A method of analysing experimental data of nuclear reaction cross sections*

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Abstract A method of analysing experimental data of nuclear reaction cross sections σ_r induced by radioactive beam is described. It can be used in analysis of experimental nuclear reaction cross section data obtained by Na-isotope radioactive beams on different targets. Neutron halo has not been found in these nuclei.

Keywords Nuclear reaction cross sections, Radioactive beams, Transmission method, Production target, Reaction target

1 Introduction

Experiments with radioactive beams have demonstrated many new possibilities for nuclear structure studies.[1] This novel technique of using radioactive nuclear beams makes it possible to study systematically properties of unstable nuclei. In particular, measured nuclear reaction cross sections σ_r of exotic nuclei have revealed a halo structure in light nuclei at and near the neutron-drip line and proton-drip line.[2] The physical significance about these data was already published.[3] In the present paper, a method of analysing σ_r obtained by radioactive beams is reported.

2 Methodology

The nuclear reaction cross section is defined as the cross section for all reactions in which the charge of proton and/or neutron number in the incident nucleus have been changed. The transmission method was used to measure the attenuation of incident nuclei in the reaction target. Both the incoming nuclei and outgoing nuclei were identified, and the number of incident nuclei and the number of non-interacting nuclei were counted.

The nuclear reaction cross section σ_r is written as

$$\sigma_r = \frac{A}{N_A t} \ln \frac{N_{inc}}{N_{out}} \tag{1}$$

where A is the mass number of the target, N_A the Avogadro number, t the target thickness in g/cm^2, N_{inc} the number of incident nuclei and N_{out} the number of non-interacting nuclei. Experimental measurements for target-in run and target-out run should be done. Then Eq.(1) can be changed into

$$\sigma_r = \frac{A}{N_A t} \ln \frac{\gamma_0 (1 - P_m)}{\gamma} \tag{2}$$

where the beam attenuation factor γ is defined as $\gamma = N_{out}/N_{inc}$ for a target-in-run, γ_0 for a target-out-run; by taking the ratio γ_0/γ, uncertainties from the counter efficiency and reactions occuring outside the reaction target would be automatically corrected; the factor $(1-P_m)$ is a correction for scattering out of non-interacting nuclei from the counter system after passing the target due to multiple Coulomb scattering or nuclear elastic scattering.

In the present study the nuclear reaction cross section data are used from the following experiments. ^{36}Ar and ^{40}Ar ion beams delivered by the GSI synchrotron accelerator were used to bombard Be production targets. Secondary beams of $^{20-23}$Na and $^{25-32}$Na at 950 MeV/u were produced through the projectile fragmentation and analyzed by the projectile Fragment Separator Facility(FRS).[4] FRS has four focal planes (F_1, F_2, F_3 and F_4). The primary beam energies and the thickness of the Be targets (1.006 g/cm^2 and 4.009g/cm^2) could be adjusted isotope by isotope so that nucleon energies of the secondary Na beams

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at the middle of the reaction targets would be identical within ± 8 MeV/u. A multi-wire proportional chamber (MWPC) was placed in front of F_2 to give the position of radioactive beams. Four position-sensitive scintillators (3cm×15cm×0.3cm) with both side (left-right) readout were mounted at F_1 to measure the time and energy-loss of radioactive beam. They are also used as track detectors. Reaction targets of C with 7.428 and 3.715 g/cm^2 were placed at the second focal plane F_2. The ununiformity of the targets in thickness was less than 10^{-4}. A multisampling ion chamber (MUSIC) was placed in front of F_4 to measure the position of outgoing particles from reaction target. A scintillator was mounted at F_4 to give the time signal and four gas detectors at F_4 to give the energy-loss of outgoing ions. Radioactive nuclei produced by the projectile fragmentation were separated according to their A/Z at F_1, then guided to the reaction target located at F_2. Individual nucleus is identified by its TOF (between F_1 and F_2) and dE/dx. Then after passing the reaction target, non-interacting nuclei are guided through F_3 to F_4. These nuclei were identified again by its TOF (from F_2 to F_4) and dE/dx. The momentum spread and the angular spread of incident beam to the reaction target were adjusted so that all non-interacting nuclei could reach F_4, where the non-interacting nuclei in the target were identified and counted, thus providing a measurement of σ_r by the transmission method. Using such setup, nucleus can be identified one by one before incident on the reaction target and thus a mixing of other nuclei in a beam does not affect the final accuracy at all.

It has been found that a wide variety of isotopes could be produced in the projectile fragmentation and fragments could be emitted into a narrow cone in the direction of the incident primary beam with the velocity nearly equal to that of projectile. This characteristic of projectile fragment ensures an efficient production of radioactive secondary beams. The identifications of radioactive beams were done by the two-dimentional plot of TOF between F_1 and F_2 with the pulse heights of all four ΔE detectors.

The TOF and energy-loss of radioactive beam were determined by

$$\mathrm{TOF}_1 = (k_1 T_{12\mathrm{L}} + k_2 T_{12\mathrm{R}}) \tag{3.1}$$

$$\Delta E_1 = \sqrt[4]{(\Delta E_1 - E_{a0})(\Delta E_2 - E_{b0})(\Delta E_3 - E_{c0})(\Delta E_4 - E_{d0})} \tag{3.2}$$

where k_1, k_2 are time calibration parameters. E_{a0}, E_{b0}, E_{c0}, E_{d0} are energy zero channel. They can be got from calibration. The effects of position of detectors and spectrometer on time and energy can be corrected as

$$\begin{cases} E_1 = \Delta E_1 + aX_{\mathrm{F2}} + bX_{\mathrm{F2}}^2 \\ T_1 = \mathrm{TOF}_1 + cX_{\mathrm{F2}} + dX_{\mathrm{F2}}^2 \end{cases} \tag{4}$$

The identification of incident nuclei can be got from the incidence of E_1 with T_1. A typical plot of E_1 with T_1 is shown in Fig.1a. The number of incoming nuclei (N_{inc}) was obtained by counting the nuclei which satisfy the conditions of only one track observed by MWPC before entering the reaction target.

After passing the reaction target, all nuclei which were transported to F_4 were identified. Using the four scintillation counters behind the reaction target, the charge was determined by two independent methods. One was to take the majority of four values of charges identified by individual detectors; the other was to take the average of the detector pulse heights. These two methods were found to give the same value except negligible number of cases. The determinations of TOF and the energy-loss of particle were taken the same method as Eq.(3) and Eq.(4) from signals of detectors between F_2 and F_4 focal planes. A typical two-dimentional plot is shown in Fig.1b. The non-interacting nuclei detected behind the reaction target were required to have the same charge and mass as those detected in the front of the reaction target. Thus the number of outgoing nuclei (N_{out}) can be got.

A small number of non-interacting nuclei could not be detected by F_4 detectors due to the large-angle scattering and reaction with tubes. This effect must be corrected by acceptance checking so that the momentum and angular emmittance have to be guaranteed to be full transmission from F_2 to F_4 for non-interacting nuclei. The momentum acceptance is restricted at F_1 and F_2 by selecting the beam position. This was studied using the simulation code MOCADI,[5] which took into account the effect of fragmentation and small angle deflection due to multiple Coulomb scattering in the reaction target. Actually, it was achieved as follows:[3] (1) operating the FRS in an optical mode which resulted in smaller vertical envelopes at focal plane F_1 and F_3, (2) limiting the incident transverse emittance at F_1, and (3) restricting the beam emittance in an off-line analysis by ray tracing with MWPC located at F_2. The geometric acceptance is selected by the incident angle of a nucleus into the reaction target. From Fig.2, one can see that σ_r becomes large for large angle. This is due to more non-interacting nuclei escaped from the detector at large angle by multiple Coulomb scattering and reaction with tubes. A window must be put on θ_x to give a correct σ_r.

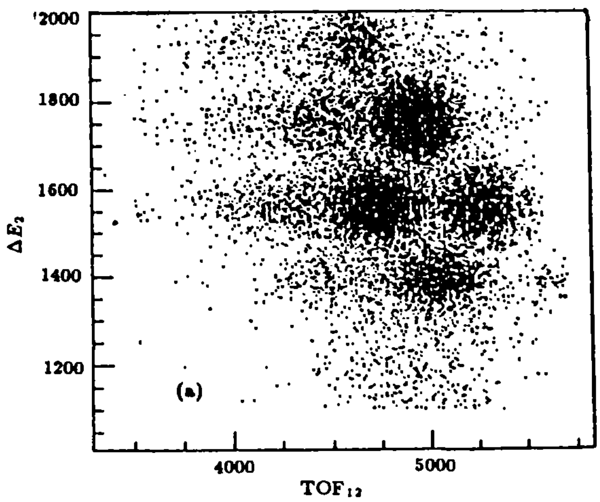

Fig.1a Identification of incident radioactive beam

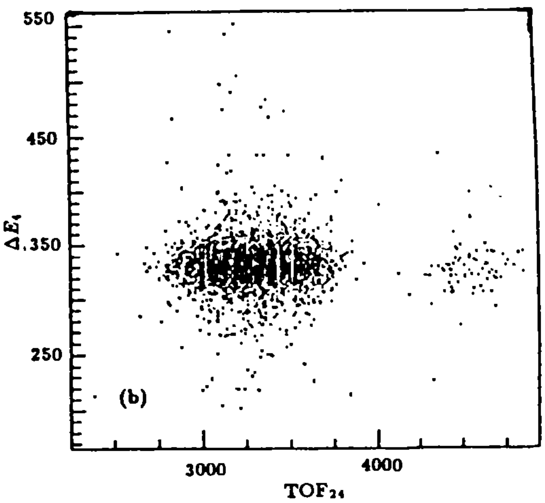

Fig.1b Identification of noninteracting nuclei

From Eq.(2), we calculated the error in σ_r as the following

$$[\frac{\Delta\sigma_r}{\sigma_r}]^2 = \{\frac{1-\gamma}{N_{inc}\gamma} + \frac{1-\gamma_0}{N_{out}\gamma_0} + [\frac{\Delta(\gamma/\gamma_0)}{(\gamma/\gamma_0)}]^2 + [\frac{\Delta(1-P_m)}{(1-P_m)}]^2\}[\frac{A}{\sigma_r N_A t}]^2 + [\frac{\Delta t}{t}]^2 \qquad (5)$$

Then errors associated with nuclear reaction cross sections were estimated by using the above equation. The main error of σ_r is arisen from the uncertainty of γ, because we found the first and the second terms in Eq.(5) is dominant.

The determined reaction cross sections σ_r of carbon target for Na isotopes from ^{20}Na (9 neutrons and 11 protons) to ^{32}Na (21 neutrons and 11 protons) are shown in Fig.3. The lines are calculated by Glauber Model with zero interaction range.[6] From the figure, an almost smoothly increasing of σ_r with mass was seen. Unlike ^{11}Li, a sharp jumping of σ_r in certain Na-isotopes was not observed. This is because the neutron separation energy ε_n for Na-isotope chain is not so small (the smallest one in Na-chain is 2.5 MeV for ^{30}Na, but for ^{11}Li, ε_n =0.3MeV). The observed mass dependence of σ_r can be reproduced by this model except ^{20}Na and ^{22}Na. Since the neutron separation energy of ^{22}Na is larger than those of its neighbour isotopes, its nucleons were bound more tightly and then ^{22}Na has a smaller radius. This gives a smaller σ_r . For ^{31}Na and ^{32}Na nuclei, neutron skin may probably exist,[3] values of our model calculation are smaller than experimental data but still within experimental error bars. It will be very interesting to have more experiments at different incident energies to give finally results in a model-independent way.

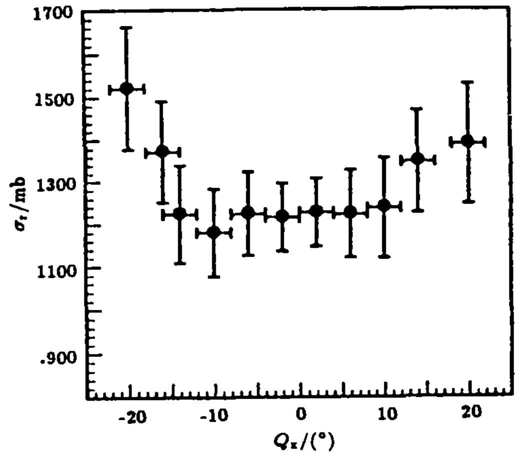

Fig.2 The effect of geometric acceptance on cross sections

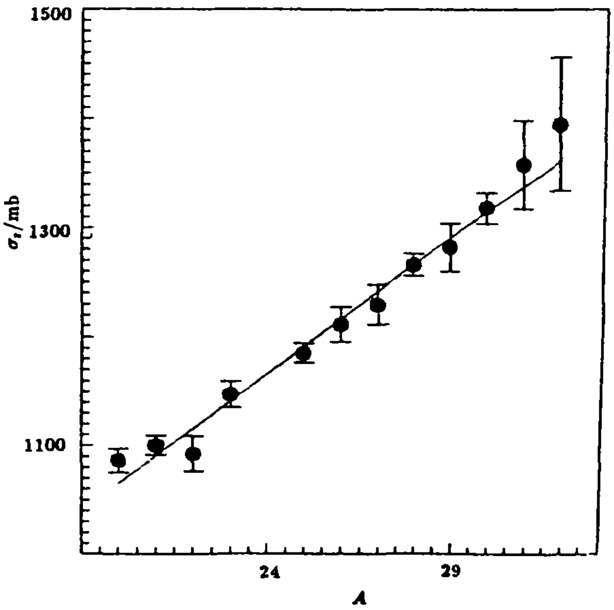

Fig.3 Comparison of experimental results with calculation ones for the reaction of Na isotope on C target at 950 MeV/u

Line is Glauber model calculation. Dots represent experimental results

3 Conclusion

A method for analysing nuclear reaction cross section experimental data of radioactive beams is discribed. The identification of incident nuclei and non-interacting nuclei are achieved. After the correction for the scattering-out of non-interacting nuclei, σ_r is derived.

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