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Zero degree cross section for the reaction $^{14}C(p,n)^{14}N_{2.31}$, $^{14}N_{3.95}$ at 200, 300, and 450 MeV

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We have measured the zero-degree cross sections for the $^{14}C(p,n)$ reaction leading to the (2.31+3.95) MeV states in ^{14}N at energies of 200, 300, and 450 MeV. Cross sections for the Fermi transition to the 2.31 MeV state and for the Gamow-Teller transition to the 3.95 MeV state have been extracted using earlier measurements of the cross-section ratios. The results are compared with calculations using G-matrix effective interactions based on the Paris potential, and on one of the Bonn potentials, and a t-matrix effective interaction derived from nucleon-nucleon phase shifts. The best fit to both the present results and earlier results at lower energies is provided by calculations based on the Bonn potential.

The cross section for a nuclear reaction is, in general, a function of the effective interaction between the incoming or outgoing particles and the target nucleus, and of the structure of the states involved in the reaction. At incident energies greater than about 100 MeV, the impulse approximation[1] provides a reasonable reaction model, and a comparison between measured cross sections and model predictions may be used to investigate nuclear structure or effective interactions.[2]

Studies of the (p,n) reaction at intermediate energies have shown that the cross section at small momentum transfer is dominated by Gamow-Teller (GT) transitions,[3] with $S=1$, $L=0$, $T=1$. For a target nucleus with spin zero, the transition to the isobaric analogue of the target ground state proceeds via the Fermi interaction, with $S=0$, $L=0$, $T_i=T_f>0$.

The reactions $^{14}C(p,n)^{14}N^*(2.31\ \mathrm{MeV})$ and $^{14}C(p,n)^{14}N^*(3.95\ \mathrm{MeV})$ have now been extensively studied to determine the energy dependence of the Fermi and GT effective interactions, respectively.[4] In addition, measurements between 200 and 450 MeV (Ref. 5) have provided a determination of the ratio of the effective interaction strengths. The present measurement extends these earlier results to provide a determination of the magnitudes of the Fermi and GT effective interactions separately at 200, 300, and 450 MeV.

Measurements of the (p,n) cross section were carried out using the TRIUMF charge exchange facility.[6] With this system, the beam may be momentum dispersed to control the energy spread of the beam incident on a strip target, and hence, provide optimum resolution. Alternatively, the beam may be focused to an achromatic spot about 2 mm in diameter on the target to permit accurate current integration. The achromatic tune was used in these measurements, with beam currents between 250 nA at 200 MeV and 65 nA at 450 MeV.

In principle, cross sections are determined absolutely from a knowledge of count rate, beam current, target thickness, and detector solid angle. In fact, for (p,n) measurements with a recoil proton radiator, the effective solid angle of the magnetic spectrometer is difficult to determine with high precision, and the cross sections for the ^{14}C target were determined relative to that from a ^7Li target, using the previously determined value of the cross section for the $^7Li(p,n)^7Be(\mathrm{g.s.}+0.43\ \mathrm{MeV})$ reaction.[7] Wire counter efficiencies and system deadtime were monitored during data acquisition, and corrections applied to measured count rates. The proton beam striking the target was bent through 20° and focused to a local shielded dump where it was measured with a charge integrator. The ratio of corrected count rate to integrated current was reproducible to about 3% in successive measurements.

The ^{14}C target was the same as that used in earlier measurements of cross-section ratios.[5] It was fabricated of elemental carbon containing 89% ^{14}C (as determined by mass spectrometer) with the remainder ^{12}C. This material was contained in a can of natural nickel approximately $3\times1.26\times0.5$ cm in dimension, with wall thickness

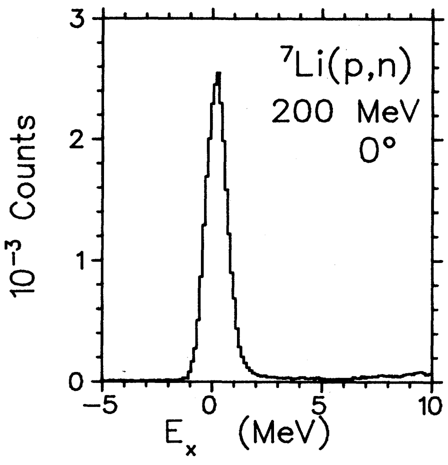

FIG. 1. Neutron spectrum from the ^{7}Li$(p,n)^7$Be reaction. The small tail on the groups leading to the ground and 0.43-MeV states arises from beam-energy spread.

40 mg/cm^2. The total thickness of the carbon target material was 170 ± 15 mg/cm^2. The lithium target was of lithium metal containing >99.9% ^{7}Li, 118 mg/cm^2 in thickness.

Count rates were measured at 0° at energies of 200, 300, and 450 MeV for both targets, and from these the ^{14}C(p,n) cross sections were determined assuming $d\sigma/d\Omega_{\rm lab}(0°) = 35 \pm 3$ mb/sr for the ^{7}Li$(p,n)^7$Be(g.s.+0.43 MeV) reaction at the three bombarding energies.[8]

Energy resolution at 450 MeV was determined mainly by the energy spread of the incident beam ($\Delta p/p \simeq 0.2\%$). At 200 MeV, beam energy spread and target energy loss made comparable contributions to the resolution, and although the fractional resolution was worse, the neutron groups of interest were better resolved at the lower energy. Typical spectra are shown in Fig. 1 for the ^{7}Li(p,n) reaction and in Fig. 2 for the ^{14}C(p,n) reaction. From Fig. 2 it is seen that the neutron groups populating the 2.31 and 3.95 MeV states in ^{14}N are resolved adequately at 200 MeV, less well at 300 MeV, and poorly at 450 MeV. In order to extract separate cross sections for the Fermi transition to the 2.31 MeV state and the GT transition to the 3.95 MeV state, counts in both peaks were summed, and a cross section determined for the sum. Earlier measurements of the ratio of the cross section[5] to these two states were then used to obtain the separate cross sections. The zero-degree cross sections are shown in Table I, along with the results of the other work[4] at 200 MeV. A separate measurement with an empty nickel container identical to the one containing the ^{14}C target material showed that the nickel contributed about 0.2% to the counts in the GT peak, and about 1% to the counts in the Fermi peak.

The uncertainties quoted in Table I for the present results arise from counting statistics, uncertainties in beam integration (~4%) and uncertainties in earlier measurements of the cross-section ratios (Ref. 5). The last factor is important mainly for the Fermi transition and amounts to 4% at 200, 7% at 300, and 16% at 450 MeV in that

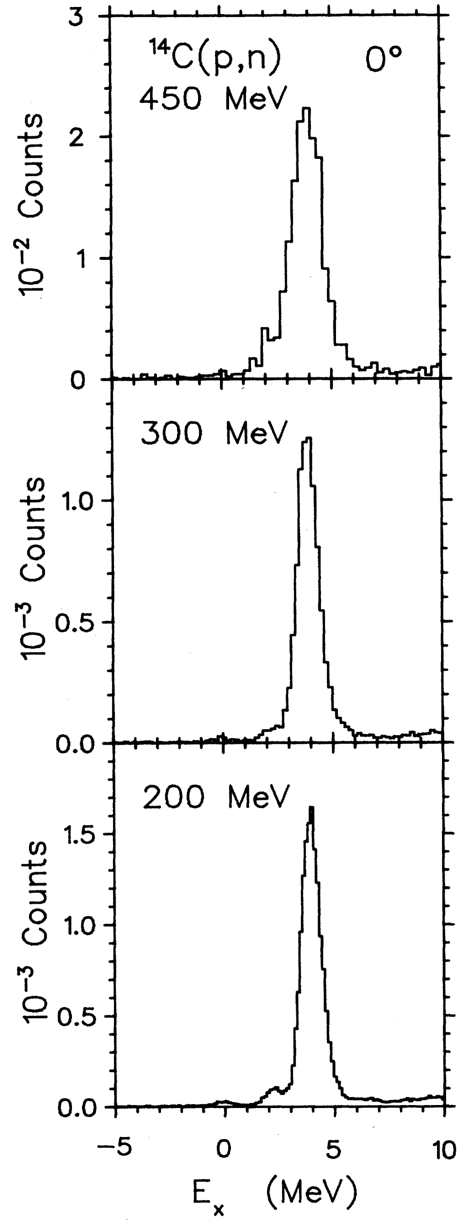

FIG. 2. Neutron spectra of the ^{14}C$(p,n)^{14}$N reaction at 200, 300, and 450 MeV. The line shape is assumed to be the same as for the ^{7}Li(p,n) measurements.

TABLE I. Cross sections for GT and Fermi transitions in ^{14}C(p,n).

E_p	$\sigma_{\rm c.m.}(0°)_{2.31}$ (mb/sr)	$\sigma_{\rm c.m.}(0°)_{3.95}$ (mb/sr)
200	1.2 ± 0.10 [a]	21.5 ± 1.9 [a]
	1.0 ± 0.06 [b]	18.3 ± 0.7 [b]
300	0.9 ± 0.08 [b]	19.5 ± 1.0 [b]
450	1.2 ± 0.21 [b]	20.3 ± 1.2 [b]

[a]Reference 4.
[b]Present results, statistical uncertainties only.

case. In addition, all results are subject to a systematic uncertainty of about 7% in the ^{7}Li(p,n) calibration cross section, and one of about 9% in the ^{14}C target thickness.

Calculations of the zero degree cross sections for the Fermi and GT transitions of interest have recently been reported by Nakayama and Love.[9] In these calculations, three different effective interactions were used: G-matrix interactions based on one of the Bonn potentials[10] and on the Paris potential,[11] and a t-matrix interaction[12] based on nucleon-nucleon phase shifts. Nuclear transition densities were taken from results of Cohen and Kurath,[13] with that for the GT transition scaled to give the observed GT strength $B(\mathrm{GT})=2.8$. Optical potentials were calculated from a folding model, using the corresponding effective interaction. In addition, for energies below 200 MeV, calculations for the Bonn potential were carried out using phenomenological optical potentials. The results of these calculations along with measured cross sections are shown in Figs. 3(a) and 3(b). Results of earlier measurements at energies up to 200 MeV are also shown. Errors indicated on the data points represent statistical uncertainties only. Possible systematic errors arising from uncertainties in target thickness and in the magnitude of the ^{7}Li(p,n) calibration cross section amount to about 13% for the data in the present measurement.

At 200 MeV, the GT cross section in this measurement is 15% less than the earlier result from Ref. 4. Part of the difference may be ascribed to the fact that the ^{7}Li(p,n) cross section was assumed to be 37 mb/sr in Ref. 4 rather than the value of 35 mb/sr used in this work. Between 200 and 450 MeV the GT cross section shows little energy dependence, in agreement with the results of all three model calculations. This is also consistent with a measurement of the energy dependence of the GT effective interaction between 200 and 400 MeV in the ^{28}Si(p,p') reaction.[14] The magnitude of the cross section is reproduced best by the G-matrix calculation using the Bonn potential if only statistical uncertainties in the data are considered. If possible systematic errors are included, then any of the model calculations could provide a reasonable fit to the data.

For the Fermi transition to the 2.31 MeV state in ^{14}N, the data are in reasonable agreement with calculations based on the Bonn potential or the t-matrix model. At energies below 200 MeV, the increase in cross section is reproduced only by the calculation using the Bonn potential, and even in this case agreement at the lowest energies requires the use of empirical rather than self-consistent optical potentials. There is additional uncertainty in the calculated cross sections for the Fermi transition since the predicted Fermi strength shows a very significant dependence on the nuclear density for both the Bonn and Paris interactions. For the calculations in Ref. 9, the local density approximation was used to estimate this dependence. Although the strong density dependence may limit the validity of this approximation, this question was not investigated in the calculations. In contrast, it may be noted that the GT strength is almost independent of density for the energies of interest in these measurements.

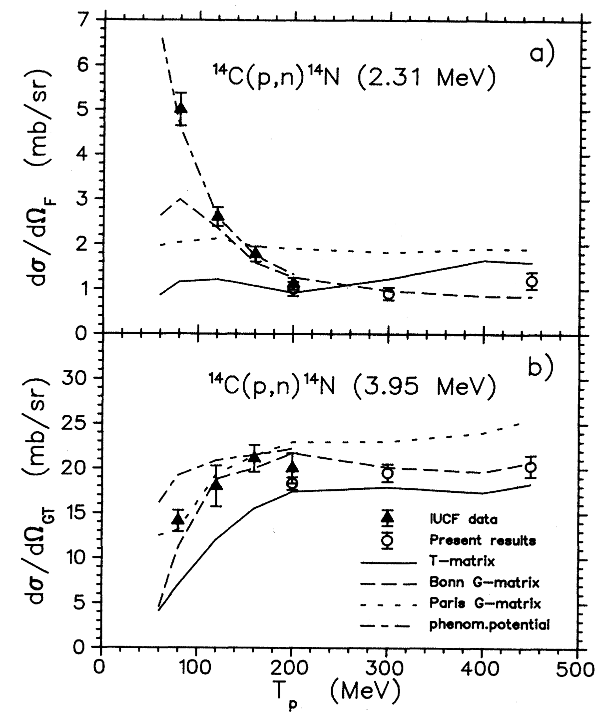

FIG. 3. Zero-degree cross section for the ^{14}C$(p,n)^{14}$N Fermi (2.31 MeV) and Gamow-Teller (3.95 MeV) transitions. Calculated curves are from Ref. 15. Calculations for energies below 200 MeV with phenomenological optical potential were carried out only for the Bonn G-matrix interaction. The △'s are results from Ref. 4 and the ○'s are the results of the present measurements. For comparison with the present results data from Ref. 4 have been renormalized assuming a zero-degree cross section of 35 mb/sr for the ^{7}Li(p,n)(g.s.+0.43 MeV) reaction rather than 37 mb/sr.

In summary, the present results, along with those of Ref. 5, provide a useful test of calculations of the nucleon-nucleus effective interaction over the energy range 100–450 MeV. The G-matrix calculation using one of the Bonn potentials provides the best overall fit to the data, but none of the calculations is completely satisfactory.

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