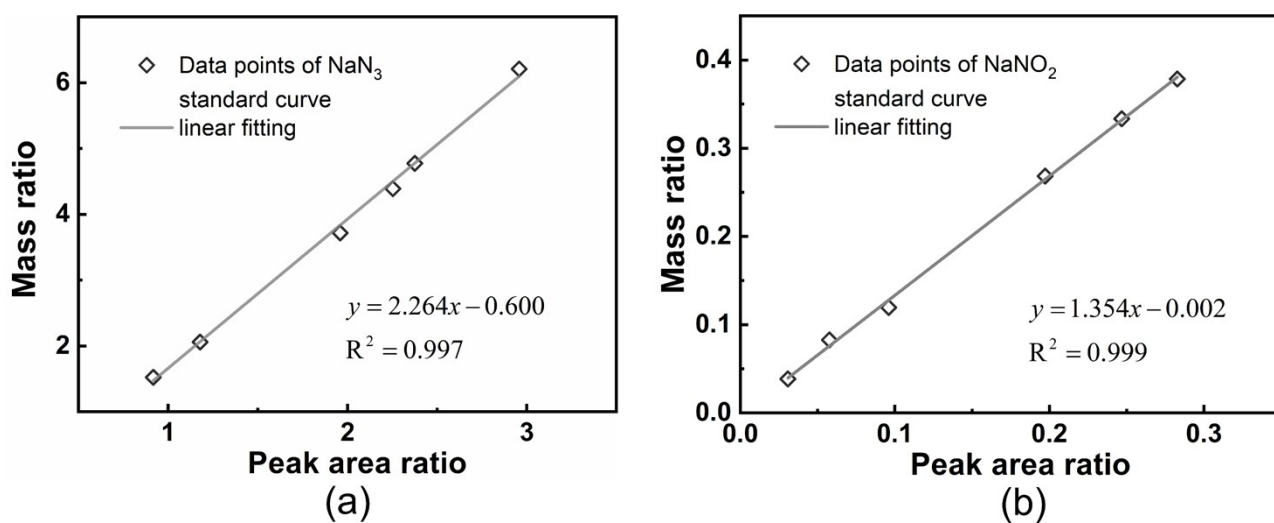|	
Device: DIONEX ICS-1100	Flow: 1 ml/min
Column: DIONEX IonPac AS15	Time: 15 min
Eluent concentration: 38 Mm KOH	Sample: 25 μL
Suppressor current: 95 mA	Quantitative method: internal standard
Column temperature: 30 °C	Internal standard substance: NaCl
Cell temperature: 35 °C	

Figure S4. IC Standard curves of NaN_3 (a) and $NaNO_2$ (b).

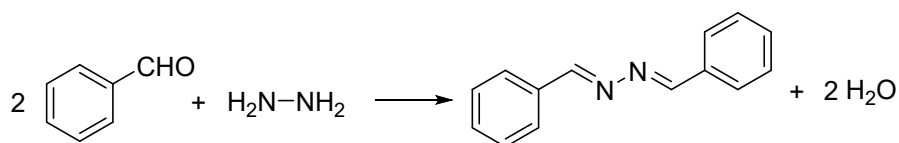## 5. Analysis method of hydrazine

Figure S5. Derivation method of hydrazine: reaction with benzaldehyde to produce benzaldehyde azine

Hydrazine hydrate cannot be directly characterized by GC. It needs to be converted to benzaldehyde azine by reaction with benzaldehyde (as shown in **Figure S5**) and then analyzed using GC. First, the sample containing hydrazine hydrate was dissolved in methanol. After addition of excess derivative reagent benzaldehyde, the hydrazine hydrate can be completely converted to benzaldehyde azine at room temperature (20 °C) for 1h or under heating condition (40 °C) for 10 min. The mass fraction of benzaldehyde azine can be determined by GC using the method in **Table S3**, and the internal standard curve of benzaldehyde azine is shown in **Figure S6**. The mass fraction of hydrazine hydrate can be calculated based on the conversion relation provided in Figure S5.

Table S3. GC testing conditions of N_2H_4

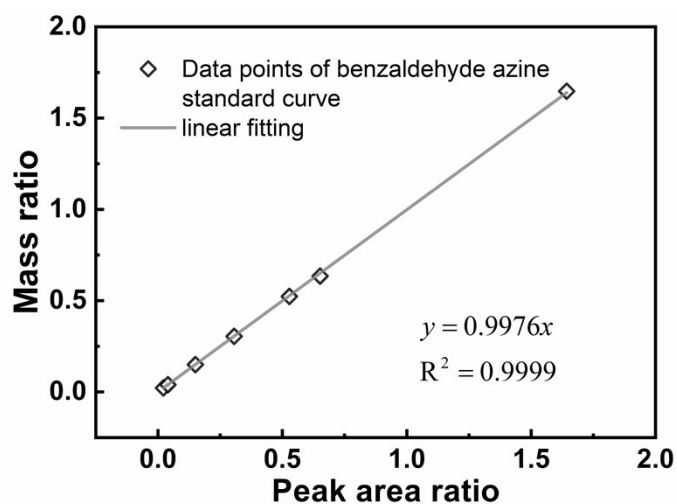|	
Device: Agilent GC-7890A	Injection temperature: 250 °C
Column: DB-17MS / 30 m × 0.25 mm × 0.25 μm	Detection temperature: 300 °C
Carrier gas: N_2, 1 mL/min; Split ratio: 30:1	Sample: 1 μL
Column temperature: start at 60 °C; 10 °C/min to 150 °C; 20 °C/min to 300 °C; maintain for 5 min	Quantitative method: internal standard
	Internal standard substance: paraxylene
Detector: FID	

Figure S6. GC standard curve of benzaldehyde azine

6. Analysis of gaseous side products

6.1 Qualitative analysis by gas chromatography tandem mass spectrometry (GC-MS)
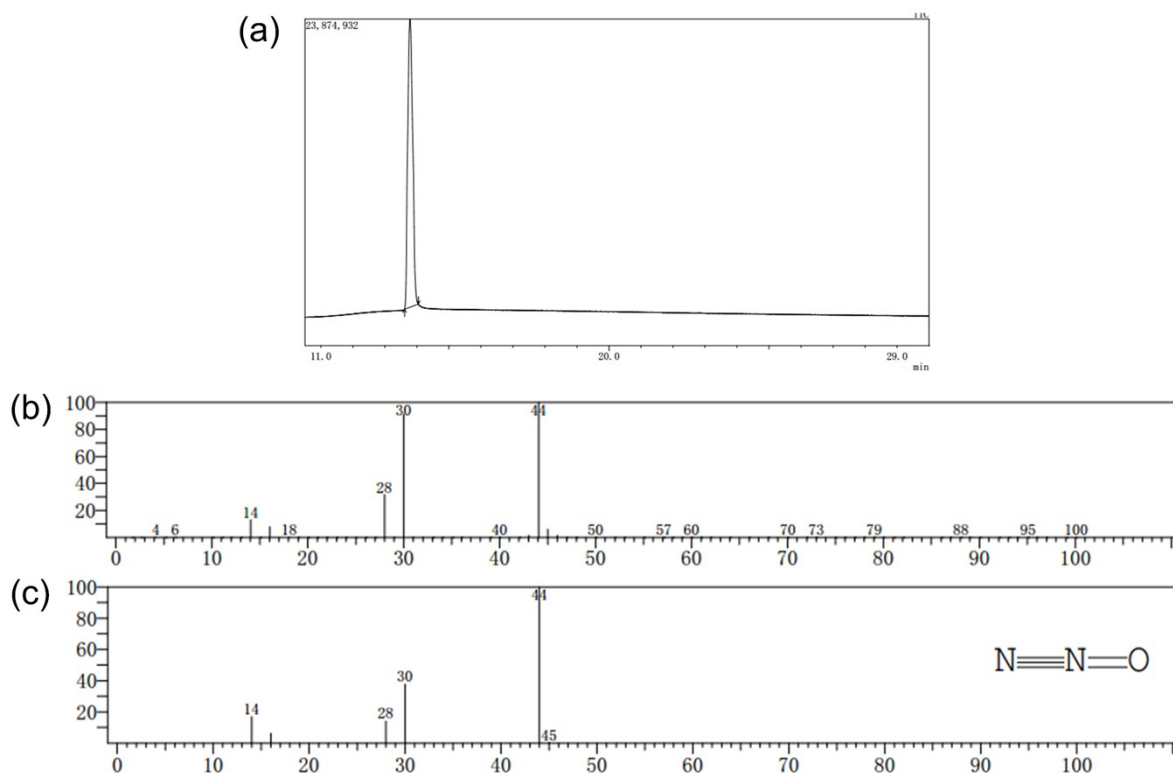

Figure S7. (a) GC chromatogram of the gaseous sample. (b) Mass spectrogram at retention time of

14 min in GC chromatogram. (c) Standard mass spectrogram of N_2O.

According to the characterization results shown in **Figure S7**, it is confirmed that there is N_2O in the gaseous sample. Therefore, the reduction reaction of nitrite ester and hydrazine hydrate in the presence of NaOH generates a gaseous side product N_2O.

When nitrogen characterization is conducted, it is essential to prevent the interference of N_2 in the ambient air throughout the experiment, sampling, and analysis procedures. Based on the reaction mechanism, it is reasonable to suggest that the formation of oxygen can be ruled out in a reducing reaction environment. Thus, any detected oxygen in the gaseous sample should be attributed to air contamination. The gaseous sample in the reactor without adding nitrite was the control group, and the sample taken after the reduction reaction was the experimental group. The characterization results are shown in **Figures S8** (a) and (b), respectively. In the control group, the volume ratio of O_2 to N_2 was found to be 1:3.6, which corresponds to the ratio in ambient air. Conversely, the volume ratio of O_2 to N_2 in the experimental group was found to be 1:16, confirming that the reduction reaction of nitrite and hydrazine hydrate generates a gaseous side product N_2.
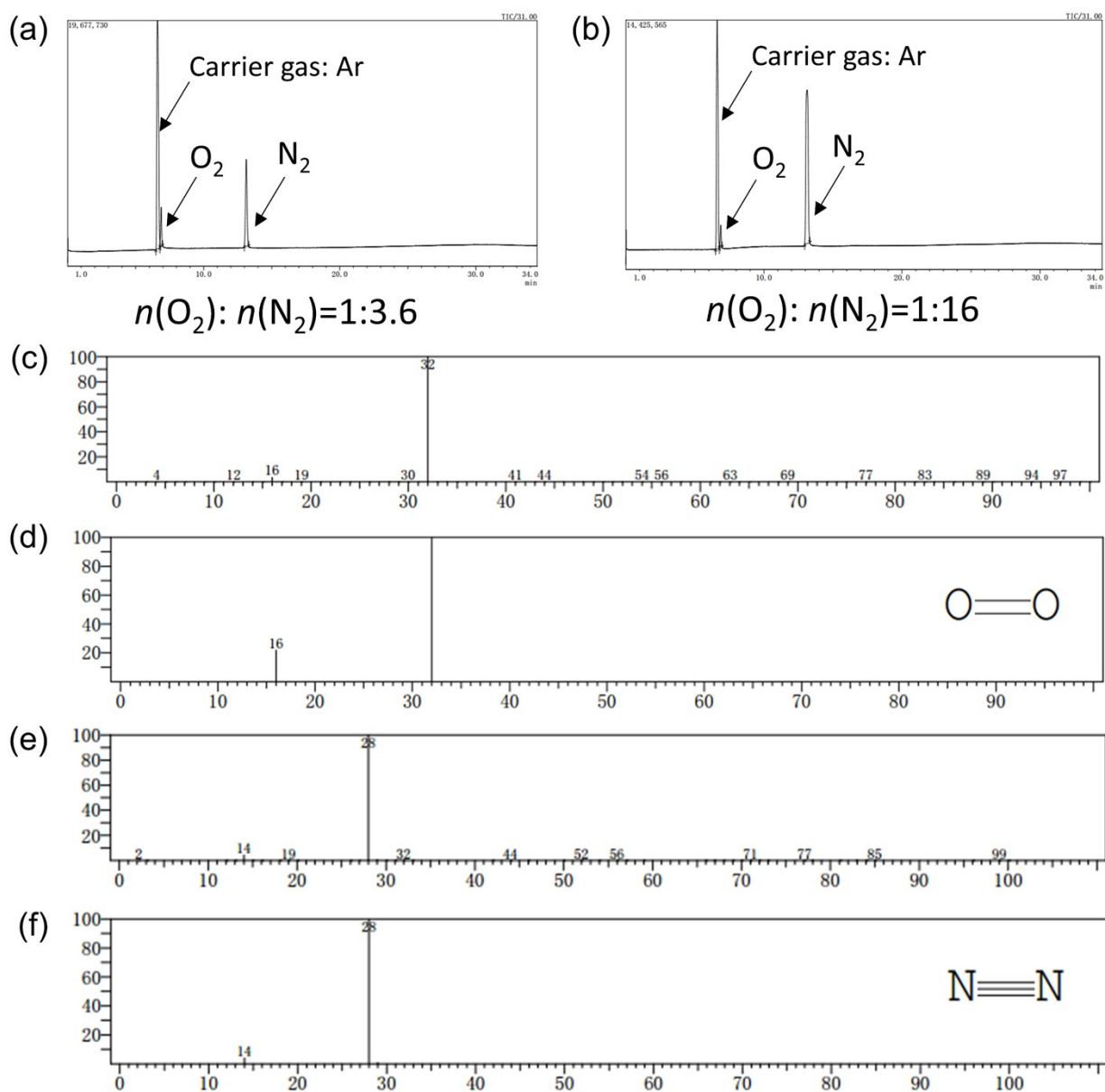
Figure S8. (a) GC chromatogram of control group (the column and method used in GC for the analysis of N_2 and O_2 is different from that of N_2O). (b) GC chromatogram of experimental group. (c) Mass spectrogram at retention time of 6.9 min in GC chromatogram. (d) Standard mass spectrogram of O_2. (e) Mass spectrogram at retention time of 13.1 min in GC chromatogram. (f) Standard mass spectrogram of N_2.
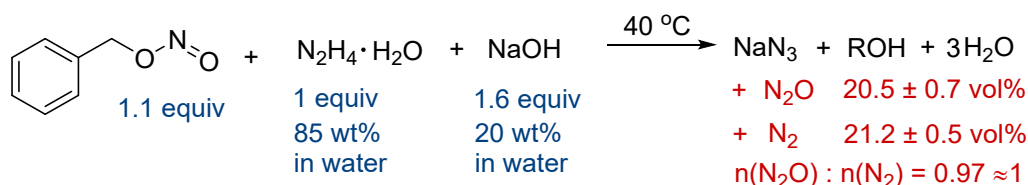
6.2 Quantitative Analysis of N_2O and N_2 by GC

Only two gaseous side products, N_2O and N_2, were identified, and the total quantity of gas generated throughout the reaction could be calculated according to the pressure change. Therefore, by quantifying the molar ratio (volume ratio) of N_2O to N_2, the quantity of each gaseous side product could be calculated. First, the external standard curves of O_2, N_2, and N_2O were established. Based on the analysis in Section 6.1, the volume fraction of N_2O can be directly measured, and the volume fraction of nitrogen ($V_{N_2}^{T}(\%)$) consists of two parts: one resulting from the side reaction ($V_{N_2}^{R}(\%)$) and the other from the contamination of ambient air ($V_{N_2}^{Air}(\%)$). The latter can be characterized according to the mass fraction of O_2 ($V_{O_2}(\%)$). Therefore, the fraction of N_2 generated by the side reaction can be calculated by subtracting the second part from the total volume fraction of N_2, as shown in Eq (1).

$$V_{N_2}^{R}(\%) = V_{N_2}^{T}(\%) - V_{N_2}^{Air}(\%) = V_{N_2}^{T}(\%) - \frac{78}{21} V_{O_2}(\%) \qquad \text{(Eq S1)}$$

Table S4 shows the results of two parallel analysis. Based on the mean value of the volume fractions of N_2O and N_2, $n_{N_2O} / n_{N_2}(\%) = 20.5 / 21.2 = 0.97 \approx 1$, thus demonstrating that the reduction reaction of nitrite and hydrazine hydrate generates equal molar of N_2O and N_2. The measuring error of O_2 and N_2 is relatively large because of the contamination of air is hard to control in the sampling and analysis process, but the needed value $V_{N_2}^{R}(\%)$ calculated by Eq S1 is accurate because it eliminates the effect of air contamination.

Table S4. Quantitative characterization of N_2O and N_2

$$\text{(BnO-N=O)} + N_2H_4 \cdot H_2O + NaOH \xrightarrow{40\ °C} NaN_3 + ROH + 3H_2O$$

1.1 equiv   1 equiv   1.6 equiv

85 wt%   20 wt%

in water   in water

$+\ N_2O$ 20.5 ± 0.7 vol%

$+\ N_2$ 21.2 ± 0.5 vol%

$n(N_2O) : n(N_2) = 0.97 \approx 1$

Entry	N_2O (vol%)	O_2 (vol%)	N_2 (vol%)	N_2 produced in reaction (vol%)
1	21.2	2.54	31.16	21.7
2	19.8	3.65	34.18	20.6
Mean value	20.5±0.7	/	/	21.2±0.5

7. Constant interface experiment in a cuvette

First, an aqueous solution of NaOH and hydrazine hydrate was added to a transparent cuvette. A high-speed camera (FASTCAM Mini AX200, Photron, Japan) was then set up to record the reaction as a mixed solution of benzyl nitrite (BN) and benzyl alcohol (BA) (each 50 wt%) was introduced. The reaction was observed and filmed at room temperature (20 °C). **Figures S9** (a) and (b) show the shooting footage of 1 minute and 1 hour after the addition of BN, respectively. The observation of precipitation and bubbles forming in the upper organic phase provides evidence that the organic phase is the primary area where the reduction reaction takes place. Videos S1 and S2 are complete video material.

Video S1. This video recorded the reaction within 84 seconds following the addition of BN (At 70 seconds, the brightness of the background light was increased to mitigate the influence of precipitate on bubble observation).

Video S2. This video recorded the reaction 1 hour after the addition of BN.
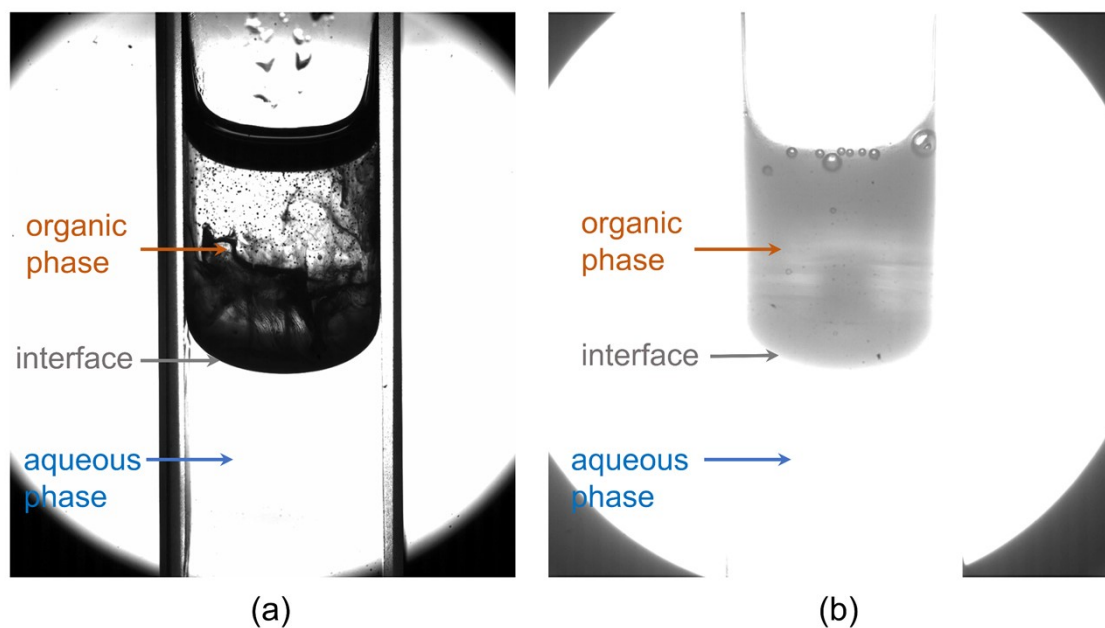
Figure S9. (a) Image of 1min after adding BN; (b) Image of 1h after adding BN, the brightness of the background light was increased to mitigate the influence of precipitate on bubble observation.

8. Substance conservation

Table S5 shows the formation and transformation of each substance in a typical reduction reaction of BN and hydrazine hydrate at 40 °C. According to Eq S2, the consumption of hydrazine hydrate ($\Delta n(\mathrm{N_2H_4})$) is approximately equal to the sum of the formed NaN₃ ($\Delta n(\mathrm{NaN_3})$) and half the gas amount generated during the reaction ($\Delta n(\mathrm{Gas})$). Similarly, according to Eq S3, the consumption of BN ($\Delta n(\mathrm{BN})$) is approximately equal to the sum of the formed NaN₃ ($\Delta n(\mathrm{NaN_3})$), the hydrolysis amount of BN ($\Delta n(\mathrm{NaNO_2})$), and the amount of gas generated during the reaction ($\Delta n(\mathrm{Gas})$). This is consistent with the transformation relation of each substance in the main and side reactions shown in **Figure S10**. Substance conservation could help prove the correctness of the reaction mechanism depicted in Figure 5(b) of the main text.

Table S5. The amount of each substance formed and consumed in the reduction reaction of BN and hydrazine hydrate in the presence of NaOH.

Substance amount	N_2H_4	BN	BA	$NaNO_2$	NaN_3	Gas
initial/mmol	45.5	51.9	63.0	0	0	0
ending/mmol	0	0.4	113.9	1.6	40.9	8.1
conversion/mmol	45.5	51.5	50.8	1.6	40.9	8.1

$$\Delta n(\text{N}_2\text{H}_4) = 45.5 \text{ mmol} \approx 44.95 \text{ mmol} = \Delta n(\text{NaN}_3) + \frac{1}{2}\Delta n(\text{Gas}) \qquad (\text{Eq S2})$$

$$\Delta n(\text{BN}) = 51.5 \text{ mmol} \approx 50.6 \text{ mmol} = \Delta n(\text{NaN}_3) + \Delta n(\text{NaNO}_2) + \Delta n(\text{Gas}) \qquad (\text{Eq S3})$$
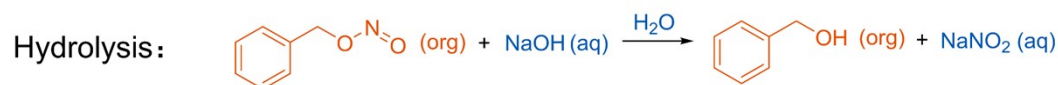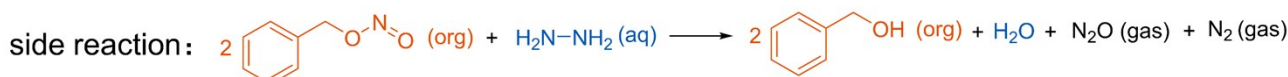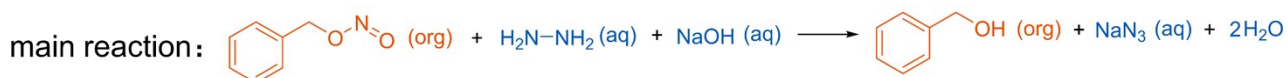

Figure S10. Reaction equations of the reduction reaction of BN and hydrazine hydrate producing NaN_3, the side reaction forming the gaseous side products, and the hydrolysis reaction of BN.

9. Reaction intermediates characterized by inline infrared spectrometer

Figure S11(a) shows the inline Fourier transform infrared spectrometer (FT-IR) and associated experimental equipment. The experiment was carried out in a flask with magnetic stirring. First, 15 ml solution containing 50 wt% benzyl alcohol (BA) and 50 wt% benzyl nitrite (BN) was added to the flask. The infrared probe was inserted to detect the spectrogram of the organic reactants as background infrared absorption. Subsequently, 0.15 ml aqueous solution of hydrazine hydrate (7.3 wt%, based on N_2H_4) and NaOH (15 wt%) was delivered by a syringe pump. The change in infrared

absorption in the reaction system was monitored in real time at an interval of 30 s. The results are shown in Figure S11(b).

According to the projection image at the bottom of Figure S11(b), the infrared absorption intensity varies significantly in the ranges of 1350~1380 cm^{-1} and 1440~1480 cm^{-1}. 1440~1480 cm^{-1} conforms to the stretching vibration of the azo (N=N) compound, and therefore corresponds to the characteristic infrared absorption of intermediate **I**. 1350~1380 cm^{-1} corresponds to the characteristic infrared absorption of intermediate **II**, which is generated by the reaction of intermediate **I** and BN, because it possesses a conjugated nitrogen-nitrogen double bond structure (N=N-N=N) that can lead to a redshift of infrared absorption. Figure 5(d) in the main text is obtained by extracting absorption signal at 1456 cm-1 and 1363 cm-1 and shown against reaction time. Infrared absorption intensity is proportional to substance concentration. Upon adding hydrazine hydrate to initiate the reaction, the infrared absorption at 1350~1380 cm^{-1} and 1440~1480 cm^{-1} both showed a trend of initially increasing and subsequently decreasing, which conforms to the regularity of concentration change of the highly active intermediates.
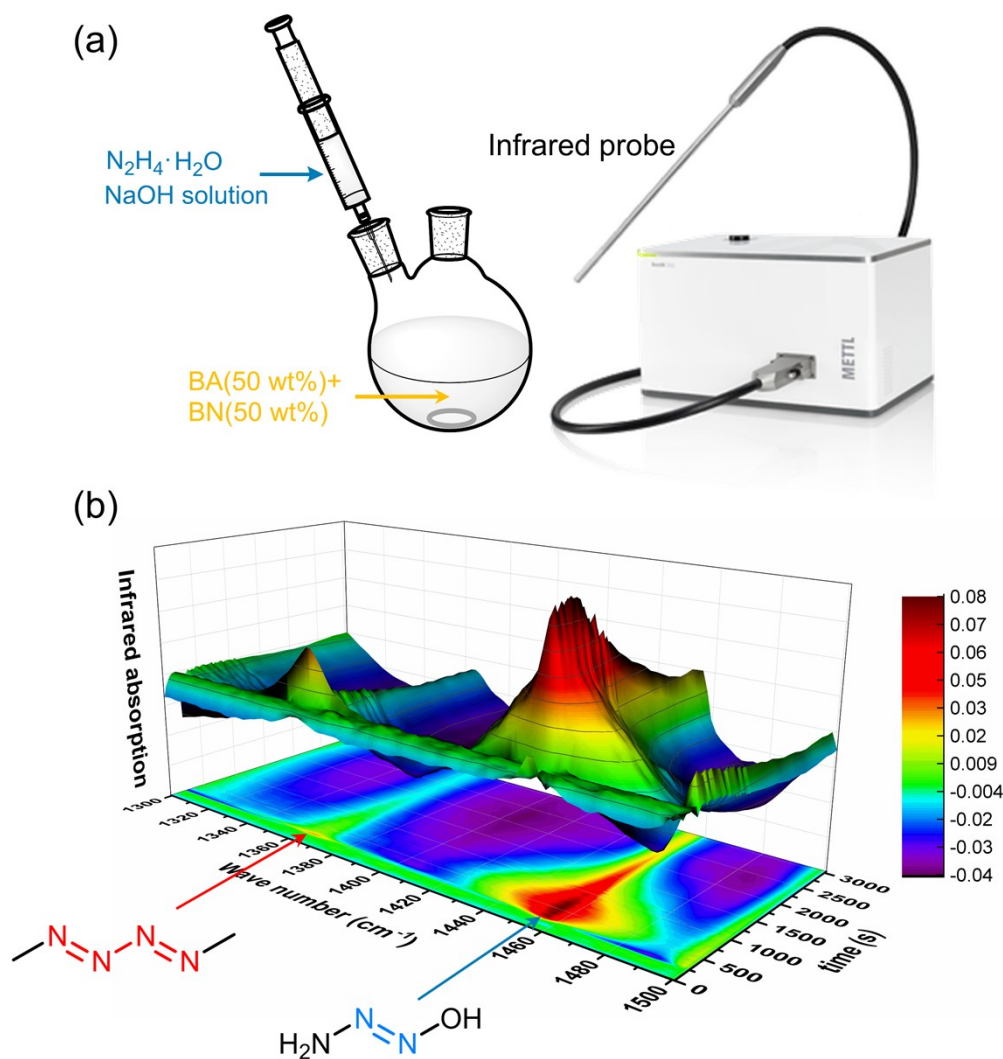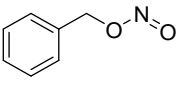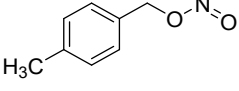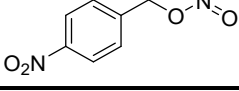
Figure S11. (a) Inline Fourier transform infrared spectrometer and associated experimental equipment. (b) The variation of infrared absorption at the wavenumber 1300 cm^{-1} to 1500 cm^{-1} with reaction time.

10. Reduction reaction using benzyl nitrite and other substituted benzyl structures

The experimental results in Table S6 compare the reaction rate and product yield that obtained in the reduction reaction using benzyl nitrite (BN) and other two benzyl nitrites with substituted groups, 4-methylbenzyl nitrite (MBN), and 4-nitrobenzyl nitrite (NBN). Based on the kinetic behaviors of the aminolysis reaction of amines with esters to prepare amides, the activation energy declines as the electron cloud density around the benzene ring decreases.[1] Therefore, MBN that connected with an electron-donating group shows a relatively lower reaction rate; in contrast, NBN exhibits a higher reaction rate because an electron-withdrawing group is presented in the benzyl structure. However, as shown in Figure S12(a), the gage pressure exceeded 100 kPa when using NBN as raw material, which means extensive gaseous side products (N_2 and N_2O, the side reaction pathways are illustrated in Figure 5 in the main text) were generated, leading to only 58% yield of NaN_3. In addition, the melting point of 4-nitrobenzyl alcohol is 93 ^{o}C, which is much higher than the temperature used for reduction reaction. As a result, a large amount of 4-nitrobenzyl alcohol generated during the reduction reaction precipitated from the system, forming a slurry state (Figure S12(c)). This means the generated alcohol can no longer function as a solvent to extract hydrazine from the aqueous phase to the organic phase, thus reducing the reaction selectivity (the strategies to improve selectivity are discussed in Figure 6 in the main text).

Table S6. Comparison of benzyl nitrite (BN), 4-methylbenzyl nitrite (MBN), and 4-nitrobenzyl nitrite (NBN) in the reduction reaction with hydrazine hydrate to produce sodium azide.

$$R\text{-}O\text{-}N\text{=}O + N_2H_4 \cdot H_2O + NaOH \xrightarrow[\text{nitrite ester dripping in 10 min}]{40\ ^\circ C} NaN_3 + ROH + 3H_2O$$

1 equiv   1 equiv   1.1 equiv
            85 wt%   30 wt%
            in water   in water

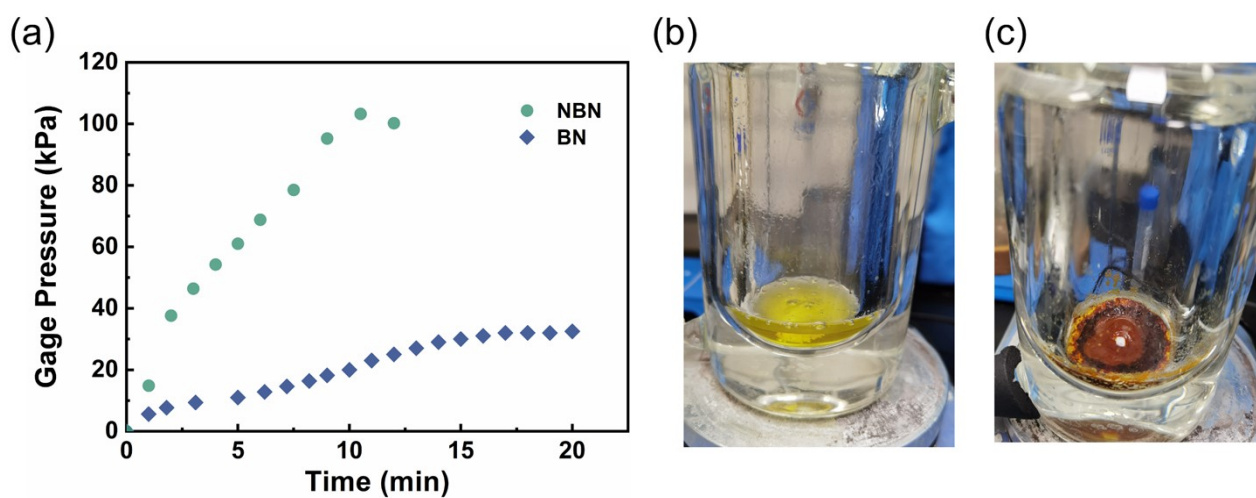| Nitrite ester	Reaction time (min)	Conversion of ester (%)	Yield of NaN_3
BN	20	94	84
MBN	20	16	12
NBN	12	100	58

Figure S12. Comparison of benzyl nitrite (BN) and 4-nitrobenzyl nitrite (NBN) in the reduction reaction. (a) Change of pressure as a function of reaction time. (b) Product state after the reduction reaction using BN as raw material. (c) Product state after the reduction reaction using NBN as raw material.

References

1. V. Findik, M. F. Ruiz-Lopez and S. S. Erdem, *Org. Biomol. Chem.*, 2021, 19, 9996-10004.