Microscopic studies of light charged particles and neutron productions in \textit{nat} Si using proton and alpha beams of energies between 20 and 65 MeV

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Abstract. Inclusive cross sections ($\frac{d^2 \sigma}{d \Omega dE}$, $\frac{d\sigma}{dE}$, $\frac{d\sigma}{d\Omega}$ and $\sigma_T$) for the production of light charged particles induced by protons of 26.5, 48.5 and 62.9 MeV and alpha-particles of 25.4, 45.5 and 57.8 MeV on \textit{nat} Si targets have been measured. The secondary emitted particles ($p$, $d$, $t$, $^3$He, $\alpha$, $^6$Li, $^7$Li and $^7$Be) were detected at angles from 10° to 165° in steps of ±10° with respect to the beam axis. Neutrons emitted in these reactions were only recorded in coincidence with, at least, one detected light charged particle. The measurements were compared with all available published data from similar or comparable reactions and with theoretical calculations based on the GNASH and TALYS nuclear-reaction codes.

1. INTRODUCTION
Silicon semiconductor devices are widely used in electronics applications. Interaction of nuclear radiations from radioactive sources, particle beams, and cosmic rays can cause effects ranging from transient recoverable errors, such as single-event upset (SEU), to permanent damage to the electronic devices in space and avionic applications. High-energy protons trapped in radiation belts or produced in solar flares are of concern for satellites. Such high-energy protons typically do not cause SEUs due to their direct energy loss and subsequent induced ionization, but through the nuclear reactions they induce in the Si material. In fact, heavy-ion recoils produced in these proton-induced reactions following light-charged-particle (lcp) emissions are primarily responsible for the SEUs. Radiation-induced damage and deterioration are important mainly for semiconductor detectors and related electronics used near high-beam flux reactors or accelerators with great luminosity. Thus, there is a need for nuclear reaction data to allow such processes to be modelled allowing improved radiation-harden electronic devices to be developed. Unfortunately there is very little appropriate data available at present and no data on the recoils at all. Another approach would be to use nuclear-reaction models to predict the lcp and recoil properties. However, many of the parameters of such models are poorly known and thus to gauge and, subsequently improve, the predictive power of these models, nuclear data of light-particle-induced reactions with Si are needed.
Due to their high penetrability, neutrons liberated from primary nuclear reactions can propagate outside of the electronic component exposed to the radiations first impact and through secondary nuclear reactions cause damage and errors in other components eventually shielded from initial radiations. The modelling of such processes is hindered by the absence of any nuclear data on neutron production.

However, the improvements of the predictive power of nuclear reaction codes need a lot of physics ranging from transport reactions such as direct reactions to evaporation, including the intermediate preequilibrium processes, transfer and knockout reactions.

The present contribution will report on the measurements of lcps and neutrons emitted from proton- and $\alpha$-particle-induced reactions on Si for beam energies ranging between 20 and 65 MeV. An important part of the results issued from these measurements has been already reported in the three following references [1, 2, 3].

2. EXPERIMENTAL METHODS

Beams of 26.5, 48.5, and 62.9 MeV protons and of 25.4, 45.5 and 57.8 MeV alpha projectiles were extracted from the Louvain-la-Neuve cyclotron, and were impinged on a 215 μg/cm$^2$ self-supporting foil of nat Si. Schematics of the experimental apparatus showing the scattering chamber of 170 cm diameter and the position of the various detectors are displayed in Fig. (1).

**Figure 1.** (color) General scheme of the experimental setup (for more details see Refs. [2, 3]).

Lcps (p, d, t, $^3$He, $\alpha$, $^6$, $^7$Li and $^7$Be) emitted at backward angles were detected and identified in seven triple-Si $E$-$\Delta E$ telescopes with thicknesses of 85, 706, and 706 μm, respectively. These detectors covered angles from 105° to 165° on both sides of the beam axis, their exact angular locations are indicated in Fig. (1). At forward angles, lcps were detected in eight $E$-$\Delta E$ telescopes. These detectors were Si-CsI telescopes. The Si-$\Delta E$ elements were 40 μm and 718 μm thick, followed by a 33 mm-thick CsI crystal. These telescopes were located at angles from 10° to 70° on both sides of the beam (see Refs. [2, 3] for more details). Particle identification was achieved from the measured $\Delta E$ and $E$ information. In the CsI counters, particle identification was obtained from the correlation between the charge integrals of the fast and slow components of the scintillator light output. This and the Si-$\Delta E$s information were combined to optimize the discrimination of lcps. For illustration see Fig. (2). The nonlinear calibration of the CsI light output was fitted to the $Z$ and $A$ dependent parameterization suggested by Horn et al. [4].

Neutrons emitted in coincidence with charged particles were detected in up to 81 DEMON counters of 16 cm diameter by 20 cm depth, filled with NE213 liquid scintillator. Neutron energy was determined from the measured time of flight. Separation of detected neutrons and
Figure 2. (color) Left: Two-dimensional $\Delta E_{c1}-\Delta E_{c2}$ discrimination spectrum from the Si-Si-CsI telescope positioned at an angle $30^\circ$, in the $\alpha$ ($57.8$ MeV) + $^{nat}Si$ reaction. One clearly observes the contributions of the $^6,^7Li$ and $^7Be$ secondary emitted particles. Right: two-dimensional $\Delta E_{c2}-Q_f$ discrimination spectrum from the same telescope and reaction correlating the charge integral of the fast component of the CsI light output $Q_f$ to the energy loss $\Delta E_{c2}$. The missing data correspond to the event stopped in the two first members of the telescope ($\Delta E_{c1}, \Delta E_{c2}$).

$\gamma$-rays and the determination of the neutron detection efficiency as a function of neutron energy and detector threshold are discussed in detail in Refs. [5, 6].

3. RESULTS

3.1. Light charged Particles

Examples of the evolution of the measured double differential cross sections with energy and angle are shown in Fig. (3) for the $^{nat}Si(\alpha,t\,x)$ reaction (where $x$ stands for all other emitted particles or recoil nuclei not detected) at $E_\alpha=25.4$ and 45.5 MeV. At the highest detected energies, especially for the most forward angles, the spectra are dominated by sharp peaks associated with direct reactions. These peaks can be associated to stripping reactions feeding the known $^{29}P$ excited states [7]. Many other similar spectra can be found in Refs. [1, 2, 3]. On the other hand for the lowest energies (<10 MeV) there is a broad peak associated with evaporation from a thermally equilibrated nucleus. In between these two regions, the spectra display a continuous yield which will be associated with the preequilibrium processes.

A gross description of the continuous part of the double differential cross section (evaporation + preequilibrium) can be obtained from multi-source fit analysis. This reduction of the data to a few fit parameters will facilitate the incorporation of this data into simulations of the radiation interaction with Si. Following Prindle et al. [8], three emitting sources were assumed. In order of increasing source velocity, these are an evaporation source (CN), a preequilibrium source (PE) and finally a projectile-like preequilibrium source (PLPE).
Figure 3. (color) Energy spectra of secondary t particles emitted in the reaction channel ^natSi(α,t x) at E_α = 25.4 and E_α = 45.5 MeV obtained from the Si-Si-CsI telescopes ((black) histogram). The (red) arrows indicate the peaks associated with the excited states of the residual nucleus ^29P while the (red) numbers indicate their ranking following Ref. [7]. The (blue) numbers indicate the laboratory lcp detection angles.

Table 1. Total cross sections σ_T|_{E_{lcp}^{min}} and uncertainties Δσ|_{E_{lcp}^{min}} for each detected particle type obtained by integrating the cross sections \( \frac{d\sigma}{dE_{lcp}}(E_{lcp}) \) over energy for the proton and α-induced reactions at all bombarding energies. Also included are the theoretical predictions σ_theo obtained by integrating the improved TALYS \( \frac{d\sigma}{dE_{lcp}} \) predicted curves, with (1) and without (2) the experimental low-energy cuts \( E_{lcp}^{min} \) (see Refs. [1, 2]).
Figure 4. Left. (color) Double-differential cross sections for the production of protons at the indicated laboratory angles, in the proton-induced reactions on natSi at \( E_p = 62.9 \text{ MeV} \). The lines correspond to the contributions of the different moving sources and their sum ((red) solid line): CN source in (blue) thin solid lines, PE source in (green) solid lines and PLPE source in (brown) dashed lines. Right. Angular distributions for the contributions (colored lines) \( \frac{d\sigma}{d\Omega} \) of the three different moving source fits and their sum ((red) solid line) [2, 3].
For the $\alpha$-induced reactions, good fits to the experimental spectra could not be obtained with a consistent set of parameters as for the proton-induced data. In the case of the proton-induced reaction, only the spectra of the secondary emitted proton required a PLPE source and this specifically at forward emission angles (see Fig. (4)). The spectra for the other secondary particles were fitted with CN and PE sources only [2]. The sources were parameterized as in Ref. [8] with a Maxwellian distribution for the CN and the PLPE sources and a Watt distribution for the PE source. The mathematical details and the list of the free and fixed parameters in these fits were thoroughly reported in Refs. [2, 3].

An example of the fitted spectra is shown in Fig. (4) for the $^{nat}\text{Si}(p,p')$ reaction at $E_p = 62.9$ MeV. The contributions from the three sources are indicated by color lines. The angular distributions of the three contributions resulting from these fits are also displayed in Fig. (4). The PLPE contribution is mostly forward peaking while the CN contribution is mainly isotropic (see Ref. [2] for other results).

Examples of the angular distributions of the yields of the peaks associated with direct reactions (DI) are shown in Fig. (5) for the $^{28}\text{Si}(p,p')$ and $^{28}\text{Si}(\alpha,\alpha')$ reactions at all the projectile energies $E_p$ and $E_\alpha$ (see sect. 5.1 for a detailed discussion on the model predictions (curves)).

Total cross sections $\sigma_T$ for each detected particle type were obtained from integrating the energy spectra. No attempt was made to extrapolate the measured yield below the low-energy detection thresholds of the telescopes ($E_{\text{lcp}}^{\text{min}}$). The integrated cross sections and the corresponding thresholds are listed in Table 1 for both reactions at all the bombarding energies. For more details see Refs. [2, 3]. Also included in this table are the predictions of the improved reaction code TALYS [1] (see Sect. 5.3 for detailed discussions).

### 3.2. Coincident Neutrons

Neutrons were only measured in coincidence with detected charged particles. Neutron double differential multiplicity spectra were constructed from these events [3, 5, 6] when there was sufficient data. These distributions were deduced by integrating the neutron counting rates at a given $(\theta_n, \phi_n)$ over all $\theta_{\text{lcp}}$ detection angles for each type of emitted lcp. This integration excluded DI events which, in principle, cannot contribute to neutron coincident emission. The measured neutron yield appeared to be largely uncorrelated with the angles of the detected lcps (see Ref. [2]). Also the neutron $\phi$ distributions appeared to be flat within the statistical errors. Thus only differential multiplicity distributions averaged over all $\theta_{\text{lcp}}$ and $\phi_n$ angles were determined.

Examples of the $\theta_n$ angular dependence of the neutron energy spectra are shown in Fig. (6) for neutrons in coincidence with proton secondary particles emitted in the $E_p = 62.9$ MeV proton-induced reaction. The lack of correlation with the coincident charged particle and the thermal-like nature of the energy spectra suggest that these neutron are dominated by the evaporation component. More precisely, the spectra were fitted with contributions from two moving sources [6]; a CN and a PE sources. The first one was assumed to be a Maxwellian type while the second one was considered to be a Watt form. The fits allowed us to extrapolate the yield below the 2 MeV threshold of the neutron detectors and thus was used to deduce the total multiplicity of coincident neutrons. The extracted coincident neutron multiplicities for all reactions and for each lcp type are listed in Table 2 (see Refs. [2, 3] for related comments).

### 4. COMPARISON WITH OTHER DATA

To check the consistency of our data, it is useful to compare them with data obtained from similar or comparable reactions. In Fig. (7), double-differential energy spectra at $\theta_{\text{lcp}}$ angle of 70° from the $E_p = 62.9$ MeV proton-induced reaction are compared to spectra obtained from similar nucleon-induced reactions at approximately the same bombarding energies. The histograms are from our work. In comparison the squares are from the $E_p = 61.7$ MeV $(p+^{27}\text{Al})$ reaction
Figure 5. (color) Left: Center-of-mass angular distributions of proton elastic and inelastic scattering (to the $2^+$ state) by $^{28}\text{Si}$, at 26.5, 48.5 and 62.9 MeV ((black) solid points). The (blue) solid lines are from CC calculations with the OMP of [9], while the (green) dashed and (purple) dotted lines are from DWBA calculations using the OMPs of [10] and [11], respectively. Right: same as the left figure but for $\alpha$-particles scattering by $^{28}\text{Si}$ at 25.4, 45.5 and 57.8 MeV. The (blue) solid, (green) dashed and (purple) dotted lines are from DWBA calculations using the OMPs of [12], [13] and [14] respectively.

measured by Bertrand and Peelle [15], while the open circles are from the $E_n = 62.7$ MeV ($n+^{nat}\text{Si}$) reaction measured by Benck et al. [16]. Concentrating on the $p+^{27}\text{Al}$ reaction first, we find that the $p$, $d$, $t$ and $\alpha$-particle spectra are almost identical, in shape and generally in magnitude, to those measured in this work. Differences do exist in the region of the DI peaks, but this is expected as the structure of the two target nuclei and the related $Q$-values are different. Otherwise, the largest observed and still unexplained difference is for the $^3\text{He}$ secondary particles. In fact, the $p+^{27}\text{Al}$ reaction has approximately a factor of two less $^3\text{He}$ particles at the lowest measurement energy. However, the difference is less significant at higher $^3\text{He}$ energies. Apart from $^3\text{He}$, the consistency of the results for the other particles suggests the structure of the target nucleus is not an important factor for PE emission. In the comparison with the $n+^{nat}\text{Si}$ data shown by the open circles, the spectra are again similar in shape and magnitude. The spectra from the neutron-induced reaction extend to higher energies, but this can be understood from the $Q$-values of the different reactions. For the proton spectra, we
Figure 6. (color) Energy distributions at different angles $\theta_n$ of the neutron multiplicities $d\nu_n(\theta_n, \phi_n)/d\Omega_n$ and related uncertainties in coincidence with protons ((black) points) in the proton-induced reaction on $^{nat}$Si at $E_p = 62.9$ MeV [2, 3]. The (red) solid lines correspond to the sum of the contributions of two moving sources fitted to the spectra: the CN source is indicated by the (blue) dotted lines while the PE source is indicated by the (green) dashed lines [2].

| $^{nat}$Si($p,n-p\times$) | $^{nat}$Si($\alpha,n-lcp\times$) |
|----------------|----------------|
| $\nu_n|_{lcp}$ | $\nu_\alpha|_{lcp}$ |
| $E_{lcp}$ (MeV) | $E_{lcp}$ (MeV) |
| $\delta (\nu_n|_{lcp})$ | $\delta (\nu_\alpha|_{lcp})$ |
| $E_p = 26.5$ MeV | $E_\alpha = 25.4$ MeV |
| $n-p$ | - | - |
| $n-\alpha$ | - | - |
| $E_p = 48.5$ MeV | $E_\alpha = 45.5$ MeV |
| $n-p$ | 3.5 | 0.5 | 0.16 | 4.5 | 0.09 | 0.06 |
| $n-d$ | 4.5 | 0.12 | 0.12 | 5.3 | 0.14 | 0.11 |
| $n-\alpha$ | 8.4 | 0.12 | 0.10 | 8.4 | 0.18 | 0.09 |
| $E_p = 62.9$ MeV | $E_\alpha = 57.8$ MeV |
| $n-p$ | 3.5 | 1.09 | 0.27 | 4.5 | 0.90 | 0.12 |
| $n-d$ | 4.5 | 0.34 | 0.46 | 5.3 | 0.44 | 0.26 |
| $n-^3$He | - | - | 12.0 | 0.67 | 0.94 |
| $n-\alpha$ | 8.4 | 0.28 | 0.43 | 8.4 | 0.40 | 0.09 |

Table 2. Neutron multiplicities in coincidence with lcp of minimum energy $E_{lcp}^{\text{min}}$ and associated errors $\delta (\nu_n|_{lcp})$ in the case of the reactions $^{nat}$Si($p,n-lcp\times$) at incident energies $E_p = 26.5, 48.5$ and 62.9 MeV and $^{nat}$Si($\alpha,n-lcp\times$) at incident energies $E_\alpha = 25.4, 45.5$ and 57.8 MeV.

observe that those resulting from the proton-induced reactions are higher in magnitude by a factor of about $(5/3)$ as already found by Kalend et al. [17]. For $t$ emission, the $n+^{nat}$Si cross...
section is almost a factor of 4 larger in magnitude. However, the $t$ spectra from the neutron-induced reaction are consistent with the $^3$He spectra from the proton-induced reaction suggesting charge-independent interactions, as shown in the lower righthand panel of Fig. (7). For detailed discussion concerning this point, see Ref. [2].

![Figure 7](image-url)

**Figure 7.** (color) Double-differential energy spectra at angle $\theta_{lcp} = 70^\circ$ ((black) histograms) in the laboratory frame for the ($p,lcp\ x$) reactions on $^{nat}$Si at $E_p = 62.9$ MeV ($lcp = p, d, t, ^3He, \alpha$). The (blue) open circles represent the cross sections for the neutron-induced reactions on $^{nat}$Si at $E_n = 62.7$ MeV [16] and the (red) solid squares the cross sections for the proton-induced reactions on $^{27}$Al at $E_p = 61.7$ MeV [15]. The $^3$He spectrum from the $p$-induced reaction is compared to the $t$ spectrum from [16] in the lower righthand panel.

5. COMPARISON WITH THEORY

In this section, the data are compared with the results of theoretical calculations. Two different codes are used, namely GNASH [18] and TALYS [12], which are based on the same nuclear-reaction models to describe reactions in the energy region from 1 keV to 200 MeV. More specifically, they use DWBA and CC calculations to account for DI to discrete, low-lying residual states. For the continuous part of the energy spectra associated with PE emission, they use either the semi-classical exciton model [19] or the quantum-mechanical model of Feshbach, Kerman, Koonin [20]. In the case of reactions with composite particles, they also incorporate the phenomenological models of Kalbach [21, 22]. To describe the CN process,
both codes use the statistical theory of Hauser-Feshbach (HF) [23]. Furthermore, they consider multiple PE emission and multiple CN emission. The main differences between these codes concern the nuclear ingredients of the above-mentioned models, i.e. the particle-nucleus Optical Model Potentials (OMP), the nuclear level densities, the γ-ray strength functions, the exciton-model effective interaction matrix $M^2$, and the different parameters entering Kalbach’s models [21, 22]. A comparison of the predictions of these two codes is therefore, equivalent to comparing the different input data of the calculations. In the following discussion, we present GNASH results for the proton-induced reactions on $^{28}$Si obtained from the tabulated cross sections of [24] and results of calculations performed with the improved version of TALYS (details in [1]).

5.1. Direct reactions
For the analysis of the elastic and inelastic scattering channels we use the TALYS code which enables us to test various OMPs, spherical and deformed [25]. In the left panel of Fig. (5), we compare the angular distributions of elastic and inelastic proton scattering by $^{28}$Si at all incident energy with the theoretical curves obtained from DWBA calculations using the global OMPs [10, 11]. For $^{4}$He+$^{28}$Si, there also exists a deformed nucleon-nucleus OMP based on the parameterization of Koning and Delaroche [9]. The latter OMP allowed us to perform more exact CC calculations to describe the elastic and inelastic scattering channels simultaneously (see Refs. [1, 2, 3]). From Fig. (5) it is clear that all three OMPs compare fairly well with the data in the forward-scattering region. At larger scattering angles and in the case of the inelastic scattering to the $2^+$ state, the three OMPs give different results. These observations suggest that the OMPs used are almost identical in the surface region of the nucleus, whereas they differ in the nuclear interior which is probed by scattering in the backward angles and inelastic scattering in general. For α scattering (see also Fig. (5)), we perform DWBA calculations using the global OMP [14, 13] and finally, the OMP used by default in TALYS [12]. The latter is based on an approximate folding of the nucleon-nucleus OMP of [26] over the number of protons and neutrons in the composite particle renormalized to the total reaction cross sections obtained from the systematics of [27]. From the results obtained at 26.5 MeV for protons and for α projectiles at all incident energies, where the measured data extend to scattering angles $\theta_{lcp} \approx 160^\circ$, we can deduce that only the OMP of [9, 12] gives the best description of the data for protons, while the OMPs of Ref. [14] and [9, 12] are able to describe the general features of the α elastic-scattering cross sections fairly well and without any normalization factor. A detailed comparison is given in Ref. [2] for the excited states observed in the $^{28}$Si(α, d)$^{30}$P reaction also.

5.2. Reactions to the continuum
For the continuous part of the energy spectra, both codes use the exciton model and the composite-particle models of Kalbach. Examples of double-differential energy spectra measured at $\theta_{lcp} = 10^\circ$ to $160^\circ$ are compared with theoretical predictions of GNASH [24] and the improved version of TALYS [1] for proton-induced reactions at $E_p = 62.9$ MeV in Fig. (8). The GNASH report does not include any results on α-induced reactions on $^{28}$Si, nor on triton or $^3$He-particle emissions for the proton-induced reactions, while with the TALYS source code we were able to treat all lept up to α particles both in the incident and exit channels. Therefore we shall only present the results for the emission of $p$, $d$, and α particles. For the results obtained by TALYS for $t$, $^3$He and all other secondary particles at other projectile energies and for α-induced reactions, see Refs. [1, 2, 3].

In the GNASH calculations and for incident protons, the evaporation part of the spectra is slightly overestimated for emitted protons and underestimated for emitted α particles. The PE region is reasonably reproduced for both emitted protons and α particles, however for the latter particles the description tends to deteriorate with decreasing incident proton energy (see
Figure 8. (color) Double-differential energy spectra (black) points for the $^{nat}Si(p,lcpx)$ reactions at $E_p = 62.9$ MeV ($lcpx = p, d, \alpha$). Left: the (green) solid lines are from GNASH [24]. Right: the (blue) solid lines are from the improved TALYS [1]. All are expressed in the laboratory frame (see text for detailed discussion).

Ref [2]). The deuteron spectra are generally underestimated in the lower-energy CN region, and overestimated in the higher-energy PE region at all proton incident energies.

In the improved TALYS predictions, there is still some overestimation of the CN emission in the proton spectra, while in the $\alpha$-particle spectra this region tends to be underestimated. PE emission is well reproduced for all emitted $lcpx$, apart from some underestimation at backward angles for deuterons and $\alpha$ particles.

Overall, both codes give comparable predictions for proton and $\alpha$-particle emissions. For
deuteron emission however, the results obtained with TALYS are by far better than GNASH, in both the low-energy CN and higher-energy PE region. However, the comparison between the measured spectra and model calculations in the laboratory frame, shown in Fig. (8), is valid only up to the DI peaks, since such a comparison requires information on the unknown a priori experimental width of these peaks.

5.3. LCP total production cross sections

In Table 1, the total emission cross sections from the model calculations using the improved version of TALYS are presented. The theoretical results (1) and (2) are obtained by integrating the theoretical \( \frac{d\sigma}{dE} \), with and without the experimental low-energy threshold \( E_{\text{lcp}}^{\text{min}} \), respectively. For the proton-induced reactions, the \( \sigma_{\text{theo}}^{(1)} \) are in reasonable agreement with the experimental total cross sections \( \sigma_T |_{E_{\text{lcp}}^{\text{min}}} \), which is a direct consequence of the improved description of the energy spectra. The sole exception is \( \alpha \)-particle production at \( E_p = 62.9 \text{ MeV} \) and \( t \) and \( ^3\text{He} \) production at \( E_p = 26.5 \text{ MeV} \), which are underestimated by the model. Furthermore, the comparison of \( \sigma_{\text{theo}}^{(1)} \) and \( \sigma_{\text{theo}}^{(2)} \) shows that the effect of \( E_{\text{lcp}}^{\text{min}} \) varies for the different particles at each incident energy, with only 9% of the \( \sigma_T \) missed for \( t \) production at \( E_p = 62.9 \text{ MeV} \) while almost 72% is missed for \( \alpha \)-particle production at \( E_p = 26.5 \text{ MeV} \). On the whole, the effect of \( E_{\text{lcp}}^{\text{min}} \) decreases with increasing energy, i.e. at \( E_p = 26.5 \text{ MeV} \) an overall 27% of \( \sigma_T \) missed, while at \( E_p = 48.5 \) and 62.9 MeV, the missing percentage drops to 24% and 21%, respectively. Similar tendencies are seen in the results obtained for the \( \alpha \)-induced reactions as shown in Table 1. The \( \sigma_{\text{theo}}^{(1)} \) are in agreement, within the experimental uncertainties, with the experimental values apart from the case of proton production which is systematically overestimated by TALYS independent of incident energy. In addition, at \( E_\alpha = 25.4 \text{ MeV} \) \(^3\text{He} \) emission is greatly underestimated while \( \alpha \) emission is overestimated. The effect of \( E_{\text{lcp}}^{\text{min}} \) globally decreases with increasing incident energy and at \( E_\alpha = 45.5 \) and 57.8 MeV approximately 27% and 21% of the \( \sigma_T \) are missed. However, the effect is much more pronounced at \( E_\alpha = 25.4 \text{ MeV} \), where almost 44% of \( \sigma_T \) goes unaccounted for when \( E_{\text{lcp}}^{\text{min}} \) is imposed.

6. CONCLUSIONS

Proton and \( \alpha \)-particle induced reactions have been studied at energies from 25 to 65 MeV. Lcps including \( p, d, t, ^3\text{He}, \alpha, ^6\text{Li}, ^7\text{Li}, \) and \(^7\text{Be} \) emitted from these reactions have been detected and characterized. Double-differential, cross section, angle-integrated energy spectra and total cross sections for the production of these particles have been extracted. In addition, neutrons emitted in coincidence with these lcps have also been detected and characterized. Differential and total coincident neutron multiplicities have been determined. The continuous parts of the double-differential spectra have been parameterized with moving source fits. The data have also been confronted with the nuclear reaction codes GNASH and TALYS. Although these codes reproduce the general features of the experimental data, they are still not satisfactory for a complete description, especially for understanding SEUs in electronic applications. A more detailed study of the reaction models utilized by these codes [1] has led to considerable improvements in the description of the lcp emission spectra of proton- and \( \alpha \)-induced reactions on silicon in the energy range from 20 to 65 MeV. These results, complemented with similar systematic studies of higher energy regions would obviously be invaluable for practical applications.

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