Analysis of the Energy Spectra and Double Differential Cross Sections for the p+^{28}Si Reaction

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Abstract

The mechanism and the observables (including cross section, angular distribution, energy spectrum and double-differential cross section) for the p+^{28}Si reaction below incident energy 200 MeV are systematically studied. A set of optimal global optical potential parameters for proton is obtained by simultaneously fitting the reaction cross sections and elastic scattering angular distributions. Utilizing the derived optical potential parameters, the direct inelastic scattering cross sections and their angular distributions based on the distorted wave Born approximation (DWBA) theory are calculated. Thus, the energy spectra and double-differential cross sections of the light charged particles are self-consistently derived on the basis of the exciton model, evaporation model and Hauser-Feshbach theory with fluctuation correction. The calculated results are in good agreement with the existing experimental data. Overall, the accuracy of this work is superior to that of the current results evaluated by Taleys-2.0.

Full Text

Preamble

Analysis of the Energy Spectra and Double Differential Cross Sections for the p+28Si Reaction

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Abstract

The mechanism and observables (including cross section, angular distribution, energy spectrum, and double-differential cross section) for the p+28Si reaction below incident energy 200 MeV are systematically studied. A set of optimal global optical potential parameters for protons is obtained by simultaneously fitting the reaction cross sections and elastic scattering angular distributions. Utilizing these derived optical potential parameters, the direct inelastic scattering cross sections and their angular distributions are calculated based on distorted wave Born approximation (DWBA) theory. The energy spectra and double-differential cross sections of light charged particles are then self-consistently derived using the exciton model, evaporation model, and Hauser-Feshbach theory with fluctuation correction. The calculated results show good agreement with existing experimental data, and overall, the accuracy of this work surpasses that of current results evaluated by TALYS-2.0.

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Introduction

Silicon-based materials are indispensable in aerospace technology, serving as the foundation for critical components such as semiconductor devices, solar cells, and microprocessors deployed in satellites. Notably, as a third-generation semiconductor material, silicon carbide (SiC) demonstrates superior radiation resistance, excellent thermal stability, and high-power capability compared to conventional silicon [?]. These properties render SiC particularly suitable for operation in extreme environments, especially under the intense radiation conditions encountered in space applications. Moreover, the remarkable stability of SiC at high temperatures and high power offers strong potential for use in next-generation nuclear energy systems, such as accident-tolerant fuel (ATF) cladding and structural components for reactors [?]. Additionally, radiation effects and displacement damage [?] along with single-event effects (SEEs) [?] pose significant threats to electronic performance and mission integrity. These phenomena are primarily induced by nuclear interactions between incident cosmic-ray particles and target nuclei in semiconductor materials. Cosmic-ray protons account for approximately 87% of the galactic cosmic ray flux [?] and over 89% of solar cosmic ray flux [?].

Given that 28Si constitutes roughly 92.2% of natural silicon, it serves as the primary target for proton-induced reactions in silicon-based aerospace instrumentation. These interactions lead to atomic displacement via primary knock-on atoms (PKAs) and produce secondary charged particles and isotopes that may trigger single-event upsets through charge deposition. Therefore, accurate nuclear data obtained through model calculations are essential for predictive radiation damage modeling and the development of effective spacecraft radiation mitigation strategies.

Double-differential cross sections (DDCSs) are essential for understanding reaction mechanisms, as they encode detailed energy-angular correlations of outgoing particles. However, the EXFOR database [?] provides only limited double-differential cross sections of light charged particles (LCPs) for the p+28Si reaction. This dataset is insufficient to impose effective constraints on model parameters to enhance the predictive power of theoretical models. Consequently, measurements using natural Si targets offer a viable alternative, owing to the high proportion of 28Si.

Nuclear reaction codes such as GNASH [?] and TALYS [?], which consider direct nuclear reactions as well as pre-equilibrium and compound nucleus emission, can reproduce the general features of experimental data for the p+28Si reaction. However, more detailed comparisons between calculated results and experimental data indicate that there remains room for improvement in these codes [?, ?]. In this work, based on the spherical optical model, direct reactions to discrete levels and intranuclear cascade nucleon emission, pre-equilibrium statistical theory, evaporation model, and Hauser-Feshbach theory with width fluctuation correction—all encapsulated within the MEND code [?]—we self-consistently calculate the reaction cross sections, angular distributions, energy spectra, and double-differential cross sections of light charged particles (including neutron, proton, deuteron, triton, 3He, and alpha). This paper is organized as follows: Section II briefly describes the theoretical framework, Section III presents the analysis and comparison of calculated energy spectra and double-differential cross sections with experimental data, and Section IV provides a succinct summary.

II. Theoretical Model

The optical model is applied to describe proton-induced reaction cross sections and elastic scattering angular distributions, and to calculate the transmission coefficient of the compound nucleus and the pre-equilibrium emission process. The optical model potential (OMP) for protons considered in this paper is expressed as

$$V(r) = V_R(r) + V_{SO}(r) + V_C(r) + i[W_D(r) + W_S(r) + W_{SO}(r)],$$

where $V_R(r)$ is the real part of the potential, $V_{SO}(r)$ is the real spin-orbit potential, $V_C(r)$ is the Coulomb potential, and $W_D(r)$, $W_S(r)$, and $W_{SO}(r)$ are the imaginary part potentials for surface absorption, volume absorption, and spin-orbit coupling, respectively. The detailed form of the OMP can be found in Ref. [?].

To obtain a set of proton optical model potential parameters for p+28Si reactions, the APMN code [?] is employed in this work. Using this code, optimal proton optical model potential parameters can be automatically searched to fit relevant experimental data, including reaction cross sections and elastic scattering angular distributions. The proton optical model potential parameters are listed in TABLE I. The neutron optical potential parameters are derived from Ref. [**?**], while the optical potentials for charged particles such as deuteron, triton, 3He, and alpha are adopted from Refs. \cite{13, 16–18}, respectively.

Direct inelastic scattering cross sections and angular distributions for discrete low-lying states play a crucial role in nuclear theory calculations. The DWUCK4 code [**?**], based on distorted wave Born approximation (DWBA) theory, is used to calculate the direct reaction contribution. The optical parameters obtained in this paper are used as part of the input data for DWUCK4. The contributions to direct inelastic scattering primarily arise from 11 discrete levels, whose deformation parameters are listed in TABLE II.

The unified Hauser–Feshbach and exciton model [**?**] is used to describe nuclear reaction equilibrium and pre-equilibrium decay processes. The improved Iwamoto-Harada model is applied to describe complex particle emission in the pre-equilibrium process [**?**]. The energy spectrum of emitted composite particle b can be expressed as

$$\sigma^b(\varepsilon_b) = \sum_{J\pi} \sigma^{J\pi} \left\{ \sum_{n=3}^{n_{\max}} P^{J\pi}(n) \frac{W_b^{J\pi}(n, E^*, \varepsilon_b)}{W_T^{J\pi}(n, E^*)} + Q^{J\pi} \frac{W_b^{J\pi}(E^*, \varepsilon_b)}{W_T^{J\pi}(E^*)} \right\},$$

where $\sigma^{J\pi}$ is the absorption cross section in the $J\pi$ channel (J and π denote the angular momentum and parity in the final state, respectively), $P^{J\pi}(n)$ is the occupation probability of the n-th exciton state, $W_T^{J\pi}(n, E^*)$ is the total emission rate at the n-th exciton state, and $W_b^{J\pi}(n, E^*, \varepsilon_b)$ is the emission rate of emitted particle b with outgoing energy ε_b. E^* is the excitation energy of the compound nucleus, and $Q^{J\pi} = 1 - \sum_{n=3}^{n_{\max}} P^{J\pi}(n)$ is the occupation probability of the equilibrium state. $W_b^{J\pi}(E^*, \varepsilon_b)$ is the emission rate of particle b at equilibrium with outgoing kinetic energy ε_b, and $W_T^{J\pi}(E^*)$ is the total emission rate at equilibrium.

According to Kalbach systematics [**?**, **?**], the double-differential cross sections of emitted composite particle b can be expressed as

$$\frac{d^2\sigma^b}{d\Omega d\varepsilon_b} = \frac{1}{4\pi} \frac{d\sigma^b}{d\varepsilon_b} \frac{a}{\sinh(a)} [\cosh(a\cos\theta) + f_{PE} \sinh(a\cos\theta)],$$

where a is the slope parameter that primarily depends on the center-of-mass emission energy, though it also varies with the incident particle species and energy, and f_{PE} is the fraction of particle emission apart from the equilibration process.

III. Theoretical Results and Analysis

Since experimental data for the energy spectra of the p+28Si reaction are currently unavailable, the calculated results of this paper are compared with experimental data obtained from natural Si targets [**?**]. Fig. 1 [Figure 1: see original paper] shows comparisons between calculated results and experimental energy spectra for protons (a), deuterons (b), tritons (c), 3He (d), and alphas (e) at incident energies of 26.5 MeV, 46.5 MeV, and 62.9 MeV, respectively. The calculated results are in rather good accordance with the experimental data. The energy spectra of proton, deuteron, triton, and 3He emissions are primarily attributed to pre-equilibrium reactions, while the energy spectra of alphas are mainly dominated by equilibrium emission in the lower energy region.

In Fig. 1(a), structural characteristics observed in the proton energy spectra within the high emission energy region arise from direct inelastic scattering processes. Similarly, for deuterons as depicted in Fig. 1(b), the observed energy spectra within the high emission energy region may stem from contributions of the knockout reaction mechanism.

Double-differential cross sections of outgoing light charged particles for natural Si were measured in Ref. [**?**]. Comparisons of calculated double-differential cross sections of outgoing protons with incident energies of 26.5 MeV, 46.5 MeV, and 62.9 MeV are shown in Fig. 2 [Figure 2: see original paper]. The vertical axes in Fig. 2 employ a logarithmic scale to display the broad dynamic range of the double-differential cross sections. Although experimental uncertainties are symmetric in linear space, the logarithmic transformation results in asymmetric error bars due to nonlinear scaling. To ensure clarity while preserving scientific accuracy, only upper error bars are displayed. The calculated double-differential cross sections are in good agreement with the experimental data. However, as illustrated in Fig. 2(a), the calculated results for proton emission energies in the range of 4–8 MeV are lower than the experimental data when the incident energy is 26.5 MeV. This is primarily due to insufficient consideration of protons from the equilibrium state in this work, especially compared to higher incident energy scenarios. The calculations also reveal that the contribution of pre-equilibrium reactions decreases with increasing outgoing angle. Furthermore, from the data for incident protons with higher energies shown in Fig. 2(b) and Fig. 2(c), we observe that the significance of pre-equilibrium emission becomes increasingly prominent as the incident energy rises.

Fig. 3 [Figure 3: see original paper] shows the double-differential cross sections of outgoing deuterons at different emission angles for the p+28Si reaction, compared with experimental data from natural Si targets [**?**]. As in Fig. 2, Fig. 3 employs a logarithmic scale and displays only upper error bars to maintain clarity in depicting asymmetric uncertainties near the axis origin. Structural characteristics are observed in the higher emission energy regions of Fig. 3, where the calculated results cannot reproduce the structural peaks. This deviation likely stems from the exclusion of direct reactions in the (p, d) channel within the current framework.

The calculated double-differential cross sections of outgoing tritons are compared with experimental data [?] at incident proton energies of 26.5 MeV, 46.5 MeV, and 62.9 MeV, as shown in Fig. 4 [Figure 4: see original paper]. Lower error bars are omitted in Fig. 4 for the same reasons as in Figs. 2 and 3. The magnitude and shape of the calculated results are in good agreement with the experimental data.

The calculated double-differential cross sections of outgoing alphas are compared with experimental data [?] at incident proton energies of 26.5 MeV, 46.5 MeV, and 62.9 MeV, as shown in Fig. 5 [Figure 5: see original paper]. Lower error bars are also omitted in this figure for the same reasons as in Figs. 2–4. The magnitude and shape of the calculated results are reasonable, although the agreement is not as good as those for protons, deuterons, and tritons in the lower outgoing energy region. This could be attributed to the fact that the contribution of alpha particles primarily stems from equilibrium emission processes, while contributions from other lighter charged particles mainly originate from pre-equilibrium processes.

We also conducted model calculations for the p+28Si reaction using the open-source TALYS-2.0 code [?]. Overall, the calculated results provide reasonable reproduction of the experimental double-differential cross sections of light charged particles [?]. Nevertheless, double-differential cross sections of tritons were not published in previous papers, and there are no experimental double-differential cross sections for outgoing 3He. To gain deeper insight into differences between TALYS-2.0 and this work, we further compared double-differential cross sections of emitted light charged particles. Fig. 6 [Figure 6: see original paper] shows results for outgoing light charged particles at an incident energy of 62.9 MeV and angle of 60° calculated by TALYS-2.0 and our model, respectively. Black points represent experimental data from Ref. [?], red solid lines denote results from our work, and blue dash-dot lines denote results from TALYS-2.0. Our model demonstrates significantly superior accuracy compared to TALYS-2.0, though minor discrepancies remain in the alpha results for the reasons mentioned above. The results of this paper demonstrate the predictive power of our model, stemming from its robust physical basis, particularly the explicit treatment of light charged particles and computational consistency.

IV. Conclusions

This study establishes a comprehensive theoretical framework for the p+28Si reaction up to 200 MeV using the MEND code, demonstrating robust predictive capability through systematic validation against experimental data. Good agreement is generally observed between calculated results and experimental data. The direct, pre-equilibrium, and equilibrium reaction contributions for different outgoing particles are analyzed in detail. The model successfully reproduces the energy spectra and double-differential cross sections of light charged particles at incident energies of 26.5, 48.5, and 62.9 MeV.

The results verify the feasibility of this work. Furthermore, the data generated by our model can provide essential nuclear inputs for spacecraft radiation shielding design and SiC electronics reliability simulation.

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Note: Figure translations are in progress. See original paper for figures.