

Nuclear spin induced transparency

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Electromagnetically induced transparency (EIT) is an important quantum optical phenomenon which provides a crucial tool for light manipulation. However, typically the transparency window is broad, limited by the coherence time of the metastable state. Here, we show that an extremely narrow transparency window can be realized using nuclear spin induced transparency (NSIT), which is achieved by combining the optical field, magnetic field, and the spin-exchange interaction between noble-gas nuclear spins and alkali-metal electronic spins. The width of the NSIT window can be several orders of magnitude smaller than that of conventional EIT, and even reaches the sub-mHz range due to the long coherence time of nuclear spins. The scheme holds great potential for applications in slow light and magnetic field sensing.

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Electromagnetically induced transparency (EIT) arises from the quantum interference between transition paths driven by light fields in three-level atoms or atomlike systems. Since the discovery of EIT [1–3], various related applications have been proposed including slow light [4–9], optical storage [10,11], and nonlinear effects [5,12], and thus EIT has become an important research area in quantum optics and quantum information [13]. In addition, various EIT-like effects based on different platforms have also been demonstrated [14], e.g., all-optical induced transparency [14–21], optomechanical induced transparency [22–27], and plasmon induced transparency [28,29]. Nevertheless, the EIT window is typically broad due to the finite lifetime of the metastable state, which limits its applications.

Meanwhile, the rare isotope of a noble-gas atom, such as ³He and ¹²⁹Xe, has nonzero nuclear spin, which is isolated from the environment due to the complete electronic shell and thus can have a coherence time longer than 1 h at or over room temperature [30–32]. Due to the unique properties, the research and applications on noble-gas nuclear spins have been extensively developed in various fields [30], including precision measurement [33–36], medical imaging [37–39], searches for new physics beyond the standard model [40–43], and quantum information technology [44,45]. Recently, the coherent spin-exchange interaction between nuclear spins of a noble-gas ensemble and electronic spins of an

alkali-metal ensemble has been confirmed [44,46,47]. Based on this interaction, the theoretical schemes of long-lived entanglement generation [48] and quantum memory [45] have also been proposed.

However, since the nuclear spins are optically inaccessible, it is difficult to construct a conventional three-level EIT system with a long-lived metastable state directly. Here, we demonstrate an analog of EIT by combining an optical field, magnetic field, and the spin-exchange interaction between noble-gas nuclear spins and alkali-metal electronic spins, which we call nuclear spin induced transparency (NSIT). This effect can be described by an effective four-level model, through which we obtain analytical results. A very narrow transparency window can be obtained, approaching the relaxation rate of noble-gas nuclear spins. The center position of the window is linearly dependent on the external magnetic field strength. The corresponding dispersion curve is extremely steep, resulting in a strong slow light effect.

The system we consider is an alkali-metal vapor mixed with a noble gas as shown in Fig. 1(a), with atomic densities n_a and n_b , respectively. The alkali-metal atom is modeled as a Λ system consisting of a ground state $|\downarrow\rangle$, a metastable state $|\uparrow\rangle$, and an excited state $|p\rangle$. A control field with frequency ω_c and a probe field with frequency ω_p drive the transitions $|\uparrow\rangle \leftrightarrow |p\rangle$ and $|\downarrow\rangle \leftrightarrow |p\rangle$, respectively. The probe field is much weaker than the control field and propagates in the same direction as the control field to eliminate Doppler broadening. The noble-gas atom with nuclear spin $1/2$ consists of down- and up-spin states $|\downarrow\rangle$, $|\uparrow\rangle$. An external magnetic field B along the quantization axis causes the Zeeman splitting of the alkali-metal and noble-gas spins $\gamma_s B$ and $\gamma_k B$, respectively, where the gyromagnetic ratios satisfy $\gamma_s \gg \gamma_k$. In this hybrid system, a coherent interaction has been demonstrated between the collective alkali-metal and noble-gas spins polarized along the same direction [44,46,47]. This interaction can be

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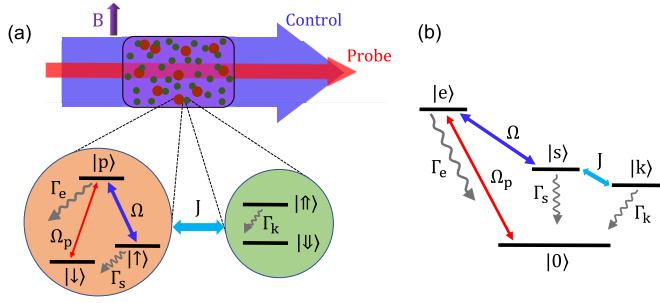


FIG. 1. (a) Schematic diagram of the alkali-metal and noble-gas mixture. The alkali-metal atom is modeled as a Λ system consisting of a ground state $|\downarrow\rangle$, a metastable state $|\uparrow\rangle$, and an excited state $|p\rangle$. The transitions $|\uparrow\rangle \leftrightarrow |p\rangle$ and $|\downarrow\rangle \leftrightarrow |p\rangle$ are driven by a control field (Ω) and a probe field (Ω_p), respectively. The noble-gas atom consists of down- and up-spin states $|\downarrow\rangle$, $|\uparrow\rangle$. The coherent spin-exchange interactions between the noble-gas nuclear spins and the alkali-metal electronic spins are marked with sky blue arrows (J). (b) Equivalent energy levels of the hybrid system in (a), with $|0\rangle \equiv |\downarrow\rangle|\downarrow\rangle$, $|e\rangle \equiv |p\rangle|\downarrow\rangle$, $|s\rangle \equiv |\uparrow\rangle|\downarrow\rangle$, and $|k\rangle \equiv |\downarrow\rangle|\uparrow\rangle$. The dissipation rates of the three excited states satisfy $\Gamma_e \gg \Gamma_s \gg \Gamma_k$.

expressed as

$$H_{\text{sec}} = \hbar \int d^3\mathbf{r} \left(\zeta \frac{[I]}{4} (X_{\downarrow\downarrow} + q_I X_{\uparrow\uparrow})(X_{\downarrow\downarrow} - X_{\uparrow\uparrow}) + \zeta \frac{\sqrt{[I]}}{2} (X_{\downarrow\uparrow} X_{\uparrow\downarrow} + \text{H.c.}) \right), \quad (1)$$

where $\mathbf{r}_a$ and $\mathbf{r}_b$ denote the positions of the alkali-metal and noble-gas atoms, respectively, and continuous atomic operators are introduced by $X_{mn}(\mathbf{r}, t) = \sum_{i=1} |m\rangle_i \langle n|_i \delta(\mathbf{r} - \mathbf{r}_i(t))$ with $m, n \in \{\downarrow, \uparrow, p, \downarrow, \uparrow\}$. The first term leads to frequency shifts of atomic ensembles, and the second term denotes the coherent spin-exchange interaction between alkali-metal and noble-gas spins [44,45].

The dynamics of the system can be described by the Heisenberg-Langevin equation (see the Supplemental Material [49], Sec. I). In the weak excitation regime of the laser fields, one can obtain the motion equations for atomic excitations as

$$\begin{aligned} \partial_t \bar{X}_{\downarrow p} &= -\left(i\Delta_e + \frac{\Gamma_e}{2}\right) \bar{X}_{\downarrow p} - i\Omega_p \bar{X}_{\downarrow\downarrow} - i\Omega \bar{X}_{\downarrow\uparrow} + \bar{F}_{\downarrow p}, \\ \partial_t \bar{X}_{\downarrow\uparrow} &= -\left(i\Delta_s + \frac{\Gamma_s}{2}\right) \bar{X}_{\downarrow\uparrow} - i\Omega^* \bar{X}_{\downarrow p} - iJ \bar{X}_{\downarrow\uparrow} + \bar{F}_{\downarrow\uparrow} \\ \partial_t \bar{X}_{\uparrow\uparrow} &= -\left(i\Delta_k + \frac{\Gamma_k}{2}\right) \bar{X}_{\uparrow\uparrow} - iJ \bar{X}_{\downarrow\uparrow} + \bar{F}_{\uparrow\uparrow}. \end{aligned} \quad (2)$$

with $\bar{X}_{\downarrow\downarrow} = X_{\downarrow\downarrow}/\sqrt{p_a n_a}$, $\bar{X}_{\downarrow p} = X_{\downarrow p}/\sqrt{p_a n_a}$, $\bar{X}_{\downarrow\uparrow} = X_{\downarrow\uparrow}/\sqrt{p_a n_a}$, and $\bar{X}_{\uparrow\uparrow} = X_{\uparrow\uparrow}/\sqrt{p_b n_b}$. Ω and Ω_p denote the Rabi frequencies of the control and probe fields, respectively, and $J = \zeta \sqrt{p_a p_b n_a n_b}/4$ denotes the spin-exchange rate. The parameters $\Gamma_{e,s,k}$ denote the dissipation rates. The laser detunings are defined as $\Delta_e = \tilde{\omega}_e - \omega_p$, $\Delta_s = \tilde{\omega}_s - (\omega_p - \omega_c)$, and $\Delta_k = \tilde{\omega}_k - (\omega_p - \omega_c)$, where $\tilde{\omega}_e$, $\tilde{\omega}_s$, and $\tilde{\omega}_k$ denote the overall frequencies of the energy levels, containing the frequency shifts due to the magnetic field and the spin-exchange interaction. The overall frequency difference between the

alkali-metal and noble-gas spins can be compensated by a specific magnetic field $B = B_0$, resulting in $\tilde{\omega}_s = \tilde{\omega}_k$, i.e., $\Delta_s = \Delta_k$. Furthermore, for the convenience of the theoretical analysis, we assume that the detunings satisfy a simple relationship $\Delta_e = \Delta_s = \Delta_k$ at $B = B_0$, which can be realized by adjusting the frequency of the control field. Accordingly, we deduce that $\Delta_s = \Delta_e + \gamma_s \tilde{B}$, $\Delta_k = \Delta_e + \gamma_k \tilde{B}$ hold for a general magnetic field $B = B_0 + \tilde{B}$ and tunable probe frequency ω_p . The last term of each equation represents the quantum noise.

By solving Eq. (2), we obtain that the normalized complex susceptibility $\chi = \chi_1 + \chi_2 + \chi_3$ of the alkali-metal atoms, which is proportional to the expected value of $\bar{X}_{\downarrow p}$, consists of three components (see the Supplemental Material [49], Sec. II):

$$\begin{aligned} \chi_1 &= -i\eta \frac{1}{i(\Delta_e - \frac{4\gamma_s \tilde{B} |\Omega|^2}{\Gamma_e^2}) + \frac{\tilde{\Gamma}_e}{2}}, \\ \chi_2 &= -\eta \frac{8(2\gamma_s \tilde{B} - i\frac{\Gamma_e}{2})|\Omega|^2}{(i(\Delta_e + \gamma_s \tilde{B}) + \frac{\tilde{\Gamma}_s}{2})\Gamma_e^3}, \\ \chi_3 &= -i\eta \frac{4J^2 |\Omega|^2}{(i(\Delta_e - \tilde{\omega}) + \frac{\tilde{\Gamma}_k}{2})(i\gamma_s \tilde{B} \Gamma_e + \frac{1}{2}\Gamma_e \Gamma_s + 2|\Omega|^2)^2}. \end{aligned} \quad (3)$$

Here, χ_1 and χ_2 correspond to the susceptibility of EIT with the background widths $\tilde{\Gamma}_e = \Gamma_e - 4|\Omega|^2/\Gamma_e$ and the EIT window width $\tilde{\Gamma}_s = \Gamma_s + 4|\Omega|^2/\Gamma_e$. The last term χ_3 represents the nuclear spin induced absorption and transparency effects, which originate from the spin-exchange interaction, and manifest the action of noble-gas nuclear spin on the optical transition of the alkali-metal atom. The corresponding frequency shift $\tilde{\omega}$ and the width $\tilde{\Gamma}_k$ are given by

$$\begin{aligned} \tilde{\omega} &= -\gamma_k \tilde{B} + \gamma_s \tilde{B} \frac{J^2 \Gamma_e^2}{\gamma_s^2 \tilde{B}^2 \Gamma_e^2 + (\frac{1}{2}\Gamma_e \Gamma_s + 2|\Omega|^2)^2}, \\ \tilde{\Gamma}_k &= \Gamma_k + \frac{J^2 \Gamma_e (\Gamma_e \Gamma_s + 4|\Omega|^2)}{\gamma_s^2 \tilde{B}^2 \Gamma_e^2 + (\frac{1}{2}\Gamma_e \Gamma_s + 2|\Omega|^2)^2}. \end{aligned} \quad (4)$$

In Fig. 2, we focus on the nuclear spin induced absorption (NSIA) effect at the resonance condition with $B = B_0$. As plotted in Fig. 2(a), there appears a dip at the center of the absorption spectrum, which corresponds to the conventional EIT window. When zooming in on the spectrum near the EIT dip [Fig. 2(b)], we can find that a very narrow absorption peak appears at the center of the EIT dip. By comparison with the case of $J = 0$, we see that this peak corresponds to the contribution of χ_3 in Eq. (3) and thus originates from the coherent spin-exchange interaction between the alkali-metal and noble-gas spins. Specifically, the alkali-metal atom exhibits a normal EIT phenomenon due to the quantum interference of the transition amplitude for two different pathways. Further, at the resonance regime of the spin-exchange interaction, the optical transition in the alkali-metal atom strongly couples with the transition in the nuclear spin of the noble-gas atom, which leads to a different quantum interference and thereby NSIA.

The performance of the NSIA signal is closely related to the exchange rate J . The spectra of the NSIA signals for various J are plotted in Fig. 2(c), and the corresponding linewidth and amplitude as functions of the exchange rate J

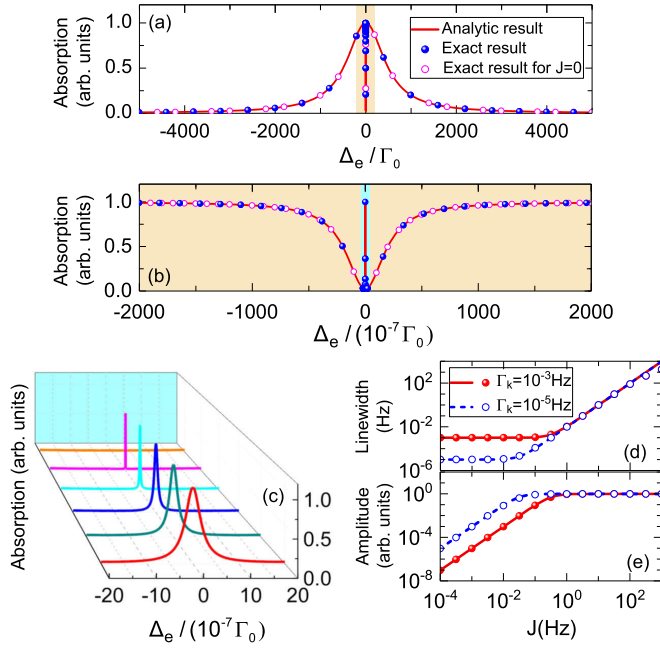


FIG. 2. (a) Normalized absorption spectrum of the optical transition $|\downarrow\rangle \leftrightarrow |p\rangle$ at $\tilde{B} = 0$, i.e., $\Delta_s = \Delta_k = \Delta_e$. Other parameters satisfy $\Gamma_e = 10^3 \Gamma_0$, $\Gamma_s = 10^{-6} \Gamma_0$, $\Gamma_k = 10^{-10} \Gamma_0$, $\Omega = 10^{-1} \Gamma_0$, $J = 10^{-6} \Gamma_0$, and $\gamma_s = 100 \gamma_k$, with Γ_0 denoting the natural linewidth of the alkali-metal atom. (b) Zoom-in view of 10^{-6} region with a brown background in (a), where the absorption peak of NSIA is revealed in the center cyan region. (c) Normalized absorption spectrum for $J = 20, 15, 10, 5, 1, 0 \times 10^{-7} \Gamma_0$ from front to back. (d) Linewidth and (e) amplitude of NSIA signal as functions of J . The lines and circles in (d) and (e) correspond to the analytical and numerical results, respectively. Natural linewidth Γ_0 is valued as $\Gamma_0 = 10^7$ Hz according to typical alkali-metal atoms to facilitate the estimation of the specific features of NSIA. Other parameters in (c)–(e) are the same as that in (a).

are shown in Figs. 2(d) and 2(e), respectively. It reveals that when J is small, the linewidth of the absorption peak can approach the lower limit, i.e., the decoherence rate of noble-gas nuclear spin Γ_k , despite the decrease of the amplitude. As J increases, the linewidth of the absorption peak increases, and meanwhile the amplitude can reach and maintain the maximum.

Next, we focus on the case without the resonance condition, for an arbitrary magnetic field $B = B_0 + \tilde{B}$. In Figs. 3(a) and 3(b), we plot the absorption spectrum corresponding to different magnetic field strengths. It reveals that in addition to the shift of EIT window, the position of the absorption peak of NSIA also shifts with the change of the magnetic field. According to Eq. (4), the shift $\tilde{\omega}$ of the NSIA peak consists of two terms. The first term corresponds to the Zeeman splitting of the noble-gas spin induced by $\tilde{B}$, and the second term is a nonlinear effect associated with the Zeeman splitting of the alkali-metal spin. Under practical experimental conditions, the exchange rate J can be significantly weaker than the power broadening $|\Omega|^2/\Gamma_e$ of the control field, and then the nonlinear effect is negligible in the weak magnetic field region. Accordingly, the shift of the narrow peak is mainly determined by the Zeeman splitting of the noble-gas spin, which

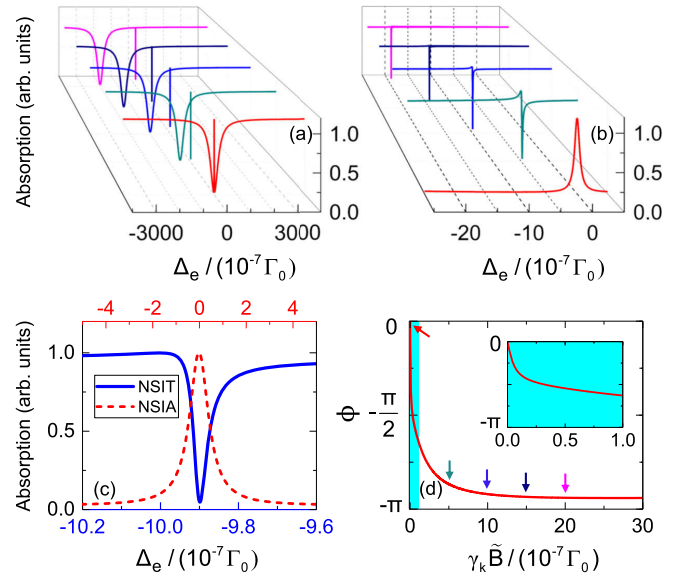


FIG. 3. (a) Normalized absorption spectrum of the optical transition $|\downarrow\rangle \leftrightarrow |p\rangle$ for $\tilde{B} = 0, 5, 10, 15, 20 \times 10^{-7} \Gamma_0/\gamma_k$ from front to back. (b) Zoom-in view of the region where the resonance signals induced by the spin-exchange interaction in (a) are involved. (c) The blue solid line and the red dashed line correspond to NSIT for $\tilde{B} = 10^{-6} \Gamma_0/\gamma_k$ and NSIA for $\tilde{B} = 0$ in (b), respectively. (d) Relative phase ϕ between different transition channels at $\Delta_e = \tilde{\omega}$ as a function of the Zeeman splitting $\gamma_k \tilde{B}$. The arrows indicate the positions corresponding to the absorption curves in (a) and (b). The inset shows the zoom-in view of the region with a cyan background. Other parameters are the same as in Fig. 2(a).

is linearly dependent on the external magnetic field strength [see Fig. 3(b)]. Meanwhile, the shape of the NSIA signal changes with the magnetic field. For relatively large $\tilde{B}$, this narrow absorption peak transforms into a dip, as shown in Fig. 3(b). Furthermore, the minimum absorption is extremely close to zero as plotted in Fig. 3(c), which indicates that a significant NSIT effect occurs. Since the decoherence rates of the alkali-metal and noble-gas spins satisfy $\Gamma_k \ll \Gamma_s$, the widths of NSIT and NSIA can be several orders of magnitude smaller than the width of the conventional EIT window. Thereby, by measuring these signals induced by nuclear spin, magnetic field detection with exceptional accuracy can be realized.

To understand the quantum interference in NSIA and NSIT, we derive the probability amplitudes for state $|e\rangle$ according to Eq. (2), from which we obtain $\langle \tilde{X}_{\downarrow p} \rangle = \frac{i\Omega_p(\Gamma_s/2 + i\Delta_s)\langle \tilde{X}_{\downarrow \uparrow} \rangle + J\Omega(\tilde{X}_{\uparrow \uparrow})}{(\Gamma_e/2 + i\Delta_e)(\Gamma_s/2 + i\Delta_s) + |\Omega|^2}$, which consists of two terms and indicates that the excitation of the alkali-metal atom results from two transition channels. The first term represents the contribution of the optical transition $|\downarrow\rangle \leftrightarrow |p\rangle$ driven by the probe field, and the second term represents the contribution of the noble-gas nuclear spin excitation through the spin-exchange interaction and the subsequent transition driven by the control field. The relative phase ϕ between these two coherent transition channels at $\Delta_e = \tilde{\omega}$, derived as $\phi = \arg[\frac{J\Omega(\tilde{X}_{\uparrow \uparrow})}{i\Omega_p(\Gamma_s/2 + i\Delta_s)\langle \tilde{X}_{\downarrow \uparrow} \rangle}]$, is plotted in Fig. 3(d). It reveals that when $\tilde{B} = 0$, the constructive interference occurs between these two transition channels, which is consistent with the

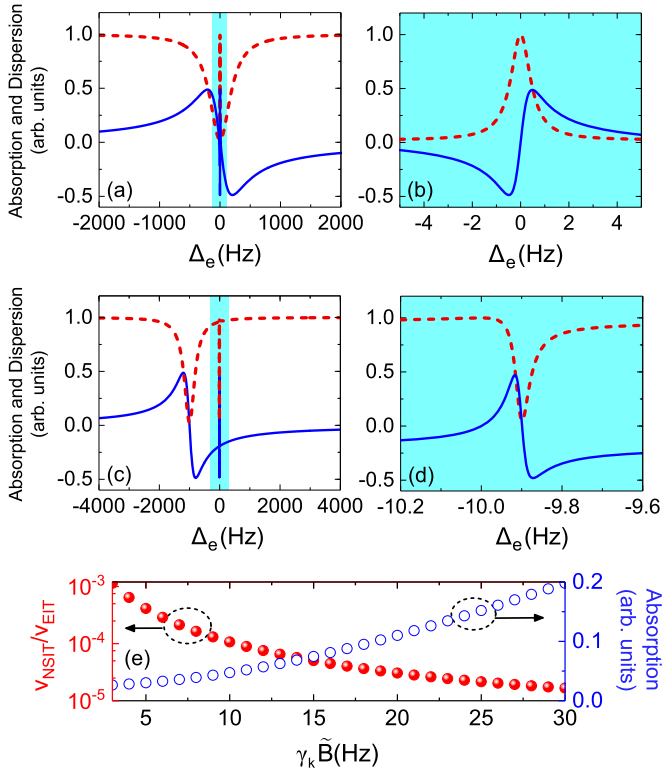


FIG. 4. Normalized absorption-dispersion spectra for NSIA at $\tilde{B} = 0$ in (a) and (b), and NSIT at $\tilde{B} = 10^{-6} \Gamma_0 / \gamma_k$ in (c) and (d) with $\Gamma_0 = 10^7$ Hz, where the blue solid line and red dashed line represent dispersion and absorption, respectively. (b) and (d) are the zoom-in views of about $1/20$ and 10^{-3} regions with a cyan background in (a) and (c), respectively, where NSIA and NSIT are revealed. (e) Minimum absorption at the NSIT window (blue open circles), and the ratio of the light group velocities at the NSIT and EIT windows (red solid circles) as functions of the Zeeman splitting $\gamma_k \tilde{B}$. Other parameters are the same as in Fig. 2(a).

appearance of NSIA. Meanwhile, as $\tilde{B}$ increases, the relative phase ϕ increases. When the magnetic field is large enough that the signal caused by the spin-exchange interaction can be distinguished from the EIT window, the destructive interference between the two coherent transition channels occurs, which explains the appearance of NSIT.

The absorption-dispersion spectra corresponding to NSIA and NSIT are exhibited in Fig. 4, where the values of the main physical parameters adopted are referenced to actual systems [46,47]. In Figs. 4(a) and 4(b), we show the case where the external magnetic field satisfies $B = B_0$, and thus NSIA arises as mentioned above. It reveals that in the region of NSIA, despite the difference in sign, the slope of the dispersion curve is much larger than that at the EIT window in Fig. 4(a). In Figs. 4(c) and 4(d), we show the case where the difference between the frequency shifts of the alkali-metal and noble-gas spins are significant, so that NSIT occurs. It reveals that besides the same sign, the slope of the dispersion curve at the NSIT window is several orders of magnitude greater than that at the EIT window.

The steep dispersion curve leads to a small group velocity of the light pulse, corresponding to a strong slow light effect,

which has important applications in various fields including optical delay [50] and nonlinear effects [5,12,51]. In Fig. 4(e) we plot the ratio of light group velocities at the NSIT and EIT windows, and the corresponding minimum absorption at the NSIT window. It reveals that the light group velocity at the NSIT window can be many orders of magnitude smaller than that at the EIT window, which results from the fact that the decoherence rate of the noble-gas spin is much smaller than that of the alkali-metal spin. In addition, as the magnetic field increases, the dispersion curve becomes sharper, resulting in a more pronounced slow light effect.

Different combinations of alkali-metal and noble-gas atoms can be chosen as candidates for protocol implementation, and the experimental configuration for observing EIT in atomic gas can act as a reference for the observation of NSIT and related effects. The appearance of NSIT and NSIA depends on the coherent spin-exchange interaction between the noble-gas nuclear spins and alkali-metal electronic spins, which has been confirmed experimentally using a K-He mixed vapor cell [47]. Further, the bidirectional interface between light and noble-gas nuclear spins has been identified, and the optical signal originating from the noble-gas nuclear spin has been observed in the transmission spectrum of the signal light [46]. We demonstrate that the NSIT phenomenon can arise under relaxed conditions, and the signal widths are tunable from sub-mHz to tens of Hz or moreover (see the Supplemental Material [49], Sec. III), which further facilitate the corresponding proof-of-principle experiment and potential applications. The Doppler effect due to atomic motions can be suppressed based on the Doppler-free technique, which is commonly applied when observing EIT in atomic gas [52,53]. Based on this technique, the narrow NSIT signal can be well maintained (see the Supplemental Material [49], Sec. IV). In addition, we discuss the role of imperfect polarization on the NSIT phenomenon (see the Supplemental Material [49], Sec. V), and demonstrate the stability of NSIT. Therefore, the proposed scheme exhibits practical feasibility under the current experimental conditions.

In summary, we demonstrate that the NSIT phenomenon can occur in a mixture of alkali-metal and noble-gas atoms, which originates from the effect of the nuclear spin of noble-gas atoms on the optical transition of alkali-metal atoms through the spin-exchange interaction between the alkali-metal and noble-gas spins. We construct an effective four-level model to describe the NSIT phenomenon and obtain analytical results. The width of the NSIT window can be several orders of magnitude smaller than that of conventional EIT, and even approaches the relaxation rate of the noble-gas nuclear spin on the order of sub-mHz range [30,54]. The center position of the window is linearly dependent on the external magnetic field strength, making it a good candidate for high-sensitivity magnetic field sensing. In addition, the dispersion curve corresponding to the transparent window is extremely sharp, which can lead to a slow light effect where the group velocity of the light pulse can be several orders of magnitude smaller than that in conventional EIT. The NSIT mechanism provides an important method for various applications including long-time light storage and high-performance sensing.

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Data availability. The data supporting this study's findings are available within the article.

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