Target effect of fragmentation reactions at intermediate energy

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Motivation

- Study on production of projectile-like fragments (PLF)
  - Production mechanism
  - Application of RIB to various fields

- Systematic measurements of
  - Momentum distribution
  - Production cross section ($\sigma_{\text{Prod.}}$)
Projectile fragmentation process

Formation of pre-fragment  
De-excitation of pre-fragment

Momentum distribution of projectile-like fragment (PLF)

Prod. Rate

\[ P_F \quad \Delta P \quad P_0 \quad \sigma_P \]
Methods to estimate $\sigma_{\text{Prod.}}$ of PLF

1. Empirical formulation
   
   EPAX2
   
   $$S = S_2 \left( A_p^{1/3} + A_T^{1/3} + S_1 \right)$$  

2. Statistical model
   
   Statistical abrasion-ablation model
   

3. Microscopic model
   
   QMD, AMD
Experimental setup

HIMAC-NIRS

A. Identification of fragments
   Measurements of momentum
   TOF : F1 - F2 (or F3)
   ΔE   : F2 (or F3)
   Bρ   : D1, D2

B. Definition and acceptance of angle
   Deflection of primary beam + F0-Slit

C. Normalization of production rate
   Measurement of primary-beam intensity
Measurements

$^{40}\text{Ar} \ (290\text{MeV/A}) \ + \ ^{12}\text{C} \ (1.0 \ \text{mm})$

$^{27}\text{Al} \ (0.8 \ \text{mm})$

$^{93}\text{Nb} \ (0.5 \ \text{mm})$

$^{197}\text{Au} \ (0.333 \ \text{mm})$

Measurements of $P_L$, $P_T$ distributions

$P_L$ distribution $\leftarrow B\rho$ distribution

$P_T$ distribution $\leftarrow$ Angular distribution

$\text{Ar} + \text{Au} \rightarrow ^{^{A}}\text{O}$
Angular distribution of PLF

$^{40}\text{Ar}(290 \text{ MeV/A}) + ^{197}\text{Au}(0.333 \text{mm}) \rightarrow ^{39}\text{Cl}$
Observed $\sigma_{\text{Prod.}}$ of PLF

$^{40}\text{Ar}(290 \text{ MeV/A}) + ^{27}\text{Al}(0.8 \text{ mm}) @ \text{NIRS}$
Isotopic/Isotonic distribution of $\sigma_{\text{Prod.}}$

![Graphs showing isotopic/isotonic distribution](image-url)
Isotopic/Isotonic distribution of $\sigma_{\text{Prod. 2}}$

$\sigma(\text{Obs.})/\sigma(\text{EPAX2})$

- **Obs.**
- **SAA**

Graphs showing the distribution of production cross-sections for different targets (C, Al, Nb, Au) with $Z_F$ and $N_F$ axes.
Isotopic/Isotonic distribution of $\sigma_{\text{Prod. 3}}$

$$\frac{\sigma(\text{Al, Nb, Au})}{\sigma(\text{EPAX2})} \div \frac{\sigma(\text{C})}{\sigma(\text{EPAX2})}$$
Isotopic/Isotonic distribution of $\sigma_{\text{Prod. 4}}$

Energy dependence: \[
\frac{\sigma(\text{Be, 90})}{\sigma(\text{Be, EPAX2})} / \frac{\sigma(\text{C, 290})}{\sigma(\text{C, EPAX2})}
\]

![Obs. graph]

![SAA graph]
Conclusion

- $\sigma_{\text{Prod}}$ of PLF measured for $^{40}\text{Ar} + ^{12}\text{C}$, $^{27}\text{Al}$, $^{93}\text{Nb}$, $^{197}\text{Au}$ at 290 MeV/u

- Isotopic/isotonic distribution of $\sigma_{\text{Prod}}$
  - Pair and shell effect
  - Target effect

- Enhancement of productivity for IMF at 90 MeV/u
Particle identification

$^{40}\text{Ar} \ (290\text{MeV/A}) + ^{197}\text{Au} \ (0.333 \text{ mm})$

$B_\\rho = 4.996 \ [\text{T-m}]$

$\Delta \theta = 26 \ [\text{mrad}]$

$\Delta P/P_0 = 1 \ [%]$

$A/Z = 2$

$Z = 18$
Momentum distribution

SD of momentum distributions

\[ \sigma_L^2 = \sigma_I^2 \quad \sigma_T^2 = \sigma_I^2 + \sigma_D^2 + \sigma_C^2 \]

1) Fermi momentum of nucleons

\[ \sigma_L^2 = \frac{F(A - F)}{A - 1} \sigma_0^2 \quad \sigma_0 = 90 \text{ MeV/c} \]

2) Deflection of projectile in target nucleus

\[ \sigma_D^2 = \frac{F(A - F)}{A(A - 1)} \sigma_{1\perp}^2 \quad \sigma_{1\perp} = 195 \text{ MeV/c} \]

3) Coulomb final state interaction

\[ \sigma_C^2 = \pm \frac{\sqrt{2\pi}}{4} (Z_A - Z_F) C_0 \sigma_{D\perp} + \]

\[ C_0^2 (Z_A - Z_F) \left\{ \frac{1}{3} + \frac{Z_A - Z_F - 1}{8} \right\} \]