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Novel effect of coupled external and internal noise in stochastic resonance[☆]

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Abstract

In this paper, on the basis of mesoscopic stochastic model of NO reduction by CO on single-crystal platinum surfaces, we report a novel effect of the external noise of reaction rate constant coupled to internal noise in stochastic resonance induced by external noise (SREN) or internal noise (SRIN). It is shown that the internal noise can enhance the SREN, and the external noise intensity for the SREN increases with increasing internal noise. However, the external noise can suppress the SRIN, and the suppressions nonmonotonously vary with the increasing external noise intensity. This result is different from the effect of the external noise of NO partial pressure coupled to the internal noise in the SR behavior of the system, which shows that the various external noise sources have different effects in the SRIN. And different roles of positive or negative feedback of the external noise terms may be a probable mechanism for the difference.

Keywords: Stochastic resonance; External noise; Internal noise; Chemical Langevin equation; Catalytic NO reduction by CO reaction

1. Introduction

Over the past two decades, stochastic resonance (SR) phenomena, a rather counterintuitive fact that the response of a nonlinear system to an external periodic signal may be enhanced through an optimal external noise, have been widely studied in physical, chemical, and biological systems [1–18]. In recent years, the effect of internal noise has attracted much attention, and the internal noise-induced SR phenomena have been observed in biological and chemical systems, including ion channel gating and neuron spiking [19–24], circadian clocks [25–28], intracellular calcium signaling [29,30], genetic regulation [31,32], CO oxidation on nanometer-sized particles or very small single-crystal surfaces [33–39], and NO reduction on small-size Pt surfaces [40,41]. Notably, the SR phenomena have already been observed in experiments [15–18,34–39]. It is shown that the internal noise can induce stochastic oscillations when the system is sub-threshold or supra-threshold, and the stochastic oscillations show the best performance at an optimal system size.

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It is known that the external noise may originate from the random variation of one or more of the externally set control parameters, such as reaction rate constants or partial pressures associated with a given set of reactions, while internal noise comes from the random fluctuations of the stochastic chemical reaction events [42–45] in a finite-size chemical system. Internal and external noise may simultaneously arise in finite-size chemical reaction systems, and hence they should be considered simultaneously.

In fact, the effects of external and internal noise on the oscillatory kinetics in biological and chemical reaction systems have already been studied. It was found that the external noise or the internal noise can either enhance or reduce the SR in ion channels [19–22]. External noise coherence resonance can be suppressed by internal noise, while internal noise coherence resonance can be enhanced by the modulation of external noise strength in a circadian oscillator [46]. However, the external and internal noise in these studies are usually considered independent, and this case is obviously unrealistic compared to the real systems in which the internal noise from the stochastic chemical reaction events might be associated with the external noise of reaction rate constants or gas partial pressures. Therefore, the external noise and internal noise are often coupled to each other, and this kind of coupling would cause different effects on the oscillatory kinetics of the systems. Recently, the effect of system size (internal noise) on the reaction oscillations and internal noise-induced SR have been studied [40,41]. Very recently, our study of the effect of the external noise of NO partial pressure coupled to internal noise in the system of NO catalytic reduction reaction has shown that the SR induced by the external noise (SREN) can be enhanced by the internal noise, and the SR induced by the internal noise (SRIN) can also be enhanced by the external noise [47]. Since the external noise may come from the random variations of various externally set control parameters, it is necessary and significant to investigate the effects of different kinds of external noises. The goal of this paper is to discuss how the coupled external noise of reaction rate constant and the internal noise affect the SREN and SRIN.

In this paper, based on the NO stochastic reaction model, we have investigated the effect of the external noise of reaction rate constant coupled to internal noise in the SREN and SRIN. It is found that an optimal internal noise can enhance the SREN, while the external noise can suppress the SRIN. However, the suppressions of internal noise nonmonotonously change with the increasing external noise intensity. In addition, the external noise intensity for the occurrence of SREN increases with the increasing internal noise. This result is different from the performance of the external noise of NO partial pressure coupled to internal noise [47]. A simple mechanism for this difference is given.

2. Model

The stochastic model here is developed on the basis of the deterministic model [48]. Following the Langmüir–Hinshelwood mechanism, the NO + CO reaction on Pt (100) can be described by the following steps [48]:

$$\mathrm{CO_{gas}} \underset{k_2}{\overset{k_1}{\rightleftarrows}} \mathrm{CO_{ads}}, \quad \mathrm{NO_{gas}} \underset{k_4}{\overset{k_3}{\rightleftarrows}} \mathrm{NO_{ads}}, \quad \mathrm{NO_{ads}} \xrightarrow{k_5} \mathrm{N_{ads}} + \mathrm{O_{ads}},$$
$$2\mathrm{N_{ads}} \rightarrow (\mathrm{N_2})_{\mathrm{gas}}, \quad \mathrm{CO_{ads}} + \mathrm{O_{ads}} \xrightarrow{k_6} (\mathrm{CO_2})_{\mathrm{gas}}. \tag{1}$$

The deterministic kinetics of (1) is governed by:

$$\frac{\mathrm{d}\theta_{\mathrm{CO}}}{\mathrm{d}t} = k_1 P_{\mathrm{CO}}(1-\theta_{\mathrm{CO}}-\theta_{\mathrm{NO}}) - k_2\theta_{\mathrm{CO}} - k_6\theta_{\mathrm{CO}}\theta_{\mathrm{O}},$$
$$\frac{\mathrm{d}\theta_{\mathrm{NO}}}{\mathrm{d}t} = k_1 P_{\mathrm{NO}}(1-\theta_{\mathrm{CO}}-\theta_{\mathrm{NO}}) - k_4\theta_{\mathrm{NO}} - k_5\theta_{\mathrm{NO}}\theta_{\mathrm{empty}}, \tag{2}$$
$$\frac{\mathrm{d}\theta_{\mathrm{O}}}{\mathrm{d}t} = k_5\theta_{\mathrm{NO}}\theta_{\mathrm{empty}} - k_6\theta_{\mathrm{CO}}\theta_{\mathrm{O}},$$

with

$$\theta_{\mathrm{empty}} = \max\left[\left(1 - \frac{\theta_{\mathrm{CO}}+\theta_{\mathrm{NO}}}{\theta^{\mathrm{inh}}_{\mathrm{CO,NO}}} - \frac{\theta_{\mathrm{O}}}{\theta^{\mathrm{inh}}_{\mathrm{O}}}\right), 0\right],$$

where $\theta_{\mathrm{NO,CO,O}}$ stand for the absorbed coverage of NO, CO, and oxygen. These equations consist of the adsorption and desorption of NO and CO (k_1, k_2, k_3, and k_4), the dissociation of NO (k_5), and the surface reaction between adsorbed oxygen and adsorbed CO to form CO_2 (k_6). P_{CO} and P_{NO} are the respective partial pressures of CO and NO gas.