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# FORWARD PEAKING IN THE ONE NUCLEON TRANSFER REACTION Ca$^{48}$(N$^{14}$,C$^{13}$)Sc$^{49}$*

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## INTRODUCTION

In an effort to further the understanding of heavy ion induced single particle transfer, we have performed the (N$^{14}$,C$^{13}$) reaction on Ca$^{48}$ at 50 MeV bombarding energy and have compared results with published (He$^3$,d)[1,2] and (O$^{16}$,N$^{15}$)[3] data on the same nucleus. Whereas in (O$^{16}$,N$^{15}$) a few strong peaks were observed, all with the now familiar bell-shaped angular distributions, this high resolution magnetic spectrometer experiment was able to resolve all known Sc$^{49}$ levels below 5.8 MeV excitation. Strong levels appeared throughout the Sc$^{49}$ spectrum and raw relative level strengths were surprisingly similar to (He$^3$,d). Furthermore, several angular distributions showed peaks at forward angles, a phenomenon often seen in various forms in heavy ion DWBA calculations. Both forward peaked and normal bell-shaped angular distributions were fit well by no-recoil DWBA calculations, which also reproduced their apparent dependence on transferred L.

## EXPERIMENT

The (N$^{14}$,C$^{13}$) experiment was performed using the 50 MeV N$^{14}$ beam of the BNL Tandem Van de Graaff to bombard a 13 μg/cm$^2$ target enriched to > 97% purity in Ca$^{48}$. Reaction products were detected by three 50 mm x 10 mm silicon position sensitive detectors in consecutive focal planes of the MIT multigap spectrograph, now at BNL. Detector positions on the focal planes were staggered so that at any magnetic field setting, each counter viewed the same excitation region (of width ≈ 1-1.5 MeV). Angular distributions for C$^{13}$ in the 6$^+$ charge state were taken for $7\frac{1}{2} \le \theta_{lab} \le 37\frac{1}{2}^{\circ}$. Amplified signals for position times energy (XE) and energy (E) were digitally divided and stored in 64(X) x 256 (E) channel arrays in the Σ-7 computer. At each magnetic field setting, the mass-energy product (mE/q$^2$) is given by position on the focal plane. Therefore, after a detector is calibrated in energy, m/q$^2$ (and hence the identity) of any particle hitting the detector is well determined. The charge state distribution of the elastically scattered N$^{14}$'s was verified to

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be the same at all angles observed. The reaction $C^{13}$'s should behave similarly; the observed $6^+$ angular distribution is then proportional to that for all charge states.

One of the purposes of the experiment was to search for forward peaking, making use of a magnetic spectrometer almost mandatory. Other advantages of a spectrometer were crucial to the experiment's success: $Ca^{48}(N^{14},C^{13})$ has a positive Q value, and separation of particles by $mE/q^2$ in the spectrometer eliminated interference of the elastic peak with the $Q \approx 0$ region, as in a counter telescope. The fine resolution of the spectrometer (typically $\sim 75$ keV in this experiment) allowed extraction of angular distributions for all levels below 5.8 MeV, albeit with some ambiguity for the closest of them, $\sim 80$ keV apart.

## RESULTS

Figure 1 shows a composite $C^{13}$ spectrum at $\theta_{lab} = 22\frac{1}{2}^o$, comprising six overlapping individual counter spectra. Immediately striking is the range of excitation energy over which strong states are seen. The classical distance of closest approach is matched for the incoming and outgoing channels (an approximate condition for maximum cross section[4]) at $Q \approx -4$ MeV, corresponding to $E_x \approx 6$ MeV. Hence below this energy one expects the level strength envelope to decrease with $E_x$. In the analogous reaction $(O^{16},N^{15})$ done at 48 MeV,[3] matching takes place at $Q \approx -3$ MeV, just below the ground state, and there level strengths decrease sharply as $E_x$ increases, as is expected. In $(N^{14},C^{13})$ however, there is little evidence of such a decrease as $E_x$ departs from the optimum value. For this reaction the "Q-window" is broad enough to permit observation of at least 6 MeV of excitation. This broadness is in fact predicted by no-recoil DWBA calculations.

The strongest states in the spectrum are those known to be largely single particle in nature. (The ground state is $\pi f_{7/2}$ with a $(He^3,d)$ spectroscopic factor, S,= 1.0, and the 3.08 MeV level is $\pi p_{3/2}$ with S = 0.68.[1]) Particle-hole states (of both parities) are weakly seen. These results strongly reinforce the assumption implicit in use of DWBA that $(N^{14},C^{13})$ is mainly a direct one-step process. It is notable that raw relative level strengths in $(He^3,d)$[1] and $(N^{14},C^{13})$ match very closely, (Fig. 2) despite strength variations over two orders of magnitude within each reaction. $(N^{14},C^{13})$ also weakly excites two known $Sc^{49}$ levels not previously seen in $(He^3,d)$. Their excitation in this experiment may give an indication of the strength of multistep processes.

The semiclassical strong absorption model predicts a single peak in all angular distributions at an angle corresponding to grazing collision. The five strongest $Sc^{49}$ levels had such angular distributions, with one notable exception: the ground state showed a higher peak at the most forward angle observed, 7½°. Since data were taken simultaneously at 7½°, 15°, and 22½°, and the relative solid angles of all gaps were carefully measured with Rutherford scattering of 50 MeV $N^{14}$ from thin tantalum and gold targets, and since the forward peaking was observed in several runs, these data are presented with confidence. Selection rules for $(N^{14},C^{13})$ (in the no recoil approximation) dictate that only the $\pi f_{7/2}$ ground state is populated by $L = 4$, offering the intriguing possibility that angular distributions are influenced by L value as with light ions. If tentative spin assignments are correct[2] the other four strongest levels would be populated by $L \leq 2$.

## INTERPRETATION

To test the L-dependence of calculated angular distributions, DWBA calculations were carried out for $(N^{14},C^{13})$ using the heavy ion finite range code DRC,[5] which makes no recoil correction. Optical parameters were obtained from fits to measured elastic scattering of 50 MeV $N^{14}$ and $C^{13}$ from $Ca^{48}$ (Fig. 3). There was considerable degeneracy in parameters which fit the elastic data, in particular very little sensitivity to the imaginary well depth was found. A set of parameters which gave good $\chi^2$ was $V = 70$ MeV, $W = 10$ MeV, and $a = 0.5$ fm in both channels, and $r_o = 1.236$ and 1.219 fm in the incoming and outgoing channels respectively for both real and imaginary wells. These absorptive wells are considerably shallower than those used in most other heavy ion work, but weak absorption has been instrumental in reproducing isotope-dependent variations in $Ni(O^{18},O^{16})$ angular distributions at this laboratory.[6] In the DWBA calculation the transferred proton was taken to be bound in $N^{14}$ and $Sc^{49}$ with the appropriate separation energies in wells of $r_o =$ 1.25 fm and $a = 0.65$ fm. The calculations did indeed show an L dependence for angles forward of ~ 15° (c.m.). Above this angle $L = 0$, 2, and 4 were quite similar in general shape, but the most forward peak appeared at 10° for $L = 4$ and at 6° for $L = 2$ (within the range $0 \leq E_x \leq 3$ MeV). This 4° difference was crucial in reproducing the experimentally seen rise in the ground state yield and fall of the 3.08 MeV $p_{3/2}$ (and other $L \leq 2$) yields at the most forward data point (9°). Figure 3 shows how accurately (probably fortuitously so) the calculations reproduce the experimental angular distributions. The pattern of small oscillations superimposed on large oscillations suggests passage of the $N^{14}$ through the nuclear surface region without strong absorption. There is no strong experimental evidence yet for the existence of the small oscillations, and it is expected that inclusion of recoil effects in the calculations would dampen them. The narrow forward peak, however, appears to be authentic. Although inclusion of recoil could degrade these fits, it would not be expected to change the prime conclusions to be drawn from Ref. 6 and the present paper. Absorption of heavy ions in the nuclear interior appears to be weaker than has been previously recognized. In addition this work demonstrates that weak absorption leads to dependence of angular distributions on form factor shapes, i.e., on transferred L.

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## FIGURE CAPTIONS

Fig. 1. Spectrum of $Ca^{48}(N^{14},C^{13})$ at $\theta_L = 22\frac{1}{2}^{\circ}$. This spectrum comprises six individual overlapping position-sensitive detector spectra, each taken at a slightly different spectrometer field setting. These have been normalized to each other leaving the vertical scale arbitrary.

Fig. 2. Comparison of raw level strengths in $(N^{14},C^{13})$ and $(He^{3},d)$. For those levels seen in both reactions relative strengths generally match within a factor of 2, except for the ground state, ~4.5 times stronger in $(N^{14},C^{13})$ on this scale.

Fig. 3. a and b Elastic scattering of $N^{14}$ and $C^{13}$ from $Ca^{48}$ at 50 MeV. The former data were taken in the multigap and the latter in a scattering chamber.

c and d $Ca^{48}(N^{14},C^{13})$ angular distributions to the ground state ($L = 4$) and 3.08 MeV state ($L = 2$) of $Sc^{49}$.

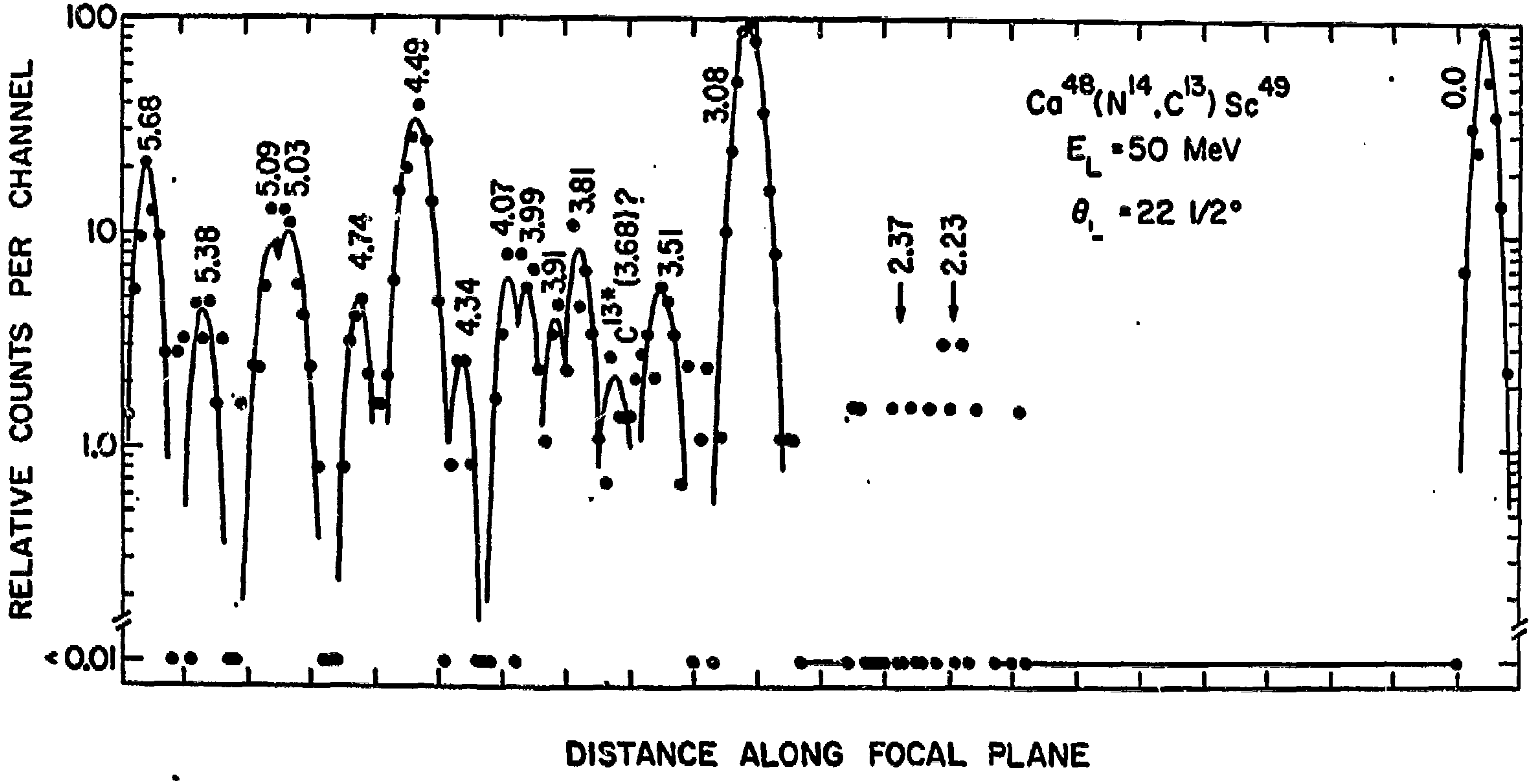
RELATIVE COUNTS PER CHANNEL
100
10
1.0
<0.01
DISTANCE ALONG FOCAL PLANE
5.68
5.38
5.09
5.03
4.74
4.49
4.34
4.07
3.99
3.91
3.81
$C^{13*}$(3.68)?
3.51
3.08
2.37
2.23
0.0
$Ca^{48}(N^{14},C^{13})Sc^{49}$
$E_L$ = 50 MeV
$\theta_L$ = 22 1/2°

Fig. 1

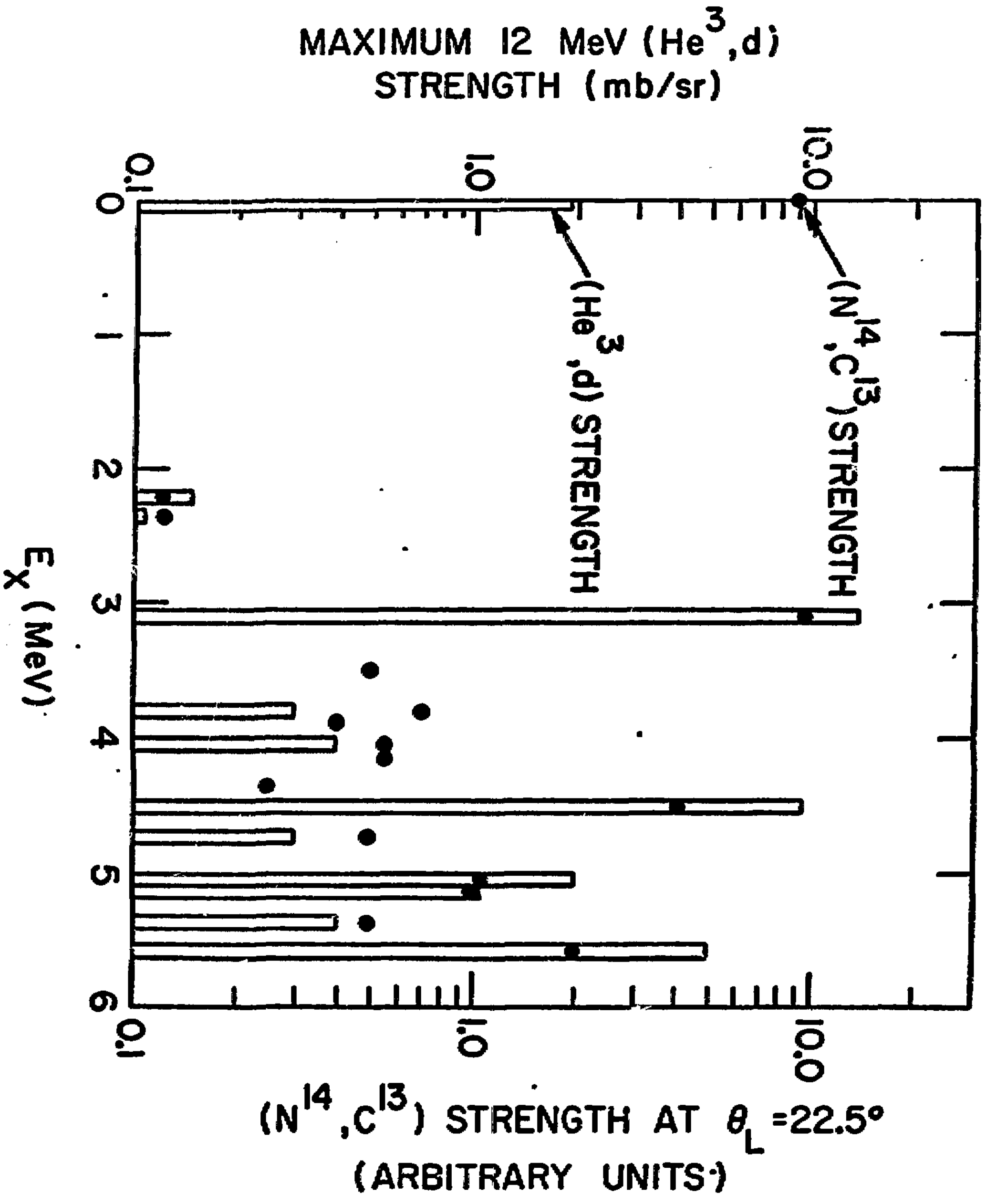
MAXIMUM 12 MeV ($He^3$,d) STRENGTH (mb/sr)
0.1
1.0
10.0
($He^3$,d) STRENGTH
($N^{14}$,$C^{13}$) STRENGTH
$E_X$ (MeV)
0
1
2
3
4
5
6
0.1
1.0
10.0
($N^{14}$,$C^{13}$) STRENGTH AT $\theta_L$ =22.5°
(ARBITRARY UNITS)

Fig. 2

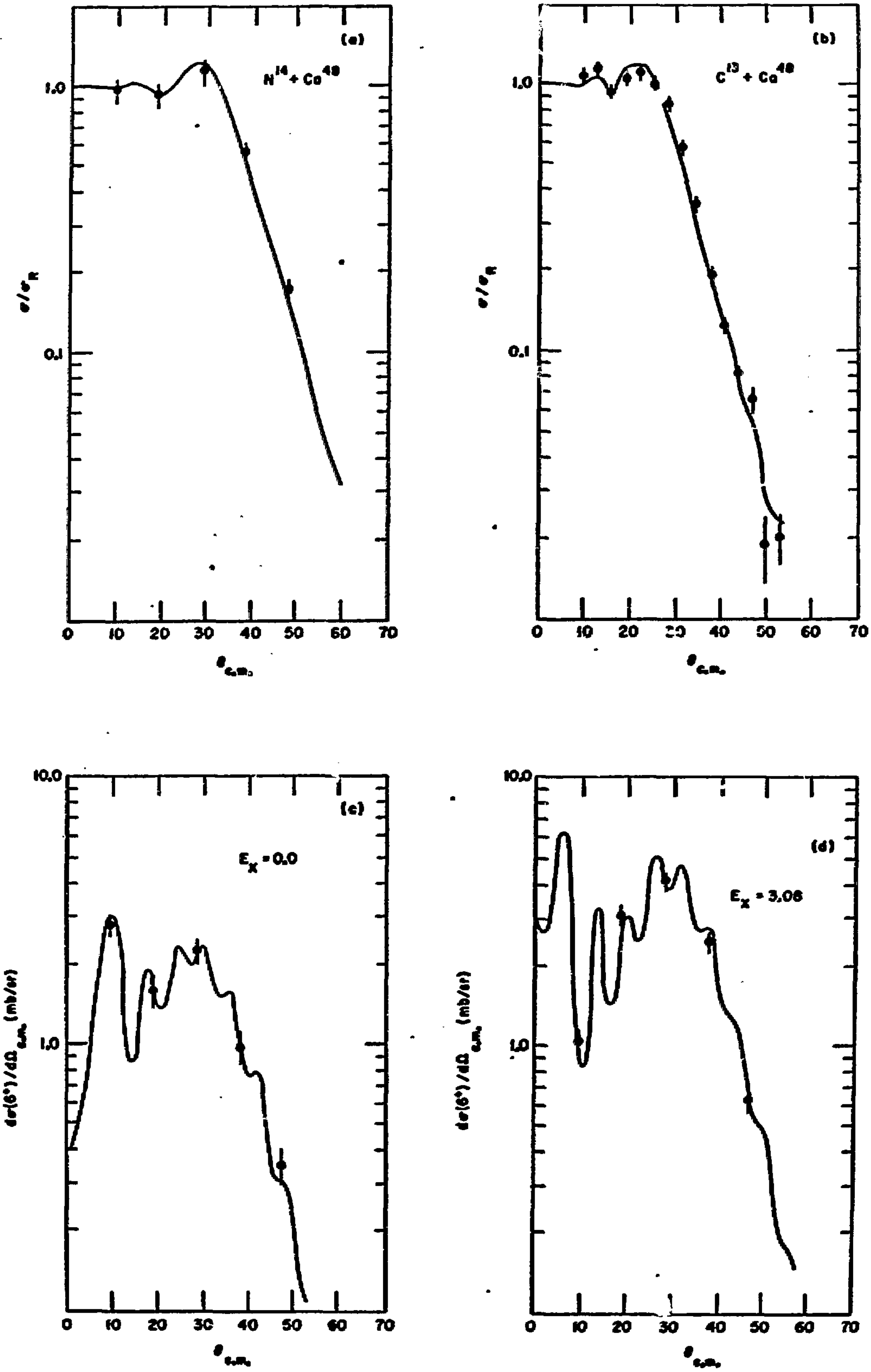
(a)
$N^{14} + Ca^{48}$
$\sigma/\sigma_R$
1.0
0.1
0
10
20
30
40
50
60
70
$\theta_{c.m.}$
(b)
$C^{13} + Ca^{48}$
$\sigma/\sigma_R$
1.0
0.1
0
10
20
30
40
50
60
70
$\theta_{c.m.}$
(c)
$E_X = 0.0$
$d\sigma(6^+)/d\Omega_{c.m.}$ (mb/sr)
10.0
1.0
0
10
20
30
40
50
60
70
$\theta_{c.m.}$
(d)
$E_X = 3.08$
$d\sigma(6^+)/d\Omega_{c.m.}$ (mb/sr)
10.0
1.0
0
10
20
30
40
50
60
70
$\theta_{c.m.}$

Fig. 3