Isovector Effective Interactions from $^{14}C(p,n)\,^{14}N$ Studies between 500 and 800 MeV

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Cross sections at 0° for the pure Fermi (0^+, 2.31 MeV) and Gamow-Teller (1^+, 3.95 MeV) states in the $^{14}C(p,n)^{14}N$ reaction have been measured at $E_p=494$, 644, and 795 MeV using the LAMPF neutron time-of-flight facility with a new 617-m neutron flight path. The measured cross sections per unit transition strength, $\hat{\sigma}$, provide a measure of the isovector spin-flip and non-spin-flip central components of the effective nucleon-nucleon interaction. Cross sections and the ratio $R^2=\hat{\sigma}_{GT}/\hat{\sigma}_F$ are compared to lower-energy measurements and to calculations using a free NN t matrix.

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Zero-degree (p,n) cross-section measurements at intermediate energies provide a highly selective probe of isovector excitations in nuclei. In the impulse approximation at such energies, nuclear-structure information can be separated from the effective nucleon-nucleon (NN) interaction responsible for the transition. An empirical determination of the ratio of spin-flip to non-spin-flip (p,n) cross sections at 0° has proven to be very valuable in the study of Gamow-Teller strength functions and isovector interaction strengths. The $^{14}C(p,n)$ reaction populating the 2.31-MeV (0^+) and 3.95-MeV (1^+) states in ^{14}N provides the optimal experimental conditions with which to systematically and simultaneously investigate pure ($\Delta L=\Delta S=\Delta J=0$) Fermi (F) and ($\Delta L=0$, $\Delta S=\Delta J=1$) Gamow-Teller (GT) isovector transitions, respectively. There is considerable interest in characterizing these types of transitions over the full energy range for which free NN data are available. Prior to the present experiment, however, the ability to resolve the two states of interest in ^{14}N has limited $^{14}C(p,n)$ reaction studies to bombarding energies below 500 meV.[1-3]

The new neutron time-of-flight (NTOF) facility has been commissioned at the Clinton P. Anderson Meson Physics Facility (LAMPF) to extend (p,n) studies having nominally 1-MeV energy resolution to the full 800-MeV energy of the linear accelerator (linac).[4] In this Letter we report results from the first high-resolution measurements utilizing this new facility. These measurements represent the first (p,n) reaction data above 500 MeV having sufficient energy resolution to study directly the energy dependence of the isovector interaction strengths via discrete transitions in the $^{14}C(p,n)^{14}N$ reaction.

From 200 to 500 MeV, large discrepancies appear between the ratio of spin-flip ($J_{\sigma\tau}$) to non-spin-flip (J_τ) isovector strengths derived from (p,n) cross sections and that calculated using a t-matrix interaction based on free NN amplitudes.[5] Such discrepancies at these energies are qualitatively consistent with theoretical studies which predict strong (weak) density and energy dependence for J_τ ($J_{\sigma\tau}$).[5-7] Previous attempts to determine $|J_{\sigma\tau}/J_\tau|$ at energies above 500 MeV have been limited by available energy resolution to the study of (p,n) data on light, odd-mass targets.[3,8] However, these results are inherently imprecise because the F cross sections must be unfolded from *mixed* F and GT ground-state transitions and the pure GT transitions to excited states are not accessible to (and thus not calibrated against) β decay. A precise comparison of empirical isovector strengths with those derived from free *NN* scattering data requires an investigation of the $^{14}C(p,n)^{14}N$ reaction having energy resolution of about 1 MeV.

Zero-degree neutron spectra for (p,n) reactions on $^{6,7}Li$ and $^{12,13,14}C$ targets were obtained using time-of-flight techniques. The ^{14}C target was 170 mg/cm^2 of carbon (enriched to 89% in ^{14}C) encased in a nickel cell of 89 mg/cm^2 total thickness. The same ^{14}C target was used previously in the (p,n) investigations at TRIUMF[2] and at the WNR facility at LAMPF.[3]

Neutrons were detected in an array of three stainless-steel tanks containing liquid scintillator.[4] Each tank was divided into ten optically isolated 10-cm×10-cm×105-cm cells oriented perpendicular to the neutron flux. Each cell was viewed by a phototube at each end to determine the position and mean time of neutron detection. Data were obtained in either a singles or a double-scattering (coincident) mode. The coincident mode is useful in kinematically selecting forward (n,p) scattering in the front detector. With a neutron flight path of 617 m and beam currents of order 50 nA, about 5 h were required to acquire in coincident mode each $^{14}C(p,n)$ spectrum at 494 and 644 MeV. Beam currents at 795 MeV were typically 10–20 nA, and 3.5 h were required to acquire the singles-mode $^{14}C(p,n)$ spectrum.

The proton beam bursts were pulse selected to provide a separation of 5 μs. This pulse separation minimizes background due to low-energy neutrons from preceding beam bursts. While the time width of the beam pulse exiting the last accelerating linac module was very small (<60 ps), the intrinsic energy spread of the beam was typically a few MeV. Over the combined drift path of the proton to the target and neutron to the detector, this energy spread can significantly degrade the ultimate time resolution (and thus the neutron energy resolution) observed. At energies below the full energy of the linac, it was possible to employ nonaccelerating linac modules to create a time focus at the neutron detector.[9] This post-acceleration rebunching reduced the beam contribution to the total time width for neutrons to a value comparable to the intrinsic time resolution of the detection system. At the two lower beam energies studied, rebunching produced a total energy resolution of about 650 keV (FWHM). At the full beam energy of 795 MeV, where such rebunching was impossible, the energy resolution was improved to about 1.3 MeV (FWHM) through momentum selection of only a fraction of the accelerated beam for use on a target.

Taped event data were replayed off line in order to process and sort all recorded events and to monitor and correct timing drifts of the stop signal via γ rays produced at the target. The time and pulse-height information from each detector was calibrated with cosmic-ray muon events obtained during each run. The coincident mode of acquisition was utilized at the two lower energies to improve energy resolution and background suppression over that obtained in a singles mode of operation. The zero-degree spectra for the $^{14}C(p,n)^{14}N$ reaction are presented in Fig. 1.

Neutron yields for the 494- and 644-MeV data were extracted by summing the number of counts in each peak of interest. At 795 MeV, yields were extracted by fitting to each of the peaks a line shape composed of a Gaussian peak with a low-energy exponential tail. This shape is consistent with that obtained for well-resolved peaks in spectra on other targets. A peak fitting program which minimized a χ^2 function based upon Poisson counting statistics was used.[10]

Cross sections were determined relative to the $^7Li(p,n)^7Be$(g.s.+0.429 MeV) transition. The cross sections reported here are based on a value at zero momentum transfer ($q=0$) at 27 mb/sr for this ^7Li center-of-mass cross section.[11] Relative cross sections were corrected for computer dead time (2%–35%), for beam pulse selection inefficiency (1%–6%), and for changes in neutron attenuation by the air due to fluctuations in air temperature and atmospheric pressure (0%–4%).

The $^{14}C(p,n)^{14}N$ runs required an additional absolute

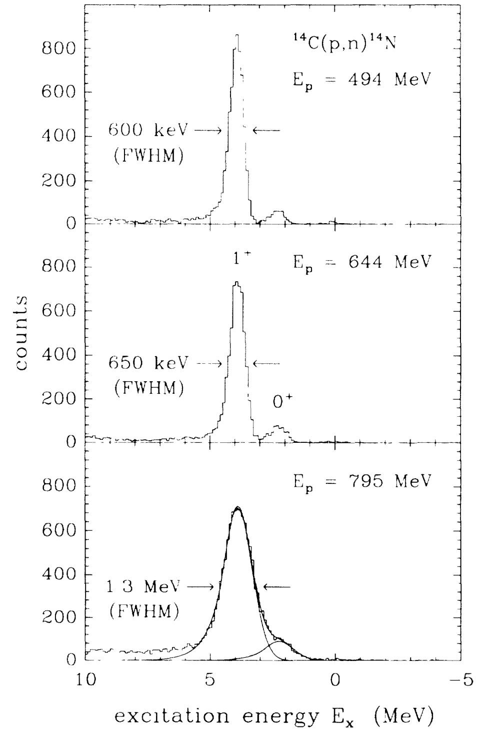

FIG. 1. Low-excitation zero-degree spectra for the $^{14}C(p,n)^{14}N$ reaction.

normalization factor. The beam spot at the target position was comparable in size to the width of the ^{14}C target. A thin natural carbon slab of width equal to that of the ^{14}C target was placed immediately behind the ^{14}C target. Comparison of the neutron yield from this thin natural carbon slab with that obtained from a wider natural carbon target which intercepted the complete beam, established the fraction of integrated beam which actually passed through the ^{14}C target.

The differential cross section at zero degrees for a pure transition of type α (GT or F) can be represented by[12]

$$\sigma(\alpha)=\hat{\sigma}_\alpha[F_\alpha(q,\omega)B(\alpha)] \quad (1)$$

$$\approx K_\alpha N_\alpha |J_\alpha|^2 B(\alpha)\,. \quad (2)$$

Transition strengths of $B(\text{F})=2.0$ and $B(\text{GT})=2.8\pm0.1$ are known for the 2.31-MeV (0^+) and 3.95-MeV (1^+) states in ^{14}N, respectively.[13] The "unit cross section" $\hat{\sigma}_\alpha$ defines the cross section per unit $B(\alpha)$ at zero q and energy loss ω. The q and ω dependence is described by the factor $F_\alpha(q,\omega)$, which is close to unity for the two transitions of interest. In an impulse approximation where the noncentral components of the interaction and its nonlocal aspects can be neglected, Eq. (2) relates $\sigma(\alpha)$ to the volume integral J_α of the relevant component of the isovector interaction at $q=0$. K_α is a kinematic factor and N_α is a distortion factor. The latter can vary significantly (±20%) with choice of optical potential and effective interaction, making extraction of J_α highly model dependent. We have, therefore, chosen to use only the absolute cross sections and the ratio of unit cross sections

$$R^2=\hat{\sigma}_{\text{GT}}/\hat{\sigma}_{\text{F}}\approx |J_{\sigma\tau}/J_\tau|^2 N_{\sigma\tau}/N_\tau \quad (3)$$

for direct comparison with predicted values in Fig. 2. Lower energy results are taken from Refs. 1 and 2.

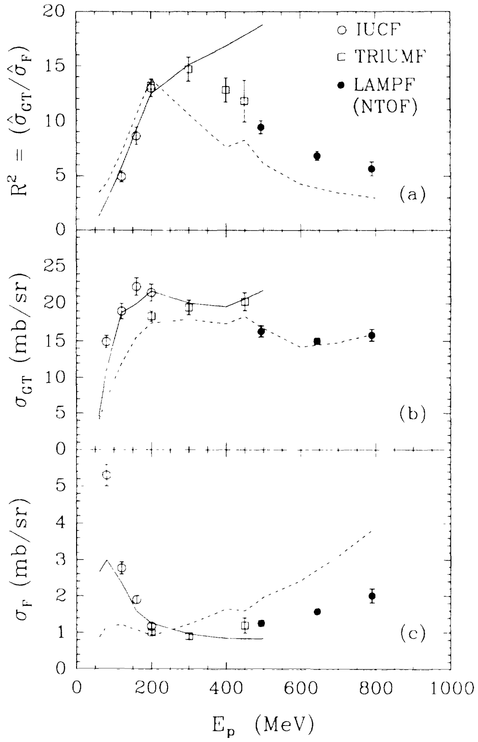

FIG. 2. Values of (a) R^2 (see text), (b) the 0° GT cross sections, and (c) the 0° F cross sections for the reaction ^{14}C$(p,n)^{14}$N at energies from 100 to 800 MeV. The dashed (solid) line is obtained using a t-matrix interaction based on free NN amplitudes (G-matrix interaction based on the Bonn potential) (see Ref. 5).

Results are presented in Table I. The agreement between the present results at 494 MeV and those of lower resolution reported in Ref. 3 from the LAMPF WNR facility at 492 MeV is excellent. Consistent with observations at lower energies, the present value of R^2 at 795 MeV is about 30% lower than that inferred from the odd-mass ^{13}C results.[8]

At energies below 200 MeV (Ref. 1) the ratio of strengths for the spin-flip to non-spin-flip isovector interactions which mediate these (p,n) transitions is in reasonable agreement with values given by a recent free t-matrix effective interaction.[5] These calculations based on the SP84 NN phases[14] are extended to 800 MeV and are compared with our experimental results in Fig. 2. The underprediction by as much as a factor of 2 of the value of R^2 at the presently reported energies is clearly to be attributed to an overprediction of σ_{F}, which is dominated by short-range processes rather than the long-range one-pion-exchange characteristic of σ_{GT}. At energies near 800 MeV, large medium modifications of the NN interaction are not expected.[7] The disagreement is most likely due to uncertainties in the underlying NN amplitudes employed.

In summary, we report the first high-resolution study of the ^{14}C$(p,n)^{14}$N reaction at beam energies above 500 MeV. Resolution of the two transitions of interest was possible with the new NTOF facility at LAMPF. These data provide the most definitive experimental determination of the ratio of the isovector spin-dependent and spin-independent components of the effective nucleon-nucleon interaction and more precisely the ratios of

TABLE I. Cross sections and the ratio $R^2=\hat{\sigma}_{\text{GT}}/\hat{\sigma}_{\text{F}}$ for the ^{14}C$(p,n)^{14}$N reaction.

E_p (MeV)	E_x (MeV)	$\sigma_{\text{c.m.}}(0°)$ (mb/sr)[a]	R^2
494	2.31	1.26 ± 0.08	9.42 ± 0.59
	3.95	16.3 ± 0.7	
644	2.31	1.58 ± 0.07	6.84 ± 0.40
	3.95	15.0 ± 0.4	
795	2.31	2.01 ± 0.19	5.67 ± 0.63
	3.95	15.8 ± 0.8	

[a] Systematic errors not included are from uncertainties in luminosity (± 10%) and ^{7}Li calibration cross section (± 4%).

$\hat{\sigma}_{GT}/\hat{\sigma}_F$ at these energies. Our results provide sensitive tests of isovector effective interactions at small momentum transfer for the higher energies considered here. These measurements should also provide important tests of nuclear medium effects in interactions based on more realistic potentials, as they become available for these higher energies. Finally, regardless of how the data are interpreted in terms of various models for the effective interaction, an empirical measure of the unit cross-section ratio can be an important tool in studies of Gamow-Teller strengths. The present data now provide such a measure over the entire energy range covered by existing (p,n) facilities.

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