Particle evaporation effect on the charge-changing cross section measurement of light isotopes

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Introduction

Radioactive ion beams have traditionally been employed to investigate exotic nuclei for decades. Projectile fragmentation reactions and in-flight separation are the most prevalent methods for creating these beams. Fragmentation reactions between stable and unstable projectiles are vital in research, including heavy-ion cancer treatment and space radiation shielding. The fragmentation of lighter ions like B, C, N, O, Ne, and Mg is important for space radiation study, as these are the most abundant.

Nuclear charge-changing cross sections are the most straightforward and commonly measured observables to study different nuclear structure properties (including halo or skin). They are also important for proper measurement of the charge radius of isotopes. In this study, we describe a systematic calculation of charge-changing cross sections of ^{12}C, ^{14}N, ^{16}O, and ^{20}Ne with beam energy 290 MeV/u and ^{24}Mg with beam energy 400 MeV/u on a carbon target. Our aim is to investigate the effect of charge particle evaporation on projectile fragmentation, which can enhance our understanding of the underlying mechanisms in the fragmentation process.

Abrasion-Ablation process

The abrasion-ablation [1] process is a two-step reaction mechanism. In the abrasion stage, prefragment is produced in excited state after removing nucleons. In the next stage, the prefragment deexcites to produce final fragment through light particle evaporation. This continues until the excitation energy of the prefragments falls below the particle emission threshold. The Glauber fragmentation model accounts for charge-changing cross sections in the abrasion stage, which depends on the proton distribution in projectile nuclei and underestimates cross sections by a significant percentage. This discrepancy can be addressed by including the effects of charged-particle evaporation processes that occur after the removal of neutrons from the projectile.

Formalism

In the abrasion-ablation model, the total charge-changing cross section follows as [1],

$$\sigma_{cc} = \tilde{\sigma}_{cc} + \sigma_{cc}^{evap}. \qquad (1)$$

$\tilde{\sigma}_{cc}$ is the charge-changing cross section in the Glauber model calculations, which can be calculated from [2]

$$\tilde{\sigma}_{cc} = \int d\mathbf{b} \left[1 - [P_p(\mathbf{b})]^{Z_P}\right], \qquad (2)$$

with $P_p(\mathbf{b}) = \exp\{-\int d\mathbf{s}\bar{\rho}_p^P(\mathbf{s},\mathbf{b})(Z_T\sigma_{pp}\bar{\rho}_p^T + N_T\sigma_{pn}\bar{\rho}_n^T)\}$ as the probability that a proton from the projectile survives the collision with the target. $\bar{\rho}_j^T(\mathbf{s})$ $(j = n, p)$ is the z-integrated density of the target neutron and proton, $\bar{\rho}_p^P(\mathbf{s})$ is the z-integrated density of projectile proton. The projectile (target) proton (neutron) densities have been calculated using harmonic oscillator density distributions and are normalised to unity. σ_{pp} and σ_{pn} are the nucleon-nucleon cross sections. Z_P, Z_T are projectile and target atomic numbers, respectively, N_T is the target neutron number, and b is the impact parameter. σ_{cc}^{evap} is the neutron removal cross section followed by charge particle evaporation. This term is calculated using the charge particle evaporation probability followed by neutron removal. Thus, $\sigma_{cc}^{evap} = \sum_x^{N_P} \sigma_{-xn}p_{-xn}$, with, $p_{-xn} = \int dE_{ex}w_{-xn}(E_{ex})f(E_{ex}, A_p - x, Z_p)$[3], A_p, N_P are the projectile mass number and neutron number respectively, E_{ex} is the excitation

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energy of the prefragment after x neutron removal, $f(E_{ex}, A_p - x, Z_p)$ is the charge particle evaporation probability at certain excitation energy, $w_{-xn}(E_{ex})$ is the excitation energy distribution (EED) of the prefragment. The partial neutron removal cross section (σ_{-xn}) is calculated in Glauber model using

$$\sigma_{-xn} = \binom{N_P}{x} \int d\mathbf{b}[P_p(b)]^{Z_P} [P_n(b)]^{N_P - x} \times [1 - P_n(b)]^x \,,$$

$P_n(\mathbf{b})$ has the same expression as $P_p(\mathbf{b})$ by swapping the role of proton with the neutron.

Results and discussions

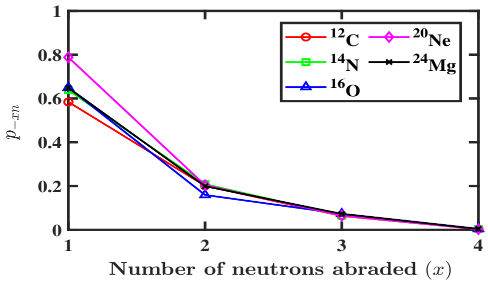

FIG. 1: Partial particle evaporation probability (p_{-xn}) for different projectiles for the abrasion of neutrons up to four.

In FIG. 1, we plot the partial probability of charge particle evaporation (p_{-xn}) after removal of $1-4$ neutrons from the projectile in the abrasion stage. The Gaimard-Schmidt (GS) approach is used to calculate the EED of the prefragment as in [3]. The GEMINI++ [4] statistical code calculates the charge particle evaporation probability ($f(E_{ex}, A_P - x, Z_P)$) at certain excitation energy based on the Hauser-Feshbach theory. We obtained the function by considering the fraction of all decay channels with at least one charged-particle emission in the sequential decay.

TABLE I: Total charge-changing cross section with charged particle evaporation effect.

Nucleus	Cross section (mb)			
	$\tilde{\sigma}_{cc}$	σ_{cc}^{evap}	σ_{cc}	Expt.
^{12}C	638	98	736	731 ($\pm$52) [5]
^{14}N	684	161	845	878 ($\pm$51) [5]
^{16}O	746	113	859	863 ($\pm$20) [6]
^{20}Ne	894	141	1035	1050 ($\pm$21) [6]
^{24}Mg	940	104	1044	1028 ($\pm$18) [6]

FIG. 1 shows that one neutron channel contributes most to evaporation; contributions after 4 neutrons removal almost vanish and are not shown here.

In TABLE I, we show the calculated σ_{cc}^{evap} and σ_{cc}, and we find a clear match with the experimental data. A maximum contribution of 102 mb from the 1-neutron channel is calculated for projectile ^{20}Ne.

In FIG. 2, we plot the measured charge-changing cross sections. The calculated total charge-changing cross sections (σ_{cc}), including particle evaporation contributions, reproduce the experimental results fairly well.

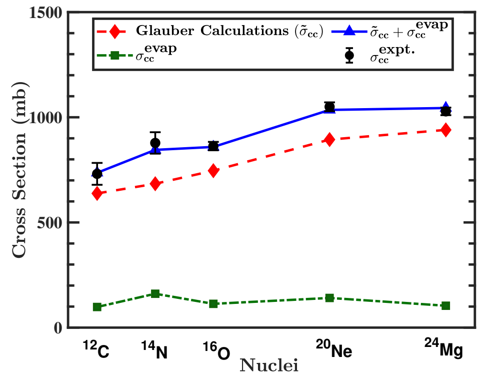

FIG. 2: Results of measured charge-changing cross section (solid triangles) of ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, and ^{24}Mg on a carbon target. Glauber (solid diamond), the contributions of particle evaporation (solid square), expt data [5, 6](solid circle) also shown.

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