I. 2. Forward Nuclear Glory in $^{13}\text{C}^{+}^{28}\text{Si}$ Scattering


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The optical glory is a well known phenomenon, which is due to the scattering of visible light from water droplets. Like the rainbow, the forward glory scattering produces an intensity enhancement in the forward direction because of the axial focusing effect. This scattering phenomenon has been predicted and observed in molecular and atomic collisions\textsuperscript{1,2}). In nuclear collisions, its existence has been predicted by many theorists\textsuperscript{3,4}). Recently, a proof of the forward nuclear glory was experimentally suggested for $^{12}\text{C}^{+}^{12}\text{C}$ scattering system in a energy region of $E_{c.m.}=6.4-11.5$ MeV\textsuperscript{5}). Furthermore, using the forward nuclear glory phenomenon at higher incident energies of E/A=4~5 MeV, the total reaction cross sections have been measured for the scattering systems, $^{12}\text{C}$, $^{15}\text{N}$, $^{16}\text{O}$, and $^{28}\text{Si}$\textsuperscript{6}).

In the present work, the elastic differential cross sections at smaller angles than that in previous experiment\textsuperscript{6}) were measured in the $^{13}\text{C}^{+}^{28}\text{Si}$ scattering system at $E_{\text{Lab}}=60$ MeV. The result of the experiment showed undoubted oscillations and undulating envelope shapes in the sum-of-differences cross sections.

The elastic differential cross sections were obtained for the scatterings of $^{13}\text{C}$ by $^{28}\text{Si}$ using $^{13}\text{C}^{4+}$ beam of E=60 MeV provided from the Tohoku University model 680-cyclotron. For the determination of the scattering amplitude $|f_{M}(0)|$ by means of the generalized optical theorem(GOT), it is necessary to measure the elastic differential cross sections in the very forward angular range. The most crucial point is how far forward angles the measurement can be performed. It comes to a problem how small errors the absolute scattering angles can be determined.

For the measurements at extremely forward angles (0.6°-4.0°), a trapezoidal scattering chamber was designed and installed at the down stream of a large scattering chamber as shown in Figure 1. A distance between a target and a defined slit of the detector system was 1599 mm. The detector system consists of two 25 µm totally depleted silicon detectors and a 240 µm position-sensitive silicon detector, i.e., this system had two telescopes. Each telescope was mounted by a thin tantalum plate with three slit apertures of 0.4x2mm² in front of the ΔE detectors. Three slit apertures defined the solid angles of 3.1x10^{-7}sr, and the
differential angles of $\Delta \theta = 0.014^\circ$ assuming a point beam spot on the target. The accuracy of angle setting was $5 \times 10^{-4}$ degree.

Four solid-state detectors to monitor relative beam deflection were symmetrically situated with respect to the beam axis. This monitor system was movable on the scattering plane and an accuracy of absolute scattering angles was $0.02^\circ$. The target was a self-supporting natural Si metal of 180 $\mu g/cm^2$ thickness. The beam was doubly collimated to a spot diameter less than 0.4 mm on the target.

The differential cross sections were measured for angles of 0.6°-1.2° with step of 0.05°, for 1.2°-8.5° with step of 0.1°, and for 8.5°-60° with step of 1.0° in the laboratory system. The statistical error was smaller than 0.3% at angles smaller than 8.5°.

For the determination of the exact scattering angles with the incident beam axis, a primary problem is an instability of the beam position on the target during taking data. The present collimator system for the incident beam has the maximum dispersive beam angle of $\pm 0.11^\circ$. However, the present measurement requires a precision of the order of $\pm 0.001^\circ$ in the scattering angles to achieve the observation of the nuclear glory phenomenon up to 0.5°. If the incident beam is very unstable, the uncertainty of the scattering angle concerning the definite slit aperture of the detector is $\pm 0.014^\circ$ in an maximum value, where the beam spot on the target is equal to 0.4 mm $\phi$.

In order to monitor the deflection of the beam intensity distribution in the beam spot, the four monitor detectors were symmetrically placed on a circle with a small corn angle of 1.1° with the incident beam axis. Figure 2 shows the relative shift of the scattering angle by the beam deflection for each data run, where $\Delta \phi$ is the shift of vertical component for the scattering plane, and $\Delta \theta$ is the shift of horizontal component. Each shift was determined in the accuracy of $\pm 0.003^\circ$ for each data run.

The secondary problem is an angle dependency of the effective area for a solid angle in a region of very small angles because of the small corn angle. Figure 3 shows deviations of the Rutherford cross sections for the practical solid angles from those assuming a constant solid angle for scattering angles. These deviations increase with $\Delta \phi$.

As the physical effects for the elastic scattering data at such very small angles, the effects of multiple scattering, the electron screening and vacuum polarization, should be considered. The effects of the first and second terms were negligible for the data at angles larger than 0.2° at least. However, the effect of the third term was taken into account for the data. In addition, the contribution from the target contaminations should be taken into account in order to keep the resulting error small. We found a contaminant material of about $3.7 \times 10^{-3}$% in $^{28}$Si target which was estimated as a mass number of near A=180, it might be Au, from the elastically scattered energy spectra at the large angles.

The determination of the absolute scattering angles was achieved by measuring the symmetry of the Rutherford scattering yields with the beam axis. Elastic scattering yields at
symmetrical angle points with the beam axis were measured. The ratios of elastic scattering yields to Rutherford cross sections should show the symmetrical structures with the beam axis. These results are shown in Figure 4. A difference between yields at symmetrical points can correspond to the deviation of $\Delta \phi = 0.003^\circ$ in the absolute scattering angles. Therefore, in the present work, absolute scattering angles could be determined with an accuracy of $\pm 0.003^\circ$.

The experimental angular distribution in $^{13}$C+$^{28}$Si scattering system is shown in Figure 5, together with the result of the optical model potential (OMP) analysis$^10$. The angular distribution at $\theta_{\text{Lab}}=0.6^\circ - 4.0^\circ$ is expanded in Figure 6. The sum-of-differences cross sections were calculated from the measured elastic cross sections. The data of elastic cross sections have been renormalized as the median of upper and lower envelopes of $\sigma_{\text{SOD}}(\theta_0)$ should become a horizontal line. This normalization could reduce systematic errors from each data of the measured elastic cross sections. Figure 7 shows the obtained sum-of-differences cross sections. It exhibits exactly those features which were predicted in Refs.3 and 4, i.e., rapid oscillations at very forward angles with constant amplitude and being nearly vanished at an angle called glory minimum. These features are proofs of an existence of the forward nuclear glory.

The quantities, which are nuclear scattering amplitude $|f_M(0)|$, reaction cross section $\sigma_R$, and glory angular momentum $l_{gl}$, should be determined from the SOD analysis. As mentioned in Ref.9. The result of the analysis has a small deviation from the measured $\sigma_{\text{SOD}}(\theta_0)$ in the angular range near the glory minimum. It may be caused because the phase of nuclear scattering amplitude $\phi_M(\theta_0)$ is approximately represented by the $\phi_M(0)$ and the C$'(\theta_0)$ has a finite value. An exact glory minimum could be estimated for the $\theta_0=4.0^\circ - 5.5^\circ$ from the SOD analysis. The values of $l_{gl}$ and $|f_M(0)|$ were 30 $\pm$ 5 and 21 $\pm$ 4 fm, respectively. The obtained reaction cross section was 2090 $\pm$ 80 mb. The result of $\chi^2$ fit for the SOD is shown in Figure 8 by a solid curve together with a value of $\sigma_\text{R}$.

The nuclear scattering amplitude $|f_M(\theta)|$ derived from the present data exhibited rapid oscillation at forward angle and nonvanishing at $\theta \rightarrow 0^\circ$. It was suggested that a forward nuclear glory in the $^{13}$C+$^{28}$Si system existed at $E_{\text{Lab}}=60$ MeV.

References

Fig. 1. Schematic layout for the measurement of forward elastic scattering.

Fig. 2. The shift of beam deflection angle for each data run.

Fig. 3. The deviations of Rutherford cross sections for practical solid angles from those for a constant solid angle. The practical solid angles depend on the scattering angles near 0 degree. Solid and open circles indicate the deviations at $\Delta \Phi = 0^\circ$ and $\Delta \Phi = +0.1^\circ$. $\Delta \Phi = +0.1^\circ, \Delta \Phi = +0.1^\circ$, respectively.
Fig. 4. Ratios of elastic scattering to the Rutherford scattering cross sections at symmetry angles with beam axis. The open squares and solid circles indicate data points at the left-side and right-side angles with the direction of beam current, respectively. A correction of scattering angles with beam axis is only 0.003° to right side.

Fig. 5. Comparison between the measured cross sections and the OMP curve.

Fig. 6. The expanded angular distribution at $\theta_{\text{lab}}=0.6^\circ$−$4.0^\circ$.

Fig. 7. The $\sigma_{\text{SDF}}(\theta_0)$ distribution as a function of $\theta_0$. 
Fig. 8. The $\chi^2$ fit of the GOT calculation for the SOD cross sections.