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Recoil distance transmission method: Measurement of interaction cross sections of excited states with fast rare-isotope beams

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ABSTRACT

The possible appearance of nuclear halos in ground and excited states close to the particle-decay threshold is of great importance in the investigation of nuclear structure and few-body correlations at the limit of stability. In order to obtain direct evidence of the halo structure manifested in nuclear excited states, we have considered a new method to measure the interaction cross sections of excited states. The combination of the transmission method and the recoil distance Doppler-shift method with a plunger device enables us to measure the number of interactions of the excited states in a target. Formulae to determine the interaction cross section are derived, and key issues to realize measurements are discussed. Dominant sources of errors are uncertainties in the excited-state lifetimes and γ-ray yields. We examine prototype experiments and perform simulations to study the impact of each uncertainty on the final result. This method provides a novel opportunity to perform cross section measurements on the excited states of rare isotopes.

1. Introduction

Nuclear halos at the drip lines are of great interest in the investigation of structure of weakly bound nuclear systems [1–7]. If the energy level of a nuclear state is close to the particle decay threshold, the state tends to have asymptotic cluster structure [8,9]. The simple cluster structure is a neutron (proton) halo structure comprising valence nucleon(s) and the core, which appears near the neutron (proton) decay threshold. Up to now, the search for halos has mainly focused on ground states of nuclei near the drip lines. Along with the development of heavy-ion accelerators, ground states of drip-line nuclei in the light mass region have been investigated, and several halo nuclei have been identified [1–7]. Among the heaviest known halo nuclei are ^{31}Ne [10–12] and ^{37}Mg [13–15], suggesting the appearance of halos across a wider mass region. However, even next-generation facilities currently under construction will not be able to produce all bound nuclei in the nuclear chart [16], indicating that the search for halos will be limited to the medium-mass region. On the other hand, the halo structure can be expected in excited states close to the threshold even for unstable nuclei closer to the stability line. Thus, reaction studies can be important for the identification of halo structure in nuclear excited states.

Ground-state halo structures have been investigated by three types of measurements: (a) interaction cross section [17,18], (b) momentum distribution [19,20], and (c) Coulomb breakup reaction [21–23]. The halo structure consists of a dilute neutron or proton cloud of extended radius, which results in a large interaction cross section. Therefore enhancement of the interaction cross section is regarded as direct evidence of halo structure. The measurement of the momentum distribution, following knockout reaction of a valence nucleon, confirms the orbital angular momentum of the halo nucleon. Coulomb breakup reactions have been utilized to investigate the extended wave function characteristic of low-ℓ orbitals.

In this paper, we propose a new experimental method to measure the interaction cross sections (σ_I^{ex}) of nuclei in the excited states. The measurement can provide direct evidence of the halo structure in the excited states. The present approach combines the transmission method and the recoil distance Doppler-shift method. Basic ideas for the method are presented in Section 2. Formalism to deduce the interaction cross section and evaluate its error is described in Section 3. Section 4 proposes prototype experiments and considers a realistic case along with simulated results. Key considerations in designing future experiments are discussed in Section 5, and Section 6 is a summary of this paper.

2. Basic ideas of the recoil distance transmission method

This section gives an overview of the new method named

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"recoil distance transmission method" to extract the interaction cross sections of nuclei in the excited states. This method utilizes the recoil-distance setup [24] to count the excited states before and after a reaction target and applies the transmission method to determine the interaction cross section σ_I^{ex}. In this section, the conventional transmission method to measure the ground-state interaction cross section (σ_I^{gs}) is briefly reviewed, and then the recoil distance transmission method is introduced.

2.1. Brief description of the transmission method

In the transmission method, the interaction cross section is obtained from the following relations (see, e.g., [18]):

$$\sigma_I^{gs} = -\frac{A}{N_A \rho x_t} \ln \frac{\Gamma}{\Gamma_0}, \tag{1}$$

$$\Gamma = \frac{N_{gs}(x_t)}{N_{gs}(0)}, \tag{2}$$

$$\Gamma_0 = \left.\frac{N_{gs}(x_t)}{N_{gs}(0)}\right|_{\text{empty target}}, \tag{3}$$

where x_t, A, and ρ represent the thickness, mass number, and density of the reaction target, respectively. N_A is Avogadro's number. Γ denotes the ratio of the number of non-reacting outgoing nuclei ($N_{gs}(x_t)$) to that of incoming nuclei ($N_{gs}(0)$). Γ_0 represents the same ratio measured without a target, which corrects for background contributions such as nuclear reactions in the detectors.

In an experiment, $N_{gs}(x_t)$ and $N_{gs}(0)$ are observables to determine σ_I^{gs}, but statistical errors are only important for $N_{gs}(x_t)$ because $N_{gs}(0)$ defines the total number of the incoming beams [25]. However, systematic errors in $N_{gs}(x_t)$ and $N_{gs}(0)$ normally dominate uncertainties in σ_I^{gs}. To study new halo candidates, a precision better than 14% is typically required for σ_I^{gs} as is the case for earlier studies [26]. For instance, the differences between the interaction cross sections of halo nuclei and neighboring non-halo nuclei range between 14% and 30% for the cases of halo nuclei ^{6}He, ^{11}Li, ^{11}Be, and ^{14}Be [26]. In the following discussion, we adopt the criterion that 14% precision of the interaction cross section is needed to distinguish a halo from a non-halo state.

2.2. Recoil distance transmission method

In the recoil distance transmission method, a "long-lived" excited state (termed excited product) with a lifetime of the order of 100–1000 ps is produced by beams (termed beam nuclei) in a production target as illustrated in Fig. 1(a). The interaction cross section of the excited state on a reaction target is measured. The number of excited products is determined by measuring γ decays before the reaction target, while decays after the reaction target give the number of outgoing excited products. The production and reaction targets are mounted on a plunger device together with a degrader placed downstream of the reaction target which helps to properly count the number of outgoing excited products. Fig. 1 (b) depicts the number of the excited products ($N_{ex}(x)$) as a function of the distance x along the beam axis, where $x=0$ and $x = x_t$ correspond to the front and back surfaces of the reaction target, respectively. The reduction rate of $N_{ex}(x)$ through the reaction target reflects the magnitude of the interaction cross section of the excited state, excluding other factors which will be discussed in Section 3.2.

The numbers of excited products immediately before the reaction target ($N_{ex}(0)$) and after the reaction target ($N_{ex}(x_t)$) are obtained by counting the de-excitation γ rays. Fig. 1(c) shows the expected γ-ray spectrum obtained from the present method. The fast, reduced, and slow peaks correspond to γ rays emitted between the production and reaction targets, between the reaction target and the degrader, and after the degrader, respectively. The numbers of γ decays in the fast region (G_1) and reduced region (G_2) can be related to the γ-ray yields for the fast peak (g_1) and reduced peak (g_2), respectively:

$$G_1 = g_1/\varepsilon_1, \tag{4}$$

$$G_2 = g_2/\varepsilon_2, \tag{5}$$

where ε_1 and ε_2 represent the detection efficiencies of the γ rays. $N_{ex}(0)$ and $N_{ex}(x_t)$ are obtained from G_1 and G_2 as

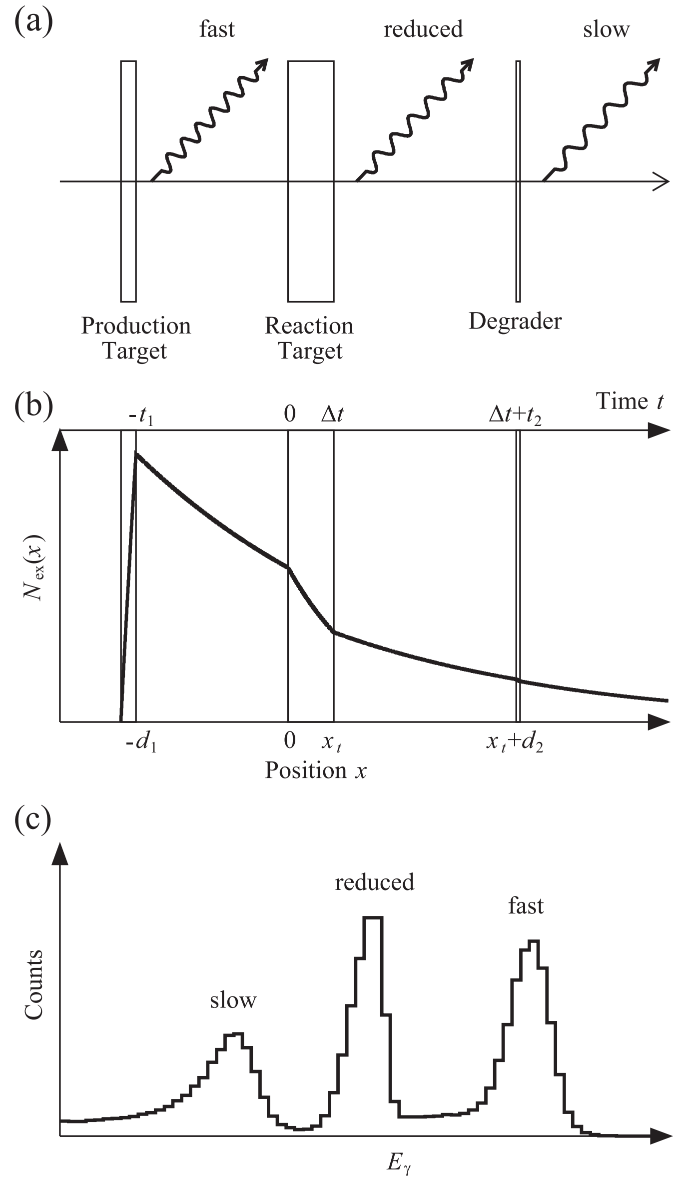

Fig. 1. Illustrations of (a) the experimental setup, (b) the number of excited states $N_{ex}(x)$ as a function of the position x along the beam axis, and (c) expected Doppler-shift corrected γ-ray spectra are shown. Different Doppler-shift components in panels (a) and (c) are termed fast, reduced, and slow. In panel (b), the time axis t is shown in top as an additional reference.