I. 4  The $^{14}\text{C}(p, n)^{14}\text{N}$ Reaction at $E_p = 35$ MeV

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The (p,n) reaction on $^{14}\text{C}$ may provides many information of isovector structure of nuclear reaction, since the $^{14}\text{C}$ target is unique candidate, in p-shell nuclei, to have even number of proton and extra two-neutrons, and is capable for observing the ground state isobaric-analog transition. Beside this unique feature, the (p,n) reaction on $^{14}\text{C}$ may be the only one case where proton or neutron scattering experiments, carried out to find optical potential parameters, are possible, since otherwise in a (p,n) reaction the residual nucleus is unstable. Thus, by analyzing proton and neutron scattering and the analog transition we are able to obtain a comprehensive set of the optical potential parameters of the isovector channel.

For the p-shell nuclei, wave functions for the initial and final states, by which we calculate transition amplitudes for distorted-wave Born approximation (DWBA) predictions, are available by Cohen and Kurath (CK)$^1$ for the positive parity-states, and by Millener and Kurath$^2$ interactions for the negative-parity states. By sampling the (p,n) reactions on $^{12}\text{C}$ and $^{16}\text{O}$ at $E_p = 35$ and 40 MeV, we have successfully examine$^3$ the reliability of the information obtained from the DWBA analysis of the low-energy (p,n) data. The tensor part of the effective nucleon-nucleon interaction, which is crucial in the DWBA prediction, has been separately tested by studying the isovector $\Delta J^M = 0^-$ type transitions in p-shell nuclei.$^4$ The effect of the higher-order process and those of the exchange process have been also checked leading to a conclusion that they give negligibly small cross section compared to the direct spin-isospin channels including tensor one.

We have carried out a systematic study for spin-isospin excitation in nuclei by using the (p,n) reaction at 35 MeV. The topics of these experiments are; 1) $0^+ \rightarrow 1^+$ transition corresponding to Gamow-Teller (GT) $\beta$-decay, 2) stretched particle-hole excitation, and 3) $0^+ \rightarrow 0^-$ transition which may be strongly connected to one-$\pi$ exchange in hadron scattering. The $^{14}\text{C}(p, n)^{14}\text{N}$ reaction contains all these subjects; 1) two GT-type transitions leading to the ground and 3.9478-MeV 1+ states have long been discussed by many authors$^5$, the former having a log ft-value of 9.0, the (p,n) transition, then, should be forbidden if proportionality relationship between (p,n) cross
section and the corresponding GT β-decay is valid, 2) 3+ and 4− states are
known at 6.444 and 8.488 MeV, respectively, suggesting the stretched
particle-hole states of 0hw (πP3/2,VP3/2−1), and 1hw (πd5/2,VP3/2−1)
character, 3) we find a 0− state at E∗x = 4.915 MeV which is another candidate
to study isovector ΔJτ = 0− transition in stead of that in the 160(p,n)16F
reaction.

The experiment was performed using 35 MeV proton beams and the time of
flight facilities6) at Cyclotron and Radioisotope Center, Tohoku University.
The 14C target was self supporting foil of carbon-14, the thickness for which is
168 μg/cm2 in 14C measured by counting elastically scattered protons, and
normalizing these yields to the calculated cross section by the optical model.
Proton elastic scattering data was taken at Institute for Nuclear Study,
University of Tokyo by using polarized proton beams from the SF-cyclotron.
The angular distribution of analyzing power was also measured. Analysis of
the data by the optical model was carried out for both cross sections and
analyzing power. Simultaneous fitting of these (p,p) data and the (p,n)
analog transition data gave a quite reliable parameter set of optical
potential, especially for LS- and U1 (isovector) terms.

A typical neutron energy spectrum is shown in Fig. 1 to illustrate back-
ward angle enhancement of the stretched high-spin 4− state at 8.488 MeV. Also
clearly seen are transitions leading to the 1+ and 0+ states at 0.0−, 2.3129−
and 3.9478–MeV states in 14N. The angular distributions for the 0+ → 1+ GT-
type transitions are shown in Fig. 2, together with DWBA predictions as
described later on. The 0+ → 1+ transition to the ground state has been
discussed as a counterexample for violation of the proportionality, since the
log ft value of the corresponding β-decay is 9.04, thus the (p,n) cross
section should be almost zero, or at least several orders of magnitude smaller
than that for the 0+ → 1+ transition to the 3.9478–MeV state if the
proportionality is valid. In the present analysis it is shown, as a rough
estimation, that the dominant part of the cross section to the ground state is
due to the ΔJ=1, but ΔL=2 instead of ΔJ=1, ΔL=0 which means the GT transition.
However, the contribution from ΔL=0 is not completely ruled out
experimentally. From theoretical points of view, the GT matrix element for
this transition is not canceled in a fully reasonable manner. More detailed
studies are required to resolve this puzzle.

DWBA calculations were made with the code DWBA74.7) Optical-potential
parameters for proton were taken from Ref. 8, and those for neutrons were
taken from Ref. 9. Choice of these parameters may introduce ambiguities of
+20% for predictions of the cross section, but not for the relative ones as
reported in Ref. 3. A set of effective interactions of Bertsch et al.10)
(M3Y) was used in the calculations. Figure 3 shows angular distributions of
the 0+ → 3+ and 0+ → 4− transitions, the former corresponding to 0hw, while
latter to 1hw stretched states as described before. We have carried out a
systematic study for the stretched states in sd-shell nuclei of 0hw11) and
character. The conclusions so far obtained, including those from intermediate (p,n), \((p,p')\) and electron scattering data, are: 1) the normalization factors are \(\sim 0.6\) or more for the \(0\omega\) transition\(^{11}\) while those for \(l\omega\) are \(\sim 0.3\)\(^{13}\), 2) fitting at small angles become worse for lower bombarding energy.\(^{11}\) On the other hand, the present results in Fig. 3 seem quite reasonable: the cross sections are fitted absolutely both for \(0\omega\) and \(l\omega\) transitions, and angular distributions are well reproduced even in small angles.

In summary, a number of typical spin-isospin excitations have been observed in the \(\text{^{14}C}(p,n)\text{^{14}N}\) reaction. Owing to the not enough target thickness of \(\text{^{14}C}\), the \(0^+ \rightarrow 0^-\) transition was not observed with a good statistic. The \(0^+ \rightarrow 1^+\) transition to the ground state was interpreted by a \(\Delta L=2\) transfer. Stretched states of \(3^+\) and \(4^-\) were clearly observed, and explained reasonably.

References

Fig. 1. Neutron energy spectrum for the $^{14}$C(p,n)$^{14}$N reaction at $E_p = 35$ MeV. Solid lines are the results of a peak-fitting analysis.
Fig. 2. Neutron angular distributions from the $^{14}\text{C}(p,n)^{14}\text{N}$ reaction at $E_p = 35$ MeV leading to the $1^+$ states at 0.0- and 3.9478-MeV states. Curves in the figure are DWBA predictions.

Fig. 3. Neutron angular distributions from the $^{14}\text{C}(p,n)^{14}\text{N}$ reaction at $E_p = 35$ MeV leading to the $3^+$, $0\hbar\omega$ and $4^+$, $1\hbar\omega$ stretched states. Curves in the figure are DWBA predictions without renormalization.