Indirect study of the $^{16}\text{O} + ^{16}\text{O}$ fusion reaction toward stellar energies by the Trojan Horse Method


1 Center for Nuclear Study, University of Tokyo, Wako, Japan
2 INFN - Laboratori Nazionali del Sud, Catania, Italy
3 Department of Physics and Astronomy, University of Catania, Catania, Italy
4 Institute of Nuclear Physics of National Nuclear Center, Almaty, Kazakhstan
5 Gumilyov Eurasian National University, Astana, Kazakhstan
7 MTA-Atomiki, Debrecen, Hungary
8 The H. Niewodniczański Institute of Nuclear Physics PAN, Kraków, Poland
9 Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland
10 National Research Center “Kurchatov Institute”, Moscow, Russia
11 Kore University of Enna, Enna, Italy

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Abstract

The $^{16}\text{O}+^{16}\text{O}$ 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. We aim to determine the excitation function for the most major exit channels, $\alpha+^{28}\text{Si}$ and $p+^{31}\text{P}$, toward stellar energies indirectly by the Trojan Horse Method via the $^{16}\text{O}$(20Ne,$\alpha^{28}\text{Si})\alpha$ and $^{16}\text{O}$(20Ne,$p^{31}\text{P})\alpha$ three-body reactions. We report preliminary results involving reaction identification, and determination of the momentum distribution of $\alpha$-$^{16}\text{O}$ intercluster motion in the projectile 20Ne nucleus.

The $^{16}\text{O}+^{16}\text{O}$ 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 $E_{cm}=7$ MeV.

We aim to determined the excitation function of the most major products, $\alpha+^{28}\text{Si}$ and $p+^{31}\text{P}$, of the $^{16}\text{O}+^{16}\text{O}$ reaction at stellar energies by the Trojan Horse Method (THM) [7].

We have performed THM measurements via the $^{16}\text{O}$(20Ne,$\alpha^{28}\text{Si})\alpha$ and $^{16}\text{O}$(20Ne,$p^{31}\text{P})\alpha$ three-body reactions at $E_{20\text{Ne}}=45$ MeV at the Heavy Ion Laboratory, Warsaw, Poland, covering center-of-mass energy ranges of 8–15 MeV. In these three-body reactions, the $\alpha$ particles in the exit channels may act as the “spectator” through the quasi-free mechanism, where the momentum transfer of $\alpha$ decaying from the possible $\alpha$ cluster state in the projectile 20Ne is sufficiently small. The momentum of the spectator is defined by masses and momenta of $\alpha$ and 20Ne: $p_s \equiv p_\alpha - m_\alpha/m_{20\text{Ne}} \times p_{20\text{Ne}}$. To guarantee quasi-free mechanism, the two-cluster $\alpha$-$^{16}\text{O}$ system in the nucleus 20Ne should preferably be in $s$ state, so that the momentum distribution of the spectator $\alpha$ is single-peaked at $p_s = 0$. Here we report preliminary $p_s$ distribution investigated for the first time, which is crucial to determine the two-body reaction cross section by THM.

The experimental setup is illustrated in Fig. 1.

The $^{20}\text{Ne}^{3+}$ beam was provided at 45 MeV from the $K = 160$ cyclotron with a typical intensity around 20 enA on target, and the production run was performed for about 180 hours in total. For the beam collimator, a $\phi 6$-, a $\phi 3$- and a $\phi 2$-mm hole are laid straight on the beam axis within a distance of 380 mm from the upstream, respectively. We used WO$_3$ evaporated onto Au backing as solid oxygen target with a typical thickness of 116 mg/cm$^2$ for
WO₃ and 193 mg/cm² for Au. 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

Figure 2: Q-value spectrum of the $^{16}$O($^{20}$Ne, $\alpha$)$^{28}$Si$\alpha$ channel. The dotted lines corresponds to the excited states of $^{28}$Si.
to measure low-energy spectator $\alpha$, while that at $50^\circ$ was 35 mm focusing on higher energy up to 40 MeV of $\alpha$ 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-mm Havar foil right in front of each $\Delta E$ layer in order to prevent the detectors from plenty of beam scattering on W and Au in the target. During the production run with the WO$_3$ target, we mostly observed protons and $\alpha$ particles in the $\Delta E$-$E$ telescopes.

By selecting only $\alpha$-particle data, we confirmed that the peaks found in the $Q$-value spectrum which is defined by

$$Q = E_{28\text{Si}} - E_{20\text{Ne}} + E_\alpha + E_{\alpha 2}$$

correspond well to the excited energy of $^{28}\text{Si}$ nucleus as shown in Fig. 2, which evinces the $^{16}\text{O}(^{20}\text{Ne},\alpha^{28}\text{Si})\alpha$ reaction.

The preliminary momentum distribution is show in Fig. 3, assuming energy and angular distribution of the differential cross section of the two-body reaction $^{16}\text{O}(^{16}\text{O},\alpha)^4\text{He}$. The fact that the momentum distribution does not have the maximum value around $p_s = 0$ suggests that the three-body reactions $^{16}\text{O}(^{20}\text{Ne},\alpha^{28}\text{Si})\alpha$ and $^{16}\text{O}(^{20}\text{Ne},p^{31}\text{P})\alpha$ might not proceed through the $0^+$ ground state of $^{20}\text{Ne}$ dominantly but the $2^+$ first excited state. Further data analysis to determine the two-body cross section of interest is ongoing, also for the $^{16}\text{O}(^{20}\text{Ne},p^{31}\text{P})\alpha$ channel.
References


