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Fermi and Gamow-Teller strength in p-shell nuclei from (p,n) reactions at 492 and 590 MeV

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Zero-degree (p,n) cross sections, measured with approximately 1-MeV energy resolution at $E_p=492$ MeV, are reported for ^{7}Li, ^{11}B, and ^{12,13,14}C. Measurements for ^{11}B(p,n) and ^{13}C(p,n) were also obtained at 590 MeV. The cross sections for Gamow-Teller and Fermi type transitions are used to estimate the strengths of the isovector spin-dependent ($J_{\sigma\tau}$) and spin-independent (J_τ) terms of the effective interaction. The measured zero-degree cross sections for the ^{14}C$(p,n)^{14}$N transitions to the 2.31 MeV isobaric analog state and the 3.95-MeV $J^\pi=1^+$ state are compared with calculated values. Values for the unit cross-section ratio $R^2=\hat{\sigma}_{GT}/\hat{\sigma}_F=(J_{\sigma\tau}/J_\tau)^2(N_{\sigma\tau}/N_\tau)$ obtained from the present data are compared with results for other energies.

I. INTRODUCTION

Zero-degree cross sections for $\Delta J^\pi=0^+$ and 1^+ (p,n) reactions at intermediate energies can be used to obtain estimates of the strengths of the isovector terms of the effective nucleon-nucleon interaction. Empirical values obtained for bombarding energies up to about 200 MeV seem to be in reasonable agreement with the strengths of the corresponding terms in the free nucleon-nucleon (NN) interaction.[1,2] However, for incident energies between 200 and 450 MeV,[3] and also at 800 MeV,[4] the empirically-derived ratio of the central isovector spin-dependent interaction strength, $J_{\sigma\tau}$, to the spin-independent interaction strength, J_τ, is much larger than that obtained from the free NN interaction.

The energy dependence of the ratio $J_{\sigma\tau}/J_\tau$ at intermediate energies has been the subject of two recent theoretical studies.[5,6] The $V_{\sigma\tau}$ interaction is dominated by the long-range one pion exchange and is mainly responsible for the excitation of Gamow-Teller (GT) type transitions. The corresponding interaction strength $J_{\sigma\tau}$ has been shown to be essentially density-independent at intermediate energies.[5] However, the V_τ interaction that is dominant in the excitation of isovector analog state (IAS) transitions (Fermi transitions) arises from the knock-on and higher-order terms associated with π and ρ exchanges[7] and its strength J_τ thus exhibits a strong density and energy dependence.[5]

Because of resolution limitations in (p,n) measurements at intermediate energies, the ^{14}C$(p,n)^{14}$N reaction is the best case for empirical studies of the interaction strengths $J_{\sigma\tau}$ and J_τ as well as their ratio. The 0^+ IAS at $E_x=2.31$ MeV in ^{14}N is well separated from the closest level at $E_x=3.95$ MeV and is thus accessible to measurement with experimental energy resolution of about 1 MeV or better. Furthermore, the strong GT transition to the 1^+ 3.95-MeV state has a transition strength B(GT) that is reasonably well determined from beta decay lifetimes and branching ratios.

Cross sections for the ^{14}C(p,n) reaction and (p,n) reactions on a variety of other targets have been used to study the interaction strengths $J_{\sigma\tau}$ and J_τ and their ratio for energies below 200 MeV.[2,8] Relative cross sections for ^{14}C(p,n) have been used to study the interaction strength ratio in the energy region between 200 and 450 MeV,[3] and values for this ratio obtained from relative cross sections for ^{13}C(p,n) transitions have been reported for 318 and 800 MeV.

In this paper we report measurements of zero-degree cross sections for (p,n) reactions on ^{7}Li, ^{11}B, and ^{12,13,14}C at 492 MeV, and for ^{11}B and ^{13}C at 590 MeV. These measurements were made with an overall experimental energy resolution of about 1 MeV. Estimates of the interaction strengths $J_{\sigma\tau}$ and J_{τ} are obtained directly from the ^{14}C$(p,n)^{14}$N cross sections. The ratio of these strengths can also be obtained from the results for ^{11}B and ^{13}C. For these odd-A target nuclei, the IAS transition proceeds via a mixture of Fermi and GT components. Interpretation of the results for these targets is therefore more complicated than for ^{14}C; however, the techniques have been well established for lower energies.[2]

The experimental method and a summary of the results are presented in Sec. II. Interpretation of the cross sections in terms of effective interaction strengths is discussed in Sec. III. Details of the theoretical calculations are given in Sec. IV. A summary of the results and conclusions based upon comparison to the data is presented in Sec. V.

II. EXPERIMENTAL METHOD AND RESULTS

The measurements were made at the WNR Target-2 Area[9] at the Clinton P. Anderson Meson Physics Facility (LAMPF). The last sections of the 800 MeV linear accelerator normally act as passive drift sections when the beam energy is less than 800 MeV. In this operational mode the excellent initial time width of individual beam bursts (<200 ps at 800 MeV) grows much wider over the long drift length between the last accelerating rf cavity and the target. The growth in time width is a consequence of the energy spread in the beam ($\Delta E/E=0.001$). For 500 MeV protons delivered to the Target-2 Area this drift length is approximately 300 m.

Neutron energies are determined from time-of-flight measurements for which narrow beam pulse widths are required. The measurements described here were made using a newly developed operational mode in which one of the last nonaccelerating cavities was tuned to adjust the phase space of the beam in such a way as to produce a time focus at the target position (for diagnostic purposes) or at the detector position (for data acquisition).[10] With this new technique beam pulse widths of 300 ps were observed at the target position.

Neutrons were detected in a 7.5 cm$\times$25 cm$\times$50 cm plastic scintillator coupled at both ends to RCA C31024 photomultiplier tubes. An intrinsic time resolution of about 300 ps FWHM has been obtained with this detector for normally incident cosmic ray muons.[4,11] The neutron detector was positioned at the end of a 240 m collimated flight path. The length of this path was determined from the observed difference in arrival times of gamma rays and neutrons produced in the (p,n) target. These arrival times were measured with respect to a time reference derived from a nonintercepting beam pickoff just up stream from the target. Time, position and pulse-height signals were transmitted from the detector to the data acquisition system via a fiber optic link. All data were stored on event tapes for later off line analysis.

In Fig. 1 we present zero-degree spectra for the ^{13}C$(p,n)^{13}$N reaction at 492 MeV with and without the time focusing described above. In the time-focused mode, the overall time width of neutron groups observed at the detector position was about 600 ps, corresponding to about 1.1 MeV energy resolution for 492 MeV neutrons.

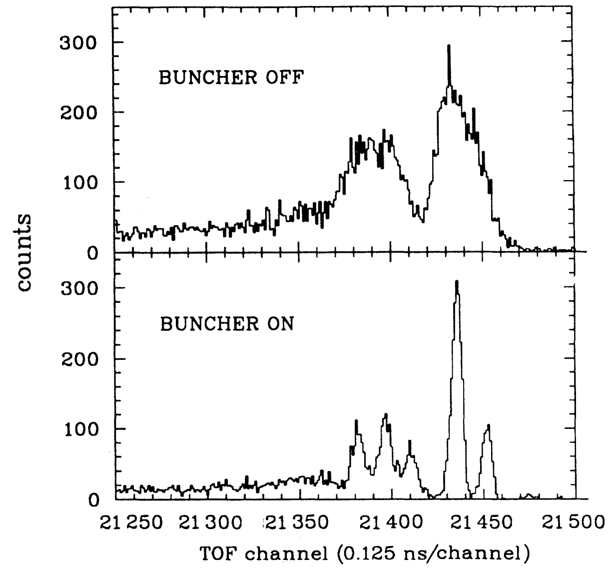

FIG. 1. Zero-degree spectra for the ^{13}C$(p,n)^{13}$N reaction at 492 MeV. The top spectrum has been obtained with a proton beam burst time resolution of about 1.2 ns, while the bottom spectrum was obtained with an optimized time resolution of about 300 ps (see text).

Targets studied included ^{7}Li, ^{11}B, and ^{12,13,14}C. Thicknesses and enrichments are presented in Table I. All targets were self-supported except for the ^{14}C target, which was made from amorphous carbon enriched to 89% in ^{14}C. This material was contained in an electroformed cell with 0.005 cm thick nickel walls. This is the same target used in the work presented in Ref. 3.

In Figs. 2–4 we present the observed zero-degree spectra for the cases studied. The dominant feature of all spectra is the excitation of states carrying GT strength. In the ^{14}C$(p,n)^{14}$N spectrum the isobaric analog state (2.31 MeV) appears as a small shoulder on the low excitation side of the strong GT transition at 3.95 MeV. A peak corresponding to the ^{12}C$(p,n)^{12}$N(g.s.) transition is also present in the ^{11}B(p,n) and ^{13,14}C(p,n) spectra because of the binder material used in the making of these targets.

TABLE I. Target compositions.

Isotope	Thickness (mg/cm^2)	Enrichment (%)
^{7}Li	534.0	99.9
^{11}B	185.0	95.0
^{12}C	48.4	99.9
^{13}C(492 MeV)	154.0	80.0
(590 MeV)	209.0	$\gtrsim 75.0$
^{14}C	170.0	89.0
	(+89 mg/cm^2 nickel)	

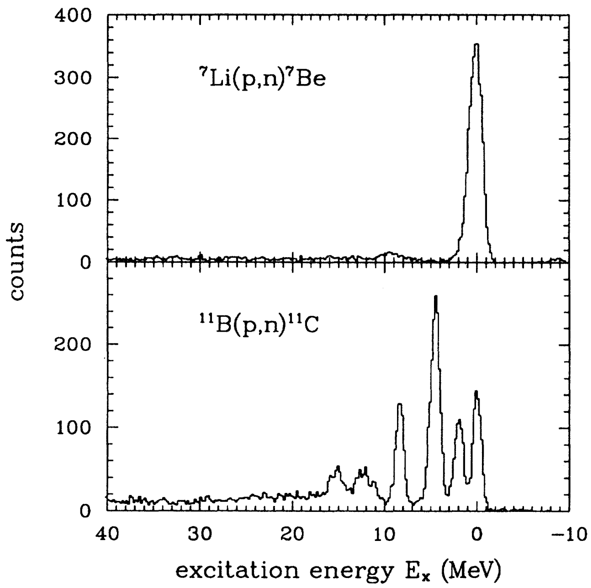

FIG. 2. Zero-degree (p,n) spectra for ^{7}Li and ^{11}B at $E_p=492$ MeV.

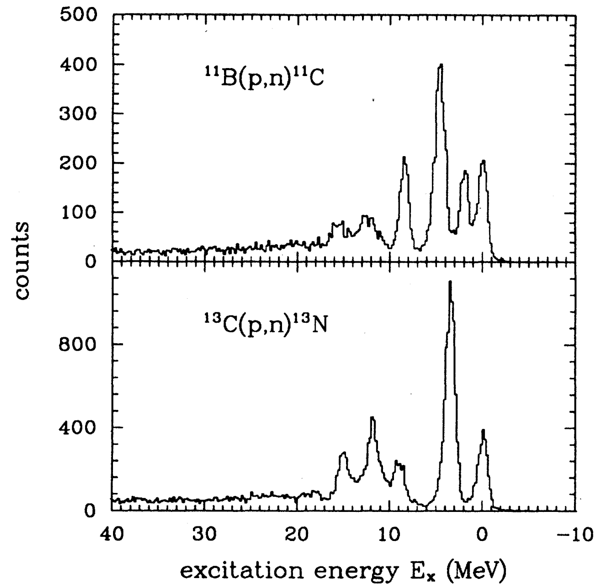

FIG. 4. Zero-degree (p,n) spectra for ^{11}B and ^{13}C at $E_p=590$ MeV.

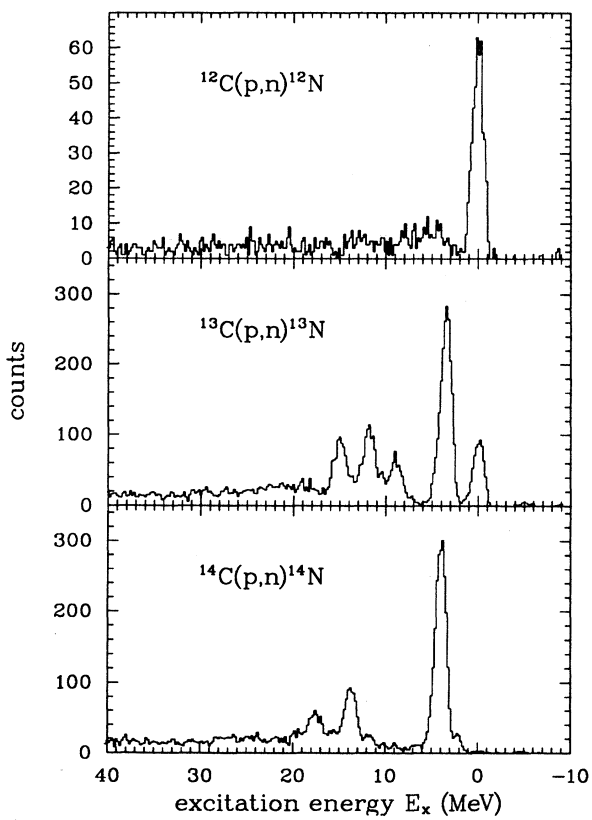

FIG. 3. Zero-degree (p,n) spectra at $E_p=492$ MeV for the carbon isotopes ^{12,13,14}C. An overall energy resolution of about 1.1 MeV was achieved.

Neutron yields were obtained by summing counts over the region of well resolved states, or by peak fitting with symmetric or asymmetric Gaussian line shapes for transitions that were not completely resolved. In this latter case the results from all three methods were used to obtain a final estimated yield and fitting uncertainty. This fitting uncertainty has been combined in quadrature with the statistical uncertainty in the results presented here. The fitting uncertainty is largest for the ^{14}C(p,n) 2.31-MeV transition, amounting to 6.9% compared to a statistical uncertainty of 4.3%.

III. ZERO-DEGREE CROSS SECTIONS

A. Normalization

The cross sections reported here have been normalized with respect to the zero-degree cross section for the ^{7}Li$(p,n)^{7}$Be(g.s.$+0.43$ MeV) reaction. This cross section has been obtained for $E_p=494$ MeV by integrating a measured angular distribution extending to $\theta_{\rm lab}=30°$ ($q_{\rm c.m.}=2.81$ fm^{-1}).[12] This integration procedure yields a value for the ratio of the zero-degree cross section to the integrated cross section:

$$I=\int_{q_{\rm min}}^{q_{\rm max}}\sigma(q)q\,dq$$

of $\sigma(0°)/I=76\pm1$ mb. The total cross section is related to this integral by

$$\sigma_{\rm tot}=\frac{2\pi}{k_i k_f}I\ ,$$

where k_i and k_f are the initial and final c.m. wave numbers. The total cross section for the ^{7}Li$(p,n)^{7}$Be(g.s. $+0.43$ MeV) reaction has been studied using activation techniques by D'Auria *et al.*[13] for energies between 25

TABLE II. Zero-degree center-of-mass (c.m.) cross sections for (p,n) reactions studied at 492 MeV.

Target	E_x (MeV)	$\sigma_{\mathrm{c.m.}}(0°)$ (mb/sr)	B(GT)	$B(F)$	$\hat{\sigma}_{\mathrm{GT}}$ (mb/sr)	$\hat{\sigma}_F$ (mb/sr)
^{7}Li	0.0	26.6±0.7	1.24±0.01	1		
	0.43		1.10±0.01			
^{11}B	0.0	4.91±0.22	0.345±0.008	1		
	2.0	4.01±0.18	0.40±0.02		10.1±0.9	
	4.32	9.68±0.24	0.95±0.05		10.3±0.8	
	4.80					
	8.10	4.32±0.16	0.43±0.02		10.2±0.8	
	8.43					
^{12}C	0.0	7.88±0.35	0.886±0.01		9.4±0.4	
^{13}C	0.0	4.26±0.16	0.199±0.004	1		
	3.51	12.60±0.27	0.83±0.03		15.3±1.1	
^{14}C	2.31	1.21±0.10		2		0.61±0.06
	3.95	16.7±0.4	2.76±0.11		6.1±0.4	

and 480 MeV. The extrapolated value for the activation total cross section at 494 MeV is 1.02±0.05 mb and the average value of the cross section integral for $80 \le E_p \le 480$ MeV is $I=0.348\pm0.008$. Combining this value with the above expression relating σ_{tot} and I yields $\sigma_{\mathrm{c.m.}}(0°)=26.6\pm1.7$ mb/sr. The uncertainty in this value includes the uncertainty in the total cross section, statistical uncertainty, and integration uncertainty (±4%).

The yields obtained for the most prominent neutron groups in all zero degree spectra were corrected for target thickness, live time and relative charge and then normalized to the measured ^{7}Li(p,n) yield and zero-degree cross section. The results are indicated in Table II. Also tabulated are the GT and Fermi transition strengths obtained from either beta decay lifetimes or from previous intermediate energy (p,n) data. See Ref. 2 for more details on how these values have been obtained.

B. Interpretation

In Ref. 2 it was noted that the differential cross section for pure Gamow-Teller or Fermi transitions may be represented as a product of three factors:

$$\sigma_\alpha=\hat{\sigma}_\alpha(A)F_\alpha(q,\omega)B(\alpha)\ , \tag{1}$$

where $\alpha=$GT or F. The "unit cross section" $\hat{\sigma}_\alpha$ is a nuclide-dependent proportionality factor, $B(\alpha)$ is the GT or F reduced transition strength, and $F_\alpha(q,\omega)$ describes the momentum-transfer and energy-loss dependence of the differential cross section distribution and by definition has a value of unity at $(q,\omega)=0$. For mixed GT+F transitions the cross section is just the incoherent sum $\sigma=\sigma_{\mathrm{GT}}+\sigma_F$.

The factor of primary interest in Eq. (1) is the unit cross section $\hat{\sigma}_\alpha(A)$. This factor may be described in the distorted-waves impulse approximation (DWIA) as a product of three additional factors[2]

$$\hat{\sigma}_{\mathrm{GT}}=K(E_p)N_{\sigma\tau}|J_{\sigma\tau}|^2\ , \tag{2}$$

for GT transitions, and

$$\hat{\sigma}_F=K(E_p)N_\tau|J_\tau|^2\ , \tag{3}$$

for Fermi transitions. The kinematic factor $K(E_p)$ is given by

$$K(E_p)=\frac{E_iE_f}{(\hbar^2c^2\pi)^2}\frac{k_f}{k_i}\ ,$$

where $E_i(E_f)$ is the initial (final) reduced c.m. total energy and $k_i(k_f)$ is the initial (final) wave number. The distortion factors $N_{\sigma\tau}$ and N_τ represent the ratio of distorted-waves to plane-waves cross sections, and $J_{\sigma\tau}$ and J_τ are the volume integrals of the spin-flip ($V_{\sigma\tau}$) and nonspin-flip (V_τ) isovector central interactions, respectively. The relationships expressed in Eqs. (3)–(4) are approximate in the sense that angular momentum transfers $\Delta L>0$ and noncentral parts of the interaction have been ignored and a short-range approximation for the knock-on exchange term is used. It is also assumed that $N_{\sigma\tau}$ and N_τ are meaningful numbers that can (in principle) be calculated.

With properly normalized experimental cross sections, Eqs. (1)–(3) may be used to obtain values for the interaction strengths $J_{\sigma\tau}$ and J_τ. Another quantity of interest that can be obtained from cross section ratios for transitions with known beta-decay strengths is[2]

$$R^2=\frac{\hat{\sigma}_{\mathrm{GT}}}{\hat{\sigma}_F}\ . \tag{4}$$

According to Eqs. (2) and (3) this quantity may be interpreted as

$$R=\frac{|J_{\sigma\tau}|}{|J_\tau|}\left[\frac{N_{\sigma\tau}}{N_\tau}\right]^{1/2}\ . \tag{5}$$

Provided that a suitable calculation of the distortion-factor ratio can be made, this quantity yields the ratio of spin-flip to nonspin-flip interaction strengths. However, different reasonable choices for the optical potential can result in calculated values for the distortion factor ratio that differ by as much as ~20%. For this reason we will concentrate on the more meaningful ratio of unit cross

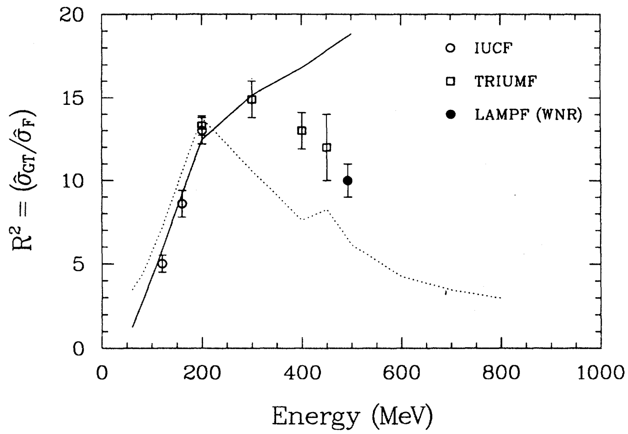

FIG. 5. Values for the ratio $R^2=\hat{\sigma}_{GT}/\hat{\sigma}_F$ obtained for the $^{14}C(p,n)$ reaction at energies between 100 and 800 MeV. The solid line represents results of calculations using a G matrix based on the Bonn potential, while the dashed line represents calculations using the t matrix interaction (see text).

sections defined in Eq. (4). Values for R may be obtained either from the ratio of pure GT and F cross sections (such as in ^{14}C), or from the ratio of a mixed GT+F cross section and one pure GT cross section (such as in ^{13}C).[2]

Experimental values of R^2 obtained from the $^{11}B(p,n)$, $^{13}C(p,n)$, and $^{14}C(p,n)$ reactions at 492 MeV and the $^{11}B(p,n)$ and $^{13}C(p,n)$ reactions at 590 MeV are presented in Table III. Experimental values obtained from $^{14}C(p,n)$ for energies between 100 and 492 MeV are presented in Fig. 5. The values for energies between 100 and 200 MeV are from Ref. 2, while values for energies between 200 and 450 MeV are from Ref. 3. The solid line in Fig. 5 corresponds to a calculation using a G-matrix interaction based on the Bonn potential (see next section).

Values for the GT and F unit cross sections are given in the last two columns of Table II. The enhanced unit cross section for the $^{13}C(p,n)$ reaction reported at lower energies[2] is also evident in the present data. Comparison of the results for ^{12}C and ^{14}C indicates a possible normalization problem with the ^{14}C data. The GT unit cross section for this target is about 60% smaller than that for ^{12}C, which is a much larger difference than that expected from normal mass-dependence effects.[2] A possible explanation for this problem is a beam spot larger than the 1.2 cm target width. This would not affect the results for the other targets, which had much larger areas, or the ^{14}C cross section ratios.

TABLE III. Values for R^2 at 492 and 590 MeV.

Target	E_p (MeV)	R^2
^{11}B	492	7.3±2.3
	590	9.4±3.6
^{12}C	492	
^{13}C	492	12.9±2.7
	590	9.9±1.4
^{14}C	492	10.0±1.0

IV. THEORETICAL CALCULATIONS FOR $^{14}C(p,n)^{14}N$ TRANSITIONS

In recent papers[5] cross section calculations for the $^{14}C(p,n)^{14}N$ IAS transition and 3.95-MeV GT transition have been reported for energies up to 450 MeV. These calculations have been extended to 500 MeV for the present paper; details are given in Ref. 5 so that only a brief account is given here.

Three NN interactions were considered: (a) the free t-matrix interaction of Ref. 14, based on the SP84 NN phases of Ref. 15, (b) the density dependent G-matrix interaction[16] based on the Paris potential,[17] and (c) an unpublished[18] density-dependent G-matrix interaction (HM86) based on the Bonn potential.[19] The DWIA calculations are nonrelativistic and include direct and exchange terms explicitly with central, spin-orbit and tensor parts for each interaction.

The optical potentials have been calculated using a folding model with the corresponding t- or G-matrix interaction. We show in Fig. 5 only the results using the G-matrix based on the Bonn potential, which yields the best agreement. The 500-MeV point was calculated using the 425-MeV G matrix. This extrapolation is shown for comparison, but it is not of course well justified, especially since the Bonn potential was only fit to N-N data up to 300 MeV. Calculations using other interactions and optical potentials for energies below 450 MeV are presented in Ref. 5.

The evaluation of $J_{\sigma\tau}$ and J_τ or the ratio of these quantities from the data assumes the exact validity of Eqs. (3)–(4). Since we know that they are only approximately valid and, as indicated in Ref. 5, J_τ is strongly energy and density dependent, we prefer instead to compare the measured and calculated values for the cross sections or to compare the ratio $R^2=\hat{\sigma}_{GT}/\hat{\sigma}_F$. Such a comparison is made in Fig. 5. Relativistic calculations are presented in Ref. 6 for the ratio $J_{\sigma\tau}/J_\tau$; however, no cross section estimates are given there, so a direct comparison to our data cannot be made.

Calculations for 500 MeV using the t-matrix interaction[14] give values $\hat{\sigma}_F=0.99$ mb/sr and $\hat{\sigma}_{GT}=5.9$ mb/sr as compared with the values 0.42 mb/sr and 7.8 mb/sr obtained with the G matrix based on the Bonn potential. It should be noted that at *this* energy, the different calculated results for the Fermi transition using the HM86 and SP84 interactions arises primarily from differences in the interactions at zero density. In particular, calculations using the isovector part of the G matrix evaluated at zero density $[G_\tau(0)]$ differ by <20% from those using the full density-dependent interaction. On the other hand, calculations of $\hat{\sigma}_F$ using $G_\tau(0)$ and the free SP84 interactions differ by about a factor of 2. In contrast, the calculated $\hat{\sigma}_F$ at 300 MeV using $G_\tau(0)$ and the SP84 t matrix differ by about 2% whereas the calculated $\hat{\sigma}_F$ using the full $G_\tau(\rho)$ is smaller than that using $G_\tau(0)$ by about 20%.

V. SUMMARY AND CONCLUSIONS

We report measurements of zero-degree (p,n) cross sections at 492 and 590 MeV for five p-shell nuclei. The energy resolution obtained was about 1.1 MeV, sufficient to resolve several discrete final states of interest. The cross sections have been normalized (with an uncertainty of about $\pm 7\%$) relative to an empirical value for the ^{7}Li$(p,n)^7$Be(g.s.$+0.42$ MeV) zero-degree cross section.

The zero-degree cross sections for GT and Fermi transitions are used to extract values of the corresponding unit cross sections $\hat{\sigma}_{GT}$ and $\hat{\sigma}_F$, which for the case of the ^{14}C$(p,n)^{14}$N reaction are compared with theoretical calculations. Calculations of $\hat{\sigma}_F$ using a free t-matrix interaction are about a factor of 2 larger than the same calculations with a density-dependent G-matrix interaction at 500 MeV and $\rho=0$. However, calculations for $\hat{\sigma}_{GT}$ are very similar for three different NN interactions, indicating the sensitivity of the calculated Fermi interaction to theoretical techniques used to construct this part of the NN effective interaction. Indeed, previous discrepancies[3,4] observed in the comparison between theoretical and empirical *ratios* appear largely due to uncertainties in calculated values of J_τ. At lower energies much of the discrepancy between the HM86 and SP84 interactions can be ascribed to the suppression of G_τ with increasing density. At 500 MeV intrinsic differences between these interactions dominate. It is suggested that a better comparison between experimental and theoretical calculations may be made with the quantities $\hat{\sigma}_{GT}$ and $\hat{\sigma}_F$, since the factorization assumed in Eqs. (2)–(3) is not used explicitly.

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