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Trojan Horse Method for the Oxygen-Burning Process Reactions

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The ^{16}O + ^{16}O fusion reaction is important in terms of the explosive oxygen burning process during late evolution stage of massive stars as well as understanding of the mechanism of low-energy heavy-ion fusion reactions. The astrophysical S factor of such a heavy-ion fusion strongly depends on energy at corresponding stellar temperatures. For the ^{16}O + ^{16}O reaction cross section, there are larger discrepancies among different experimental data as the energy decreases, and a complete lack of data below $E_{\mathrm{c.m.}}$ = 7 MeV. We aim to determine the cross sections for the two main exit channels, α + ^{28}Si and p + ^{31}P, toward stellar energies. The measurements were performed indirectly by the Trojan horse method (THM) via the ^{16}O(^{20}Ne, $\alpha\alpha$)^{28}Si and ^{16}O(^{20}Ne, $p\alpha$)^{31}P three-body reactions, respectively. We performed measurements twice using ^{20}Ne beams at Heavy Ion Laboratory ($E_{20\mathrm{Ne}}$ = 45 MeV) and at Gumilyov Eurasian National University ($E_{20\mathrm{Ne}}$ = 35 MeV). We discuss the applicability of the THM to such a heavy nuclear system showing preliminary results of the momentum distribution of α-^{16}O intercluster motion in the TH nucleus ^{20}Ne observed for the first time, which implies a possibility of a multi-step breakup of the TH nucleus.

KEYWORDS: Oxygen burning, fusion reaction, Trojan horse method

The ^{16}O+^{16}O fusion reaction is important in terms of the explosive oxygen burning process during late evolution stage of massive stars as well as understanding of the mechanism of heavy-ion fusion reactions at low energies. The astrophysical S factor of such a heavy-ion fusion strongly depends on energy at corresponding stellar temperatures far below the Coulomb barrier. There are large discrepancies among different experiments [1–4], and among theoretical predictions [5, 6], and is a lack of data below $E_{\mathrm{c.m.}}$ = 7 MeV. We aimed to determine the excitation function of the most major products, α+^{28}Si and p+^{31}P, of the ^{16}O+^{16}O reaction at stellar energies by the Trojan horse method (THM) [7].

We have performed THM measurements via the ^{16}O(^{20}Ne, $\alpha\alpha$)^{28}Si and ^{16}O(^{20}Ne, $p\alpha$)^{31}P three-

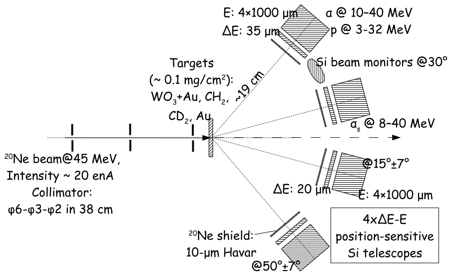

Fig. 1. Schematic view of the experimental setup.

body reactions at two different ^{20}Ne beam energies; 45 MeV at the Heavy Ion Laboratory, and 35 MeV at Gumilyov Eurasian National University. These beams are able to cover center-of-mass energy ranges of 8–15 MeV and of 5–11 MeV respectively. The higher-energy measurement was mainly in purpose of normalization of the THM cross section to known excitation functions in the higher part of this energy range, while the lower energy measurement aims at exploring the new data below $E_{\rm c.m.}$ = 7 MeV. In these three-body reactions, the α particles in the exit channels may act as the "spectator" through the quasi-free mechanism, where the momentum transfer of α decaying from the possible α cluster state in the projectile ^{20}Ne is sufficiently small. For the projectile-breakup measurement, the momentum of the spectator is defined by subtraction of the beam velocity contribution from the momentum of α; $\boldsymbol{p}_s \equiv \boldsymbol{p}_\alpha - m_\alpha/m_{\rm 20Ne} \times \boldsymbol{p}_{\rm 20Ne}$. To guarantee quasi-free mechanism, the two-cluster α-^{16}O system in the nucleus ^{20}Ne should preferably be in s state, so that the momentum distribution $|\phi(p_s)|^2$ of the spectator α has the largest peak at $p_s = 0$. This is not obvious for our case since it is the first application of the THM to such a heavy nuclear system, in which more realistic treatment might be more appropriate. Here we report the analysis status of the higher-energy experiment for the momentum distribution investigated for the first time.

For the higher-energy run, a ^{20}Ne^{3+} beam was provided at 45 MeV with a typical intensity around 20 enA on target, and the production run was performed for about 180 hours in total. The experimental setup is illustrated in Fig. 1. For the beam collimator, a ϕ6-, a ϕ3- and a ϕ2-mm hole are laid straight on the beam axis within a distance of 380 mm from the upstream, respectively. Au-backing WO_3 was used as the solid oxygen target with a typical thickness of 116 mg/cm^2 for WO_3 and 193 mg/cm^2 for Au. In addition, CD_2, CH_2 and Au targets were used for calibration purpose. Three silicon beam monitoring detectors were installed at 30°. For the reaction product measurement, four ΔE-E silicon telescopes were mounted symmetrically with respect to the beam axis at 15° and 50°. The thickness of each ΔE layer at 15° was 20 μm in order to measure low-energy spectator α, while that at 50° was 35 mm focusing on higher energy up to 40 MeV of α of the coincidence pair. Each E layer consisted of a stack of four 1-mm-thick silicon detectors for high-energy proton up to 32 MeV. The first E layer was position-sensitive by charge division, and the distances from the target were typically 190 mm. We put a 10-μm Havar foil right in front of each ΔE layer to shield beam scattering and heavy-ion products. During the production run with the WO_3 target, multiplicative particles were mostly identified as protons and α particles with the ΔE-E telescopes.

By selecting α-α coincident data, we confirmed that the peaks found in the Q-value spectrum which is defined by $Q = E_{\rm 28Si} - E_{\rm 20Ne} + E_{\alpha 1} + E_{\alpha 2}$ correspond well to the excited energy of ^{28}Si nucleus as shown in Fig. 2, which evinces the ^{16}O(^{20}Ne, $\alpha\alpha$)^{28}Si reaction. Momentum distribution $|\phi(p_s)|^2$ can be determined by the following relations [7];

$$|\phi(p_s)|^2 \frac{d\sigma}{d\Omega}^{\rm HOES} \propto \frac{d^3\sigma}{d\Omega_\alpha d\Omega_{\rm Si} dE_{\rm c.m.}} / [KF] \propto Y_{\rm exp.}/Y_{\rm sim.}\ , \tag{1}$$

where $d\sigma/d\Omega^{\rm HOES}$ is the half-off-energy-shell differential cross section of the ^{16}O(^{16}O, α)^{28}Si reac-

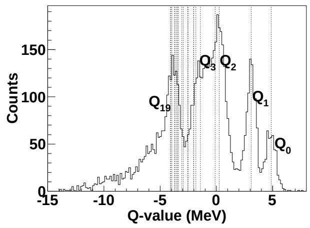

Fig. 2. Q-value spectrum of the ^{16}O(^{20}Ne, $\alpha\alpha$)^{28}Si channel. The dotted lines corresponds to the excited states of ^{28}Si.

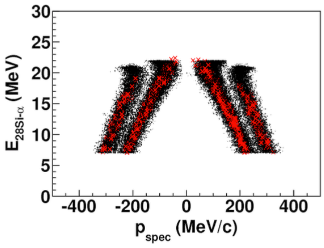

Fig. 3. ^{28}Si-α relative energy vs. spectator's momentum of Monte Carlo simulation (black) and the experimental data (red).

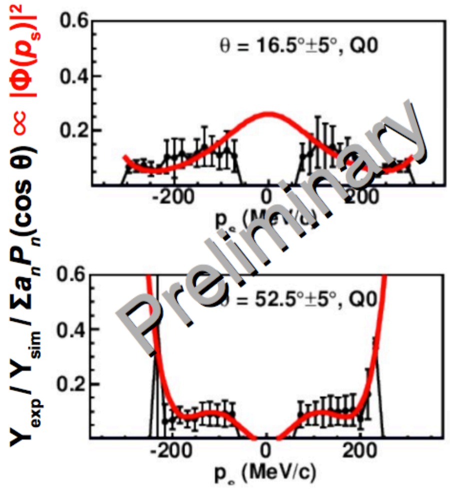

Fig. 4. Preliminary momentum distribution of α in ^{20}Ne at $\theta_{\text{c.m.}}$ = 16.5° and $\theta_{\text{c.m.}}$ = 52.5°.

tion, $d^3\sigma/d\Omega_\alpha/d\Omega_{\text{Si}}/dE_{\text{c.m.}}$ is the triple differential cross section of the ^{16}O(^{20}Ne, $\alpha\alpha$)^{28}Si reaction, $[KF]$ is the kinematic factor, $Y_{\text{exp.}}$ is the experimental yield of the ^{16}O(^{20}Ne, $\alpha\alpha$)^{28}Si reaction, and $Y_{\text{sim.}}$ is that of the Monte Carlo simulation performed isotropically in the phase space. Since we observed the spectator α, the kinematic E-vs-p_s space could not be covered widely as shown in Fig. 3. We thus approximately obtained the linear relation between momentum and energy from Fig. 3. Then we checked the angular distribution of $Y_{\text{exp.}}/Y_{\text{sim.}}$, which enables us to determine $|\phi(p_s)|^2$ at each angle despite the unknown $d\sigma/d\Omega^{\text{HOES}}$. Examples of the preliminary momentum distributions at different angles are shown in Fig. 4. The momentum distributions do not look to have peaks around $p_s = 0$ and show some complicated structures. The red curves are linearly combined momentum distributions calculated with assumption of virtual decays of ^{20}Ne both via the ground and the first excited states [9]. The fact that the calculations may apparently fit the experimental momentum distributions suggests a possibility of such a multi-step breakup of the TH nucleus including the first excited state.

In summary, this study is an approach to the lowest energy region ever of the ^{16}O + ^{16}O fusion reaction cross sections by means of THM. Since this THM application is for the heaviest nuclei system ever, and the ^{20}Ne is used as the TH nucleus for the first time, we primarily investigated the momentum distributions of the α-^{16}O cluster in ^{20}Ne. The preliminary momentum distributions of the α spectator show no clear peak around $p_s = 0$, which requires a proper understanding of virtual decay mechanism of ^{20}Ne nucleus. Further data analysis to determine the definitive momentum distributions, and also a theoretical investigation are needed to describe the behavior of the current experimental momentum distribution.

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