Measurement of hole-state distribution for Ca isotopes by using (p,2p) reaction

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Recent studies on unstable nuclei have expanded (Z,N)-space of existing nuclei drastically and have revealed that the shell structure of nuclei far from stability is significantly changed from that for stable nuclei. Otsuka *et al.* have proposed the existence of a mechanism which causes gradual change of an apparent ℓs splitting when a valence orbit is filled up [1]. The effect is caused by a monopole contribution of the isovector tensor term in NN interaction.

This effect is expected to be observed even for stable nuclei. In the case of Ca isotopes, when the $1f_{7/2}$ neutron orbit is filled up, the angle-averaged contribution, or monopole contribution, of the tensor force pushes down and pulls up the $1d_{3/2}$ and $1d_{5/2}$ proton orbit energies, respectively. Therefore the energy difference between these two levels decreases as a function of the neutron number.

On the other hand, the experimental data show different neutron number dependence and the deduced energy difference for ^{48}Ca is significantly less than that for ^{44}Ca. The data are results of an experiment using (d,^{3}He) reaction on calcium isotopes, ^{40,42,44,48}Ca [2]. Actually, both of $1d_{3/2}$ and $1d_{5/2}$ states are significantly fragmented. The single particle energies are deduced as a weighted mean of many $1d_{3/2}$ or $1d_{5/2}$ levels. One serious problem of this data are that only ℓ-values of these levels were determined directly. Because of lack of polarization measurement, j-values are not determined experimentally and they were conjectured for some levels and guessed or simply assumed for many other levels. Thus the result is not necessarily reliable enough.

In order to obtain reliable experimental data for single particle energies of $1d_{3/2}$ and $1d_{5/2}$ orbits, we performed an experimental measurement of the differential cross section and the analyzing power (A_y) for (p,2p) reaction on the same calcium isotopes. The incident beam energy was 200 MeV and the two-arm spectrometer consisting of GR and LAS was used for detection of two outgoing protons. Figure 1 shows a spectrum for ^{40}Ca(p,2p) reaction. The overall energy resolution is about 240 keV FWHM, so that many levels are not separated each other. It is worth mentioned that we found new peaks around 19 MeV of the proton separation energy which was outside of the energy region of the previous (d,^{3}He) measurement.

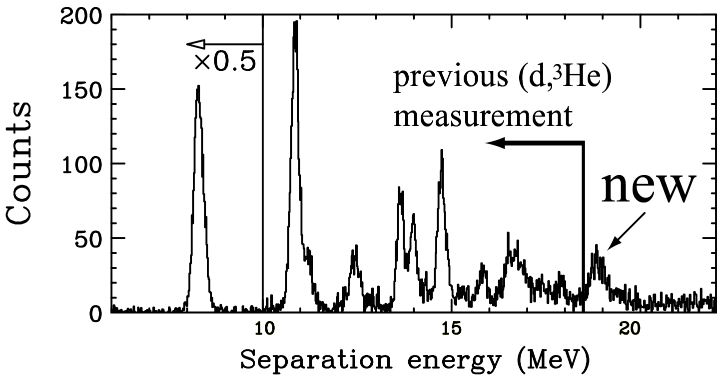

Figure 1: ^{40}Ca(p,2p)^{39}K spectrum.

Analysis of the present data has been performed in the following procedure. First, we confirmed that both of ℓ and j values are well determined by using two kinds of observable, differential cross section and A_y.

In Fig. 2, our cross section and analyzing power data for $1d_{3/2}$ and $1d_{5/2}$ knockout from ^{40}Ca target, observed as separated peaks, are plotted against the recoil momentum and compared with DWIA calculations. All of the data are well reproduced by the calculations.

Secondly, we tried a Multipole Decomposition Analysis (MDA) for a couple of peaks which were not separated each other completely. In this analysis, the sum of the cross sections for the peaks, two peaks denoted as $1d_{3/2}$ and $2s_{1/2}$ in Fig. 3, is expressed by a linear combination of those predicted by DWIA calculations for two kinds of knockout. By using the recoil momentum distribution of the experimental summed cross section, we

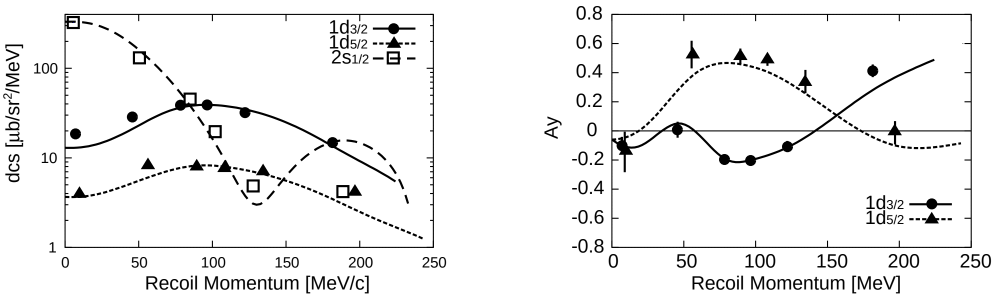

Figure 2: The cross section (left) and the analyzing power (right) of the ^{40}Ca(p,2p)^{39}K reaction leading to the $3/2^+$ (●), $5/2^+$ (▲) and $1/2^+$ (□) plotted as functions of the recoil momentum. The solid, dashed and dotted lines represent results of DWIA calculations. Clear ℓ and j-dependences are observed for the cross section and analyzing power, respectively.

optimized normalization factors for the linear combination, which correspond to the S-factors for two peaks. The result is shown in Fig. 4. The closed circles show the experimental summed cross section and the dotted line and the dashed line show contributions from the s and d states estimated by using MDA, and the solid line is the sum of those. Since the peaks are partially separated, we can obtain the total counts of each peak by using a peak-fitting procedure. The differential cross sections calculated with those total counts are shown as the open squares and the closed triangles in the same figure. The result of MDA is agree with this result. This is shows that MDA is reliable enough.

Thirdly, MDA was performed in a region of separation energies, 10.3 MeV ≤ Esep ≤ 20.3 MeV, for ^{40}Ca target. Actually, the region was divided into eight sections and MDA was applied for each of these sections. We used both of the cross section data and the A_y data for MDA in this case, because both ℓ and j are to be identified. As a result, $1d_{3/2}$ components were found in some sections where all d-states had guessed to be $1d_{5/2}$. In addition, a part of the newly observed peak was assigned to be $1d_{3/2}$. The difference of the single particle energies between the two d states was consistent with that deduced from the (d,^{3}He) data when the newly observed peaks were not included in MDA, but 10∼30% smaller values were derived when they were included.

Analysis for ^{42,44,48}Ca targets has been suspended because of low statistics and significant oxygen contaminations. Additional data will be required to obtain conclusive results.

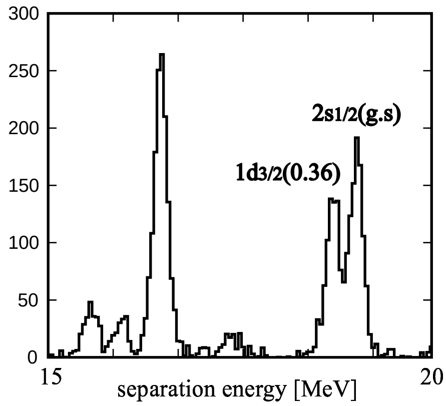

Figure 3: Separation energy spectrum for ^{48}Ca(p,2p)^{47}K reaction.

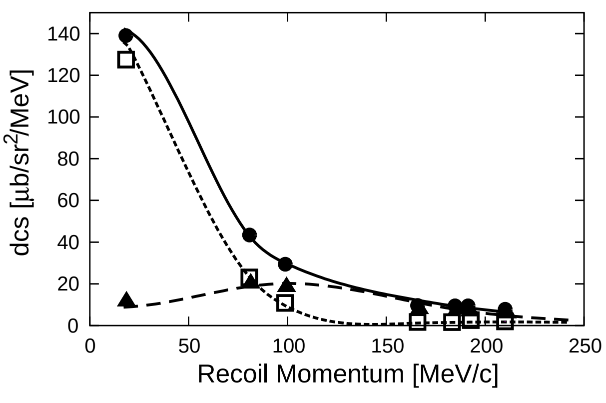

Figure 4: Comparison of the cross section deduced by using MDA and that obtained by a peak fit analysis for ^{48}Ca(p,2p)^{47}K reaction. The closed circles show experimental differential cross section deduced from the sum of two peaks, shown as $1d_{3/2}$ and $2s_{1/2}$ in Fig. 3. And the solid line is a fit by MDA, which $2s_{1/2}$ and $1d_{3/2}$ components are shown by the dotted line and the dashed line respectively. The dashed and dotted lines show contributions of the $2s_{1/2}$ and $1d_{3/2}$ states estimated by MDA. The squares and the triangles represent $2s_{1/2}$ and $1d_{3/2}$ cross sections obtained by using the peak fit analysis.

References

[1] T. Otsuka *et al.*, Phys. Rev. Lett **95**, 232502 (2005).
[2] P. Doll *et al.*, Nucl. Phys. **A263**, 210 (1976).