I. 3. Comparative Study of the (p,n) Reactions on $^{40}\text{Ca}$ and $^{40}\text{Ar}$ for the 1.6 MeV-State in the A=40 Isobar Triplet


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Charge independence of the nuclear force provide us corresponding information between mirror nuclei and that among isobar multiplets, while a number of discussions about charge symmetry breaking have been reported for details of the nuclear phenomena. The nuclei $^{40}\text{K}$, $^{40}\text{Ca}(T=1)$ and $^{40}\text{Sc}$ form a family of the isobar triplet. In deed, the spin-parity of their ground state is 4+, though except that no spin-parity assignments have been made for $^{40}\text{Sc}$. Discussions for nuclear structure of $^{40}\text{Sc}$ have so far been based on that of well known $^{40}\text{K}$ or $^{40}\text{Ca}$.

Supposing a double closed shell for $^{40}\text{Ca}$, the (p,n) reaction on $^{40}\text{Ca}$ excites selectively $1\hbar\omega$ jump negative parity states, while that on $^{40}\text{Ar}$ primarily yields positive parity states. Thus, a comparative study of the (p,n) reaction on $^{40}\text{Ar}$ and $^{40}\text{Ca}$ may give us a complete set of nuclear structure of A=40 isobar triplets. The (p,n) reaction has provided us with information about spin-isospin, as well as isospin excitation modes in nuclei. One can selectively excite the spin-flip components in the (p,n) reaction at intermediate energies through the relatively strong spin-isospin effective interaction ($V_{\sigma\tau}$). Low energy (p,n) reactions, due to the strong spin non-flip isovector effective interaction ($V_{\tau}$), give us equivalent information on both excitation modes. Moreover, it gives us a sufficient energy resolution to discuss (p,n) strength for individual nuclear levels\textsuperscript{1,2}, although exchange contributions are important at low energies. Various problems associated with the distorted-wave (DW) analysis of low-energy (p,n) data were discussed in detail by Ohnuma et al.\textsuperscript{3}. It has been found possible to obtain basically the same information as that at intermediate energies if careful analysis including exchange terms is carried out.

In this report, we discuss mainly about the second excited state located around 1.6 MeV in A=40 nuclei\textsuperscript{4}, the spin-parity for which is assigned as 0+ in $^{40}\text{K}$, then this state should be weakly populated in the (p,n) reaction on $^{40}\text{Ca}$, if this assignment is valid for $^{40}\text{Sc}$ too.
The experiment was carried out using a 35 MeV proton beam from the AVF cyclotron and the time-of-flight facilities\textsuperscript{5,6} at the Cyclotron and Radioisotope Center at Tohoku University. A beam swinger system was used to measure angular distributions of emitted neutrons between 0° and 140° (lab).

The Ar target was argon gas enriched to 99% in $^{40}$Ar. The gas was contained in two types of gas cell. A drum-shaped cell having a longitudinal length of 2 cm was used for small-angle measurements ($\theta_{\text{lab}} \leq 30^\circ$). The target for large-angle measurements ($\theta_{\text{lab}} \geq 30^\circ$) was 20 cm long cylindrical cell to allow us to shield the neutron detectors against neutrons emitted from the window foils. The effective target thicknesses were of the order of 1 mg/cm$^2$, and overlap region of detection angles was used for relative normalization. The window material was metallic calcium foil for the drum-shaped cell, while it was Havar foil for the cylindrical cell, their thicknesses being $\sim$10 mg/cm$^2$. Backgrounds due to the window materials did not give any serious problems because of the large Q-value difference. These backgrounds were measured in separate "empty runs", and subtracted from the data. The Ca target was a metallic foil of enriched $^{40}$Ca prepared by vacuum evaporation. The thickness and enrichment of the target were, respectively, 2.0 mg/cm$^2$ and 99.9%.

Neutrons were detected by an array of twelve detectors, which were located at 44.3 m from the target and contained a total of 23.2 liters of NE213 scintillator. The detector efficiencies were obtained from Monte Carlo calculations for monoenergetic neutrons with $E_n \leq 34$ MeV. Absolute detector efficiencies were also measured by counting neutrons from the $^7$Li(p,n)$^7$Be reaction and comparing its yield with the absolute neutron fluence determined by activation. They were in good agreement with the Monte Carlo calculations. Overall time resolution was typically 1.3 ns corresponding to 175, and 90 keV for the most energetic neutrons to $^{40}$K and $^{40}$Sc, respectively. Main contributions to the former resolution were attributed to the small Q-value in negative, and the energy loss and straggling of incident protons in the entrance-window of the target gas cell. Errors in the absolute scale of the cross sections were estimated to be less than 15%.

In Fig. 1, neutron excitation energy spectra are compared for the (p,n) reactions on $^{40}$Ar and $^{40}$Ca. Remarkable deferences are clearly seen; i.e. neutron spectrum begins at 1.6 MeV in the former, while it starts at the ground state in the latter as predicted by theoretical calculation by the shell-model and DW theories, which will be discussed later on. Figures 2 and 3 show experimental and theoretical cross sections for the transitions leading to the 1.6-MeV states in $^{40}$K and $^{40}$Sc, respectively. These for the transition to the IAS is also illustrated in Fig. 2 for comparison.

The cross-section data were compared with the DW results calculated by the computer code DWBA-74\textsuperscript{7), which includes knock-on exchange effects in an exact manner. Optical potential parameters of Becchetti and Greenlees\textsuperscript{8) were used for the entrance channel. Those for the exit channel were self-consistent potential parameters derived by Carlson et al.\textsuperscript{9). The effective nucleon-nucleon interactions used in the present DW analysis were those by Bertsch
et al. (M3Y)\textsuperscript{10}). Spectroscopic amplitudes for the transition to the 0\textsuperscript{+} state in 4\textsuperscript{0}K were obtained from the sd\textit{pf} shell-model calculations with the SDPFM interaction\textsuperscript{11} in the code OXBASH\textsuperscript{12}, assuming the configurations of \([\pi(f_{7/2}p)^2,4 (f_{5/2}p)^{0,2}, \nu(s_{5/2}d)^{16,16}(d_{3/2})^{2,4}]\) for both the initial and final states. That for the transition to the 1.6-MeV state in 4\textsuperscript{0}Sc were obtained, assuming \(\Delta J=1\) with \([\pi(fp)^{0,2}, \nu(sd)^{24,22}]\) and \([\pi(fp)^{1}, \nu(sd)^{-1}]\) for the initial and final states, respectively. Single-particle radial wave functions used in DW calculations were generated in a Woods-Saxon potential with \(r_0 = 1.25\) fm, \(a = 0.6\) fm, \(V_{LS} = 6\) MeV and the depth adjusted to reproduce the binding energy of a valence nucleon.

Firstly, we discuss about the 1.64 MeV transition in the \(4\textsuperscript{0}Ar(p,n)4\textsuperscript{0}K\) reaction, the angular distribution for which is shown in Fig. 2 together with theoretical predictions obtained by the DWBA calculation with transition amplitudes listed in Table 1. Also tabulated are those for the IAS transition leading to the 4.38-MeV state in 4\textsuperscript{0}K. The latter indicates that the 1.64-MeV 0\textsuperscript{+} state is the anti-analog state being orthogonal to the IAS. Cross section magnitudes and angular distribution shapes are well reproduced as shown in Fig. 2.

As for the \(4\textsuperscript{0}Ca(p,n)4\textsuperscript{0}Sc\) reaction, we have identified the 1.69-MeV state to be due to a \(\Delta J^x=1^-\) transition based on the shell-model and DW calculations. As shown in Figs. 3, the experimental cross section magnitudes, their angular distribution shape and its excitation energy are quite reasonably explained by the theoretical comparison. With a reasonable ground state correlation for \(4\textsuperscript{0}Ca\) mentioned above we have obtained transition amplitudes listed in Table 1. The cross sections thus obtained for the \(\Delta J^x=0^+\) transition are two orders of magnitude smaller than those for \(\Delta J^x=1^-\) as shown in Fig. 3. As such, we have assigned this transition to be \(\Delta J^x=1^-\). The present result dose not reject the possibility of the existence of \(J^x=0^+\) state in 4\textsuperscript{0}Sc at \(E_X \approx 2\) MeV, except that we will emphasize the existence of \(J^x=1^-\) state.

In conclusion, by means of the comparative study of the \((p,n)\) reactions on \(4\textsuperscript{0}Ar\) and \(4\textsuperscript{0}Ca\), we have separately made clear the positive and negative parity states in \(A=40\) asobar multiplets. Especially, we have located a \(J^x=1^-\) state at \(E_X = 1.64\) MeV in 4\textsuperscript{0}Sc, and have observed the \(0^+\) anti-analog state by a charge-exchange reaction at \(E_X = 1.69\) MeV in 4\textsuperscript{0}K.

References

Table 1. One body transition densities (OBTD).

<table>
<thead>
<tr>
<th>Particle-Hole</th>
<th>$^{40}$Ar(p,n)$^{40}$K reaction</th>
<th>$^{40}$Ca(p,n)$^{40}$Sc reaction</th>
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<tr>
<td></td>
<td>T=2, $0^+$, #1 (4.384MeV, IAS)</td>
<td>T=1, $0^+$, #1 (1.644MeV)</td>
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<tr>
<td>$\pi d_{5/2}\nu d_{5/2}^{-1}$</td>
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<td>-</td>
</tr>
<tr>
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<td>-</td>
</tr>
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<td>$\pi p_{1/2}\nu p_{1/2}^{-1}$</td>
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<td>-0.00001</td>
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$^{40}$Ar(p,n)$^{40}$K
θ$_{\text{lab.}}$ = 15deg
$E_p$ = 35 MeV

$^{40}$Ca(p,n)$^{40}$Sc
θ$_{\text{lab.}}$ = 15deg
$E_p$ = 35 MeV
Fig. 1. Excitation energy neutron spectra for the (p,n) reactions on $^{40}$Ar and $^{40}$Ca.

Fig. 2. Experimental and theoretical cross sections for the $0^+ \rightarrow 0^+$ transitions to IAS and to the 1.644-MeV state in $^{40}$K.

Fig. 2. Experimental and theoretical cross sections for the $0^+ \rightarrow 1^-$ transitions to the 1.69-MeV state in $^{40}$Sc. The theoretical prediction for the $0^+ \rightarrow 0^+$ transition is also plotted for comparison.