I. 1. Search for the 4α Condensed State in $^{16}\text{O}$

Itoh M., Matsuo R., Ouchi H., Ozeki K., Sakemi Y., Sugimoto N., and Terazono T.

Cyclotron and Radioisotope Center, Tohoku University

Recently, Tohsaki et al\textsuperscript{1)} explained the 7.65 MeV, $0^+_2$ state of $^{12}\text{C}$ as a Bose-Einstein condensation-like state, in which all constituent $\alpha$ clusters condense into the lowest S-orbit, and are loosely bound. They predicted the 4\$\alpha$ condensed state also exists around the 4\$\alpha$ breakup threshold energy of 14.4 MeV in $^{16}\text{O}$. In the experimental study, Wakasa et al\textsuperscript{2)} found a new candidate for the 4\$\alpha$ condensed state in $^{16}\text{O}$ by measuring inelastic $\alpha$ scattering at $E_{\alpha} = 400$ MeV. The excitation energy of $13.6 \pm 0.1$ MeV, the width of $0.6 \pm 0.2$ MeV, and the cross section of this candidate state were consistent with the theoretical prediction. However, since there are some $0^+_2$ states around the 4\$\alpha$ threshold energy in $^{16}\text{O}$, they could not assert conclusively it was the 4\$\alpha$ condensed state. In this study, on the other hand, we would determine experimentally the 4\$\alpha$ condensed state by measuring decay-$\alpha$ particles via the $^{12}\text{C}(^{16}\text{O},^{16}\text{O}^*[\alpha+X])^{12}\text{C}$ reaction. The branching ratio of the $\alpha$ decay from N\$\alpha$ condensed state to the (N-1)\$\alpha$ one is larger than those of other channels, because the overlap of their wave functions is very large. Thus, if the excitation energy of the 4\$\alpha$ condensed state is higher than the $^{12}\text{C}(0^+_2) + \alpha$ threshold, we can select the 4\$\alpha$ condensed state from the candidates.

The test experiment was performed at the CYRIC 41 course beam line by using the $^{16}\text{O}^{5+}$ beam accelerated up to 160 MeV in the K=110 MeV AVF cyclotron. The momentum spread of the beam was limited to less than a few percent by a slit installed between two analyzer-magnets, ANA1 and ANA2 (see Ref. 3). High quality $^{16}\text{O}^{5+}$ beam bombarded a self-supported natural carbon foil. The thickness of the carbon foil was a 200 $\mu$g/cm$^2$. The recoiling $^{12}\text{C}$ nucleus was detected in a silicon detector (SSD1) of a surface barrier type. The decay-$\alpha$ particle was caught in a 50×50 mm$^2$ silicon detector (SSD2), which was segmented into 10 silicon diodes of a 5×50 mm$^2$ size. In order to reduce
background particles such as elastically scattered $^{16}\text{O}$, beam halo, and so on, we installed a 200 $\mu$m aluminum plate in front of SSD2. The observed particles were identified by the TOF method. Figure 1 shows the TOF spectra of the SSD1 and SSD2. Since SSD1 was placed at the 100 mm distance from the target, it was difficult to identify a locus of $^{12}\text{C}$. Then, we have recognized the locus of $^{12}\text{C}$ by measuring the recoiling $^{12}\text{C}$ of elastic scattering. In SSD2, which was put at the position of 200 mm from the target, it was almost only for $\alpha$ particles to come into the detector. The aluminum plate worked very well. In the present experiment, we measured decay $\alpha$ particles from the states at the excitation energy of 15.5 MeV on $^{16}\text{O}$. The setting angles of SSD1 and SSD2 were 61° and 10°, respectively. The energy of the recoiling $^{12}\text{C}$ was 6.0 MeV. Figure 2 shows the energy spectrum of SSD2. The energy of decay $\alpha$ particles to the 0$_2^+$ state of $^{12}\text{C}$ are about 30 – 40 MeV, which depend on angles of decay particles. The $\alpha$ particles of the energy over 40 MeV arise from the $^{12}\text{C}(2_1^+)+\alpha$ or $^{12}\text{C}(\text{g.s.})+\alpha$ channels. As shown in Fig. 2, decay $\alpha$ particles from the 0$_2^+$ state of $^{12}\text{C}$ were observed. However, we could not separate decay channels in this stage because of the lack of the angular resolution. Now, we are preparing the double-side silicon strip detector for improvement of the angular resolution.

References

\( \alpha \)

\( ^{12}\text{C}(0^+_2)+\alpha \)

\( ^{12}\text{C}(2^+_1)+\alpha \)

Figure 1. TOF spectra of SSD1 and SSD2.

Figure 2. The energy spectrum of decay \( \alpha \) particles from the excited \(^{16}\text{O}\) state at the excitation energy of 15.5 MeV.
I. 2.  Production of Radioactivities for Undergraduate Students

Kanda H.\(^1\), Iguchi A.\(^1\), Maeda K.\(^1\), Miyase H.\(^1\), Ohtsuki T.\(^2\), Shinozuka T.\(^3\), and Yuki H.\(^2\)

\(^1\)Department of Physics, Graduate School of Science, Tohoku University
\(^2\)Laboratory of Nuclear Science, Tohoku University
\(^3\)Cyclotron and Radioisotope Center, Tohoku University

We are providing the introductory nuclear physics for undergraduate students with use of the radioactive isotopes as a subject in the “Basic Research in Physics (Butsurigaku kiso kenkyuu)\(^1\)\(^2\)”.

The aim of this class is to instruct students in the fundamentals of the radiation and the radioactivity with the measurement of the radiation. The production of the radioactive isotopes with use of the accelerator and the measurement of the gamma-ray from them enabled us of (1) the measurement of the life time of the radioactive decay and its randomness, (2) the demonstration of the conversion of the element and (3) the practical presentation of the nuclear size via measurements of the cross sections of the nuclear reaction. The proton beam of 20 MeV was irradiated on the natural iron and titanium and the gamma-ray from the produced nuclides was measured with use of a NaI(Tl) probe once a week in 2–3 weeks. By measuring the energy spectra of the gamma-ray, students identify the produced nuclides. By the decrease of the counting rates, half lives of the nuclides are measured. The cross section of the concerned reaction is measured by the counting rates, the branching ratio of the gamma-ray, the time after the production, and the some assumptions on the detection efficiencies. We prepare ten plates of iron of 0.1 mm thick for the measurement of the energy dependence of the \(^{56}\text{Fe} (p, n) ^{56}\text{Co}\) reaction.

The half life of the \(^{56}\text{Co}\) produced via \(^{56}\text{Fe} (p, n) ^{56}\text{Co}\) reaction is 77.3 days which leads small change of counting rates in several weeks. On the other hand, the half life of \(^{48}\text{V}\) produced via \(^{48}\text{Ti} (p, n) ^{48}\text{V}\) reaction is 16.0 days, and it is sufficiently short for the measurement of the decrease of the counting rates. The experiments were performed three times with changing the group of students. The results from three groups of students and the reference value from the Table of Isotopes\(^3\) are shown in Table 1. Because students were not well trained for the estimation of errors in their measurements, no error was shown.
on each data except for one measurement. As seen in the table, discrepancy of the half lives between the measured values and the reference value for $^{56}\text{Co}$ is larger than that for $^{48}\text{V}$. The simple estimation of the statistic errors on the measured half lives of $^{56}\text{Co}$ ranged from 10 to 20 days. It means these results are consistent with the reference value within the statistic errors. The statistic errors on the measured half lives of $^{48}\text{V}$ ranged from 0.5 to 0.9 days. These differences were useful for the students to consider the errors on the measurements.

The measurement of the cross section for $^{56}\text{Fe} (p, n) ^{56}\text{Co}$ was not always successful. A result by one group which is relatively good one in the results by the three groups is compared with the reference values from Experimental Nuclear Reaction Data $^{4}$ (Fig. 1). It seemed difficult to make students to understand the realistic idea on the scale of the nucleus and the cross section of the nuclear reactions with the current explanations for them. On the other hand, the energy loss of the proton in the iron was reasonably derived. It shows that the students can imagine a concrete idea of the resistance which was suffered by a charged particle travelling through matter. For convincing the students of the nuclear scale, we may have to improve our explanation about the method of the measurements and the relation between the nuclear size and the cross sections of the nuclear reactions.

This year we continued the experiments with the production of radioactivities at CYRIC as a subject in the “Basic Research in Physics (Butsurigaku kiso kenkyuu).” Though we designed this experiment to be comprehensive for the students, there is still a room for the improvement in the measurement of the cross sections. By taking account of the new class: “Physics Experiment III” which is the continuing class of the “Basic Research in Physics” and starts from 2008, we improve the experiment and prepare for the new class.

References
3) WWW Table of Isotopes, http://ie.lbl.gov/toi/.
Table 1. The half lives of $^{56}$Co and $^{48}$V reported by three groups of students and from the reference\textsuperscript{3)} in the unit of day.

<table>
<thead>
<tr>
<th>Group</th>
<th>$^{56}$Co</th>
<th>$^{48}$V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69</td>
<td>17.3</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>18.5/0.9</td>
</tr>
<tr>
<td>3</td>
<td>57.5</td>
<td>16.7</td>
</tr>
<tr>
<td>Reference</td>
<td>77.27</td>
<td>15.9735</td>
</tr>
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Figure 1. The cross sections of $^{56}$Fe ($p$, $n$) $^{56}$Co reaction with respect to the incident energy of the proton. Open circles represent the data from Experimental Nuclear Reaction Data Library\textsuperscript{3)} and red closed circles are the data from students’ measurement.