

Study of the atmospheric neutron radiation effects using compact laser-driven spallation neutron source

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(Received 31 October 2024; accepted 2 January 2025; published 21 January 2025)

We propose a laboratory accelerated test method for study of the atmospheric neutron radiation effects by using a compact laser-driven spallation neutron source (LDSNS). The LDSNS is obtained by injecting a GeV quasimonoenergetic proton beam accelerated by light-sail (LS) radiation pressure of intense lasers into a lead target. According to the LS scaling law, proton energy spectra can be regulated by adjusting the laser and foil target parameters, so that the neutron spectra at various atmospheric altitudes are well reproduced. Integrated PIC and MC simulations have verified the scheme (for that at altitude 12 km, laser intensity of 10^{22} W/cm² is required) and shown that the neutron fluence per laser shot is as high as 1.73×10^8 n/cm², equivalent to 3.7 year flux accumulation in atmosphere. Using the G4SEE toolkit, we estimate that the HM628128 SRAM may undergo an average of ten single event upsets per shot for the proposed laboratory test.

DOI: [10.1103/PhysRevResearch.7.013071](https://doi.org/10.1103/PhysRevResearch.7.013071)

I. INTRODUCTION

Neutrons exist throughout the earth's atmosphere—at sea level and even more abundant at aircrafts altitude, in avionic and space environments, since they are generated from the interaction of cosmic ray particles with nuclei in the molecules composing the atmosphere, aircraft, and spacecraft components, or the surface of planets. Atmospheric neutron radiation can not only cause degradation but can also cause failure of the electronic and electrical systems in space vehicles or satellites. Radiation hardness assessment of onboard electronics has become a critical issue and has aroused great interest [1–4].

There are kinds of radiation effects caused by neutrons. The most common one is single event upsets (SEU) [2,5], which are running errors in electronic devices, regarded as soft damages. To accurately estimate the SEU, life testing under natural environments is carried out at high plateaus [6] or during aviation flights [7], however, it is time consuming and expensive, requiring continuous monitoring of thousands of chips for several months or years. Laboratory accelerated testings using accelerator-based [1,8] and/or reactor-based [9] neutron sources have been proposed. However, as the atmospheric neutrons generally have a broad energy spectrum

and are rather diverse at different altitudes, latitude, and solar activity cycles, these methods with a monoenergetic test beam are not applicable. The advent of spallation neutron sources [10–12] has opened up opportunities for simulation of broadband atmospheric neutron radiation. However, since the high-energy protons that induce the spallation reaction are generated from conventional accelerators, generally having a fixed monoenergy, the obtained neutron spectrum is resultantly fixed as well in spite of being broad. Moreover, it is much different from the realistic atmospheric neutron spectrum in most situations. Therefore, for conventional accelerator-based spallation neutron source, it is still hard to make an adjustment to emulate the real atmospheric neutron radiation with a specific energy spectrum.

In this paper, to resolve the above issue, we propose using laser-driven accelerators to achieve the spallation neutron sources as the test beams for emulating the atmospheric neutrons. Different from previously laser-driven neutron sources in the pitcher-catcher scheme [13–18], in order to obtain the GeV proton beams [19] that are required for achieving the spallation reactions, we choose the light-sail (LS) radiation pressure acceleration (RPA) for protons, which are then injected into a thick lead target, shown schematically in Fig. 1. Furthermore, to reproduce the diverse neutron spectra at various atmospheric situations including altitudes, latitudes, solar activities, and so on, the proton energy spectra are regulated by properly adjusting the laser and foil target parameters, according to the straight scaling law of LS acceleration (as the whole foil undergoes direct acceleration by light pressure) [20,21]. Integrated particle-in-cell (PIC) and Monte Carlo (MC) simulations have verified the scheme and shown that the neutron fluence per laser shot for those with energy > 10 MeV is as high as 1.73×10^8 n/cm², equivalent to 3.7 year flux

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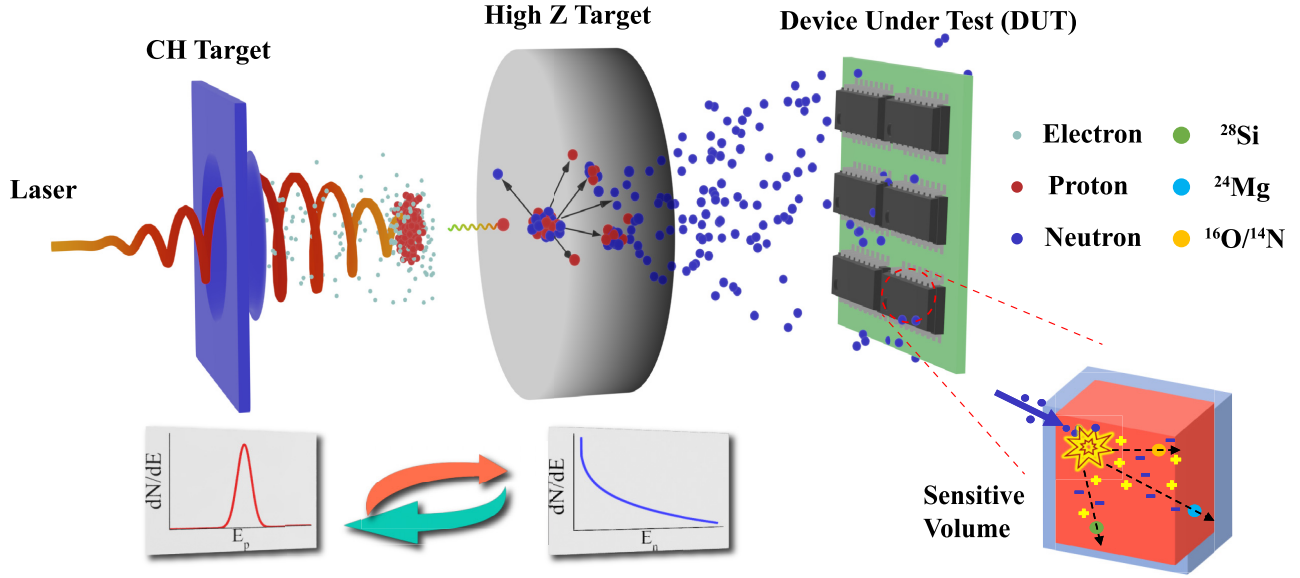


FIG. 1. Schematic view of the proposed laboratory accelerated test method for study of atmospheric neutron radiation effects using a compact laser driven spallation neutron source.

accumulation in atmosphere. G4SEE [22] simulations imply that the SEU soft error rate (SER) of HM628128 SRAM is about ten events per shot, which requires at least 3.7 years of life testing in natural atmosphere.

II. DETERMINATION OF THE REQUIRED PROTON SPECTRUM

In the scheme, we start from determining the required proton spectrum based on the real atmospheric neutron spectrum. Note that the real atmospheric neutron spectrum depends on both altitude and latitude as well as other radiation environments, and several software tools such as “space radiation 7” [23] and “OMERE” [24] can provide data on the space radiation environment experienced by spacecraft based on flight time and trajectory. Here, taking the factor of latitude as an example, Figs. 2(a) and 2(b) show the real neutron spectra for a year at altitudes of, respectively, 0 km (blue solid, data obtained from JESD89B [25]) and 12 km (red solid, data obtained from the modified Boeing model [19]), which both exhibit an exponentially decreasing profile extending to GeVs. It has been proved that the SEU cross section of the electronics tends to saturate [26] above 1 GeV since the neutron number is too small there. For simplicity, we assume the energy spectrum of the produced quasimonoenergetic protons from LS RPA [20,21] can be fitted as a Gaussian distribution $g(E_p) = g_0 \exp[-\frac{(E_p - E_0)^2}{2\sigma^2}]$, where E_p represents proton energy, E_0 represents the peak energy, σ denotes the width of the distribution, and g_0 is a normalized parameter. Then, the energy spectrum of neutrons produced by the spallation reaction of such Gaussian narrow-banded proton beams can be expressed as

$$\begin{aligned} \tilde{F}(E_n) &= \int g(E_p) \times f(E_p, E_n) dE_p \\ &= \int g_0 \exp\left[-\frac{(E_p - E_0)^2}{2\sigma^2}\right] \times f(E_p, E_n) dE_p, \end{aligned} \quad (1)$$

where E_n represents neutron energy, and $f(E_p, E_n)$ denotes the energy spectrum of neutrons produced by the spallation reaction of protons at monoenergy E_p . The dependence relation of $f(E_p, E_n)$ on E_p can be numerically obtained by Geant4

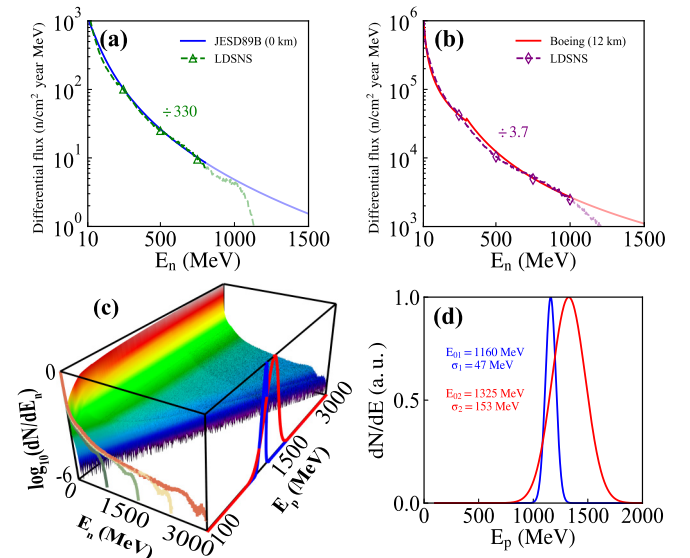


FIG. 2. (a) and (b) The blue and red solid lines plot the real atmospheric neutron spectra at altitudes of, respectively, 0 km from JESD89B [25] and 12 km from the modified Boeing model [19]. The green and purple dashed lines (with markers) plot the corresponding neutron spectra obtained from integrated PIC and MC simulations by using LDSNS in our proposed scheme. (c) The neutron spectra obtained from Geant4 simulations by injecting protons with monoenergy ranging from 100 to 3000 MeV into a 10 cm-thick lead target. The blue, green, yellow, and orange lines at the front surface of (c) plot specifically the neutron spectra for proton mono-energies of, respectively, 750, 1500, 2250, and 3000 MeV. (d) The required proton energy spectra $g(E_p)$ for simulation of the atmospheric neutron spectra at altitudes of, respectively, 0 km (blue) and 12 km (red).

TABLE I. Parameters of the required proton energy spectra and of the corresponding lasers and targets in LS acceleration for reproduction of the atmospheric neutron spectra.

	0 km	12 km
E_0 (MeV)	1160	1325
σ (FWHM) (MeV)	47(111)	153(360)
I (W/cm ²)	3.9×10^{22}	4.4×10^{22}
τ (T ₀)	7.5	7.5
target composition	C ₆ H	C ₂ H
n_0 (n_c)	320	320
l_0 (nm)	119	124

simulations [27–29], assuming injecting into a 10 cm-thick lead target, which is plotted in Fig. 2(c) with E_p ranging from 100 MeV to 3 GeV.

Using Fig. 2(c) and applying the gradient descent method to minimize the difference between $F(E_n)$ and the real atmospheric neutron spectrum $F(E_n)$, defined as a loss function $L(F, \tilde{F}) = \int_{E_{\min}}^{E_{\max}} (\frac{F(E_n) - \tilde{F}(E_n)}{F(E_n)})^2 dE_n$, we can find the optimized parameters g_0 , E_0 , and σ of proton spectrum $g(E_p)$, which are listed in Table I. As a result, the required proton energy spectra $g(E_p)$ are determined, as shown in Fig. 2(d) for the cases at altitudes of, respectively, 0 km (blue) and 12 km (red). In other words, through adjusting the variable parameters E_0 and σ of proton spectrum obtained by LS acceleration, the realistic broad atmospheric neutron spectra for various situations can all be matched.

Next, we further determine the laser and foil target parameters required for proton acceleration according to the LS scaling law [30,31], where the ion peak energy scales as $E_0 = \frac{\epsilon^2}{2(1+\epsilon)} m_p c^2$ under an optimal foil thickness $l_0 = (1/\pi)(n_c/n_0)a_0\lambda$. Here $\epsilon = 2\pi(\sum Z_i n_i)m_e/(\sum m_i n_i)a_0^2\tau/\zeta$ with Z_i , n_i , m_i , m_e representing charge, number density, mass of ions, and mass of electrons, a_0 and τ the normalized laser amplitude and pulse length, and $\zeta = \pi(n_0 l_0)/(n_c \lambda)$ with n_0 , n_c , and λ representing electron density, critical density, and laser wavelength. Furthermore, to suppress the acceleration instabilities and achieve a stable ion LS acceleration [32,33], on the one hand, we choose the multispecies ultrathin plastic foil targets at ion density ratios $n_C : n_H = 6 : 1$ and $2 : 1$ for, respectively, the cases at altitudes 0 km and 12 km, where $n_0 = 320n_c$. On the other hand, the pulse duration τ is chosen to be in the time-limited LS acceleration regime [34] as $\tau \leq \tau_{RT} \approx 136a_0^{-1}(\sqrt{4(1+a_0^2)^{1/2}l[\mu\text{m}]\lambda[\mu\text{m}]\sqrt{n_0/n_c}})^{1/2}$. Based on the above conditions and scaling laws, the required laser and foil target parameters to obtaining the proton spectrum $g(E_p)$ in Fig. 2(d) (or those in Table I) can be eventually determined, shown in Table I as well.

III. PIC SIMULATIONS

In the following, we verify our proposed scheme by integrated PIC and MC simulations. Two-dimensional (2D) PIC simulations with EPOCH [35] are carried out to demonstrate production of the required quasimonoenergetic proton beam from LS acceleration for the case at altitude 12 km. All laser and target parameters including laser intensity, pulse duration,

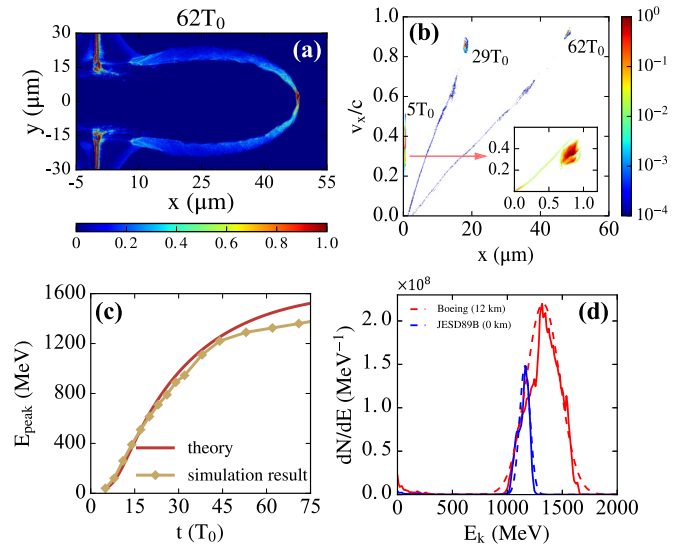


FIG. 3. (a) Proton density n_i/n_c at $t = 62T_0$ for a C_2H foil of $n_0 = 320n_c$ and $l_0 = 124$ nm irradiated by CP lasers with $I_0 = 4.4 \times 10^{22}$ W/cm². (b) Proton velocity phase space distributions at $t = 5, 29$, and $62T_0$. (c) Temporal evolution of peak proton energies, where the red line is from LS theory. (d) Comparison between the final proton energy spectrum (solid lines) in simulations and the required spectrum (dashed lines) in theory, where the red solid and red dashed lines are those for the case at altitude 12 km, the blue solid and blue dashed lines are those for the case at altitude 0 km.

foil density, and thickness are chosen to be consistent with those in Table I, where laser spatial profile is Gaussian with radius $r = 5 \mu\text{m}$. The simulation box size is $90 \times 70 \mu\text{m}$ consisting of 20232×9835 cells along x and y directions. Laser enters from $x = -10 \mu\text{m}$ at time $t = -10T_0$ and propagates along the x direction. The foil is located at $x = 0 \mu\text{m}$, containing 500 quasiparticles per cell.

Figure 3(a) shows proton density distributions at $t = 62T_0$. As expected, we see that the whole foil is under stable LS acceleration, where the phase space distributions, see Fig. 3(b), display typical concentrating characters [36–38]. Figure 3(c) plots time evolution of the proton peak energy (yellow line with markers), agreeing well with the LS theoretical expectation (red line) as $\frac{dp}{dt} = \frac{2I}{\sum_i m_i n_i l c^2} \frac{\sqrt{1+p^2}-p}{\sqrt{1+p^2}+p}$ [39]. The final proton energy spectrum is plotted by the red solid line in Fig. 3(d) with peak energy about 1320 MeV and FWHM spread about 365 MeV ($\approx 27\%$), which matches well with the required spectrum in theory [the red dotted line in Fig. 3(d) and/or the red line in Fig. 2(d) and/or the relevant parameters in Table I]. Simulations for the case at altitude 0 km are also run, whose results agree well with the theory as well, see the blue solid and dashed lines in Fig. 3(d).

IV. MC SIMULATIONS

To self-consistently simulate the neutron production process, we convert the 2D position and momentum information of protons obtained from above into 3D by randomly rotating along the x axis and then use them as the input for the Geant4 simulations. These protons are injected into a lead target with

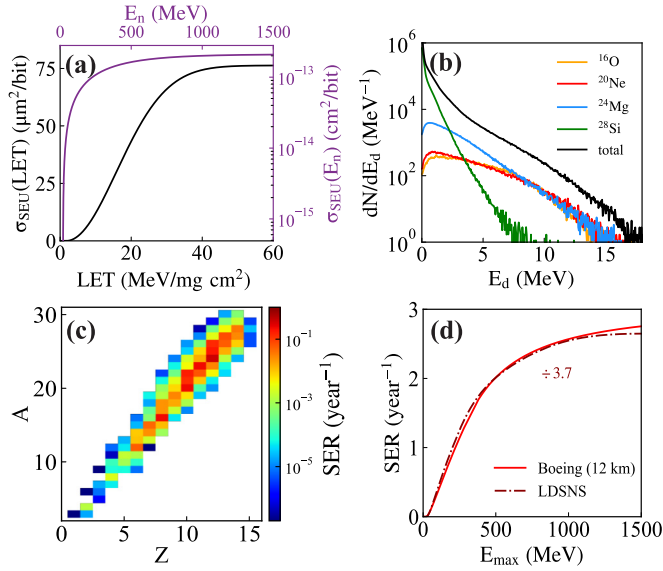


FIG. 4. (a) HM628128 heavy ion (black) and neutron (purple) SEU cross section curve [40]. (b) Deposited energy spectrum in the SV of HM628128 (black line). The orange, red, blue, and green lines simultaneously display the deposited energy spectra of events that produce ^{16}O , ^{20}Ne , ^{24}Mg , and ^{28}Si isotopes. (c) Classification of the SER based on the different generated isotopes. (d) SER of HM628128 as a function of maximal neutron energy.

thickness 10 cm. The QGSP_INCLXX_HP Physics List is used, which is specifically designed for nuclear spallation reactions. The obtained neutron spectra behind the lead target are shown in Figs. 2(a) and 2(b) for, respectively, 0 km (green dashed line) and 12 km (purple dashed line) cases, matching well with the real atmospheric neutron spectra (respectively, the blue solid and red solid lines). However, as labeled in Figs. 2(a) and 2(b), the neutron fluxes per laser shot are, respectively, 330 and 3.7 times higher than the real ones. In other words, the neutron fluxes per shot in our scheme are equivalent to respectively 330 year and 3.7 year fluxes accumulation in atmosphere.

For simulation of the neutron radiation test stage, we have extended the G4SEE toolkit to have capabilities of the complete input of neutron position, momentum, and energy information via external files. As an example, we choose to emulate the atmospheric neutron irradiation at altitude 12 km on the widely used 1-Mbit HM628128 SRAM [7] and consider the most typical SEU effect. As shown in Fig. 1, we see that when neutrons irradiate on the sensitive volume (SV) of a storage device, such as HM628128 SRAM, they undergo elastic and inelastic scattering, nuclear reactions with the atomic nuclei (mainly ^{28}Si). As a result, a large amount of high linear energy transfer (LET) recoil nuclei are produced, such as ^{28}Si , ^{24}Mg , and ^{16}O , which leads to ionization of a significant number of electron-hole pairs and accumulation of charges. Eventually, when the accumulated charges surpass the critical threshold, a SEU is triggered.

The black line in Fig. 4(a) plots the heavy ion SEU cross section $\sigma_{\text{SEU}}(\text{LET})$ of HM628128 SRAM, obtained from the experimental data fitting. $\sigma_{\text{SEU}}(\text{LET})$ can be typically described by a Weibull function [41]: $\sigma_{\text{SEU}} =$

$\sigma_{\text{sat}} \{1 - \exp[-(\frac{\text{LET} - \text{LET}_{\text{th}}}{W})^S]\}$, where $\sigma_{\text{sat}} = 76.3 \mu\text{m}^2/\text{bit}$ is the saturation value, $\text{LET}_{\text{th}} = 1.7 \text{ MeV}/\text{mg cm}^2$ is the LET threshold, and $W = 20 \text{ MeV}/\text{mg cm}^2$ and $S = 2$ are width and shape factors [40]. Based on the rectangular parallelepiped (RPP) model [42] and experimental data [43], the SV length and width is about $l = w = \sqrt{\sigma_{\text{sat}}} = 8.7 \mu\text{m}$, and the thickness about $h = 4 \mu\text{m}$. Since the majority of the recoil nuclei in Si have a range of less than $5 \mu\text{m}$, we choose the G4SEE simulation box size with length, width, and height all additional $10 \mu\text{m}$ larger than those of the SV. Further, for simplicity, we assume that both the SV and its surrounding regions are composed of purely Si.

To investigate the differences in SEU caused by different nuclear reactions, we classified the neutron reaction event by the maximum atomic nucleus entered or produced in SV in each event. Figure 4(b) plots the deposited energy spectra of the events that generate, respectively, ^{16}O , ^{20}Ne , ^{24}Mg , and ^{28}Si , and their sum. Since $\text{LET} = E_d/\rho/h$, where E_d is the deposited energy, $\rho = 2.32 \text{ g}/\text{cm}^3$ is the Si density, we calculate the corresponding SEU cross section, shown in Fig. 4(a). Integrating the deposited energy spectrum with the $\sigma_{\text{SEU}}(\text{LET})$ curve in Fig. 4(a), we obtain the soft error rate (SER) caused by each category of nuclear reactions, see Fig. 4(c). We see that the reactions for production of ^{24}Mg , ^{20}Ne , and ^{16}O contribute the most to SER. Overall, we observe an average of 10 SEUs per laser shot for simulations of atmospheric neutron radiation at altitude of 12 km.

Figure 4(d) shows the SER curve as a function of the maximum neutron energy, defined as $\text{SER}(E_{\text{max}}) = \int_0^{E_{\text{max}}} \sigma_{\text{SEU}}(E_n) \frac{d\phi(E_n)}{dE_n} dE_n$, where $\frac{d\phi(E_n)}{dE_n}$ represents the differential neutron flux in Figs. 2(a) and 2(b), and $\sigma_{\text{SEU}}(E_n)$ is the neutron SEU cross section curve [the purple line in Fig. 4(a)]. Clearly, the number of SEUs observed from HM628128 SRAM exposed to the neutron irradiation for years is very similar to the number of SEUs obtained from our proposed scheme through a single-shot laser experiment.

V. CONCLUSIONS

In summary, we have proposed a laboratory accelerated test route for study of the atmospheric neutron radiation effects by using a compact laser-driven spallation neutron source (LDSNS). The scheme using the LS-accelerated proton beam with a unique narrow-banded energy spectrum have solved the critical issue of how to emulate the realistic atmospheric neutron spectra in laboratory, by providing two variable parameters for adjustment, i.e., the peak energy E_0 and the band width σ . This is eventually achieved by properly choosing the laser and foil target parameters according to the LS acceleration scaling laws. Integrated PIC and MC simulations have verified the scheme and shown that by applying the currently achievable petawatt lasers at intensities $10^{22} \text{ W}/\text{cm}^2$ [44,45], we can obtain the neutron fluence per laser shot as high as $1.73 \times 10^8 \text{ n}/\text{cm}^2$, equivalent to 3.7 year flux accumulation in atmosphere. Using the G4SEE toolkit, we estimate that the HM628128 SRAM may undergo an average of ten single event upsets per shot for the proposed accelerated test.

ACKNOWLEDGMENTS

This work is supported by the National Key R&D Program of China (Grants No. 2022YFA1603200, No. 2022YFA1603201, and No. 2024YFA1613400), the National

Natural Science Foundation of China (Grants No. 12135001 and No. 12475243), the Strategic Priority Research Program of CAS (Grant No. XDA25050900), and the National Natural Science Funds for Distinguished Young Scholars (Grant No. 11825502).

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