Odd-even staggering of reaction cross sections for ^{22,23,24}O isotopes

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The interaction cross sections of 22,23 O nuclei at 900 MeV/nucleon have been measured recently by Kanungo *et al.*. We show that the odd-even staggering parameter of interaction cross sections deduced from these new data agrees well with the theoretical systematics expected for the neutron separation energy of S_n =2.74±0.120 MeV for 23 O. We also discuss briefly the energy dependence of the staggering parameter.

PACS numbers: 25.60.Dz, 21.10.Gv, 24.10.-i, 27.30.+t

Interaction cross sections σ_I as well as reaction cross sections σ_R have been measured for many unstable nuclei far from the β -stability line. The nuclear size has been deduced from these measurements[1], and it has been revealed that the root-mean-square radii of unstable nuclei are significantly larger than the systematics known for stable nuclei. Particularly, a largely extended spatial structure, referred to as "halo", has been found for light neutron-rich nuclei close to the neutron drip-line [2–4].

The experimental interaction cross sections for neutron-rich nuclei often show a large odd-even staggering (OES). That is, the cross section for an odd-mass nucleus is significantly larger than the cross sections for the neighboring even-mass nuclei. A typical example is the interaction cross sections for ^{30,31,32}Ne, measured recently by Takechi et al.[5]. In Ref. [6], we have argued that these large OES can be attributed to the pairing correlation. That is, in odd-mass nuclei, the increase of radius of an orbit for an unpaired nucleon with a small angular momentum l is largely suppressed by the pairing correlation in the even-mass nuclei. We have introduced the staggering parameter and shown that it increases for l=0 or 1 as the neutron separation energy, S_n , decreases. We have also shown that the large OES extracted from the experimental interaction cross sections for ^{30,31,32}Ne is consistent with the theoretical systematics for $S_n = 0.29 \pm 1.64$ MeV for ³¹Ne [7].

Recently, new measurements of the interaction cross sections for $^{22,23}\mathrm{O}$ were performed by Kanungo et~al.[8]. The new data for the $^{23}\mathrm{O}$ nucleus is significantly smaller than the previous measurement by Ozawa al.[4], which had shown an anomalously large cross section. It is also shown that the matter radii extracted from these new data are consistent with the prediction of the ab~initio coupled-cluster theory [8]. It is therefore of interest to investigate how the experimental OES parameter for $^{22-24}\mathrm{O}$ extracted from the new data is compatible with the theoretical systematics shown in Ref. [6].

The aim of this paper is to discuss the OES parameter of reaction cross sections for the ^{22,23,24}O. Notice that, for neutron-rich nuclei, cross sections for inelastic scattering are expected to be negligibly small[9, 10], and the interaction cross sections are almost the same as the reaction cross sections. Since the reaction cross sections are

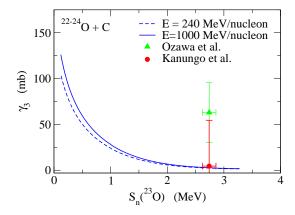


FIG. 1: (Color online) The staggering parameter γ_3 for $^{22,23,24}\mathrm{O}+^{12}\mathrm{C}$ reactions as a function of the neutron separation energy S_n for the $^{23}\mathrm{O}$ nucleus. The solid and the dashed lines correspond to the staggering parameters for the incident energies of $E=1000~\mathrm{MeV/nucleon}$ and $E=240~\mathrm{MeV/nucleon}$, respectively. The filled triangle and the filled circle are the experimental staggering parameters extracted with the experimental data of Refs. [4] and [8], respectively, plotted at the empirical separation energy, $S_n=2.74\pm0.120~\mathrm{MeV}$.

much easier to calculate theoretically than the interaction cross sections, we consider in this paper the reaction cross sections for our analysis. In the previous study, we considered the $^{22,23,24}{\rm O}+^{12}{\rm C}$ reactions at E=240 MeV/nucleon [6]. Since the experiments by Kanungo et al. were performed at E=900 MeV/nucleon[8], we will first discuss the energy dependence of the OES parameter.

Figure 1 shows the OES parameter defined as [6]

$$\gamma_3 = -\frac{\sigma_R(^{24}O) - 2\sigma_R(^{23}O) + \sigma_R(^{22}O)}{2},$$
 (1)

for these systems, where the reaction cross sections σ_R are calculated with a Glauber theory. We use the optical limit approximation of the Glauber theory, supplemented by the higher order corrections [11]. The density distribution for the ²⁴O nucleus used in the Glauber calculation is constructed with a Hartree-Fock-Bogoliubov method by using a Woods-Saxon mean-field potential together with a density-dependent zero-range pairing interaction.

The density distributions for 22,23 O, on the other hand, are constructed without taking into account the pairing interaction with the same Woods-Saxon mean-field potential, with which the valence neutron in 23 O occupies the $2s_{1/2}$ state. The OES parameter is plotted in the figure as a function of the one neutron separation energy of 23 O. To this end, we vary the depth of the Woods-Saxon potential for the $s_{1/2}$ states. See Ref. [6] for details of the calculations.

The solid line in Fig. 1 shows the OES parameter for $E=1000~{\rm MeV/nucleon}$ while the dashed line shows that for $E=240~{\rm MeV/nucleon}$. We use the parameters given in Table I in Ref. [12] for the nucleon-nucleon profile function Γ_{NN} at each energy, that is related to the nucleon-nucleon scattering cross section. One can see that the energy dependence of the OES parameter is rather weak. The OES parameters at the two energies behave similarly to each other, although there exists a small deviation at small binding energies. This clearly indicates that the staggering parameter γ_3 provides a good measure for the OES of reaction cross sections, which will shed light on the pairing correlations in weakly bound nuclei.

Let us now compare the theoretical curves with the experimental staggering parameter. With the experimental data of Ozawa et al. [4], the staggering parameter is extracted to be $\gamma_3 = 63 \pm 32$ mb. This value is plotted in Fig. 1 by the filled triangle for a separation energy of $S_n = 2.74 \pm 0.120$ MeV for ²³O [13]. One can see that the experimental staggering parameter γ_3 ex-

tracted from the previous measurement largely deviates from the theoretical systematics, for which the OES parameter is expected to be around 2.4 mb at $S_n \sim 2.74$ MeV. In marked contrast, the new data by Kanugo *et al.* for 22,23 O [8], together with the previous data by Ozawa *et al.* for 24 O, leads to $\gamma_3 = 4.5 \pm 50.0$ mb. It is remarkable that this value agrees well with the theoretical systematics, as shown by the filled circle in Fig. 1.

In summary, we have studied the odd-even staggering of reaction cross sections for the $^{22,23,24}O + ^{12}C$ reactions. We first showed that the staggering parameter depends on the incident energy only weakly, and thus it provides a good tool to study the pairing correlations in weakly bound nuclei. We then compared the theoretical systematics of the staggering parameter with the experimental values. The new data by Kanungo et al. leads to a consistent value of staggering parameter to the theoretical systematics, eliminating the anomaly seen in the previous data. The new data are now consistent not only with the theoretical systematics of the staggering parameter, but also with the predictions of the coupled-cluster theory and a simple $^{22}\text{O}+\text{n}$ description for $^{23}\text{O}[8]$. All of these studies point to a conclusion that a halo structure is absent in the ²³O nucleus.

This work was supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology by Grant-in-Aid for Scientific Research under the program numbers (C) 22540262 and 20540277.

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