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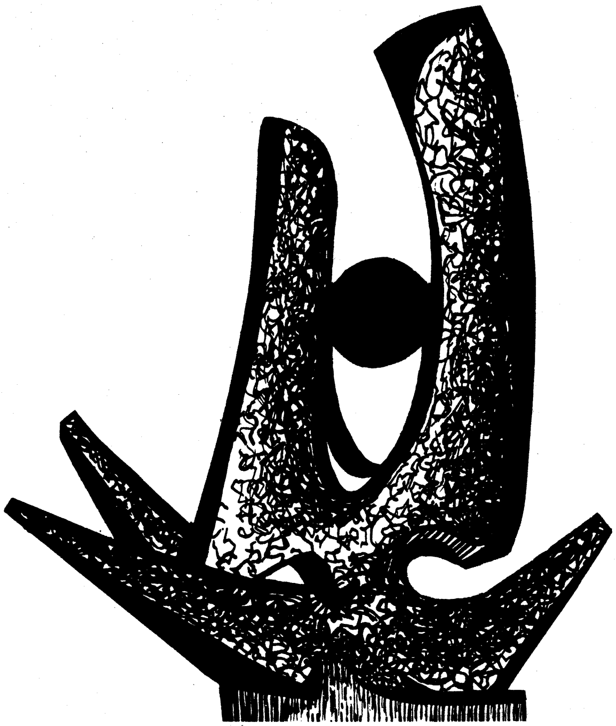
HEAVY ION REACTIONS AS SPIN PROBES

SAM M. AUSTIN, N. ANANTARAMAN and J.S. WINFIELD



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ABSTRACT

Heavy ion reactions can be powerful probes for spin-transfer strength in nuclei, provided their reaction mechanism is simple so that a correlation can be established between cross sections and the relevant matrix elements. We discuss the desirable features of heavy ion reactions in general and a series of tests of reaction mechanisms that have been carried out for two of the most favorable reactions: (^{6}Li, ^{6}He) and (^{12}C, ^{12}N). We establish that the (^{6}Li, ^{6}He) reaction is one-step in nature above 25 MeV/nucleon and establish a calibration function relating cross sections and Gamow-Teller matrix elements. We also find that the (^{12}C, ^{12}N) reaction is likely to be dominated by the one-step process above about 50 MeV/nucleon.

INTRODUCTION

Heavy ion charge exchange reactions offer several potential advantages over (p,n) and (n,p) reactions as spectroscopic tools for the study of Gamow-Teller(GT) and other spin dependent transitions in nuclei. Perhaps most important is the selectivity of the spin-transfer channel for certain projectile-ejectile choices: for example, the charge exchange reactions (^{6}Li,^{6}He) and (^{12}C, ^{12}N) both involve 0^+ to 1^+ transitions and hence will selectively excite $\Delta S = \Delta T = 1$ transitions. One then expects that backgrounds of $\Delta S = 0$ processes will be lower, facilitating observations of higher multipole strength that is overwhelmed by the underlying background in (p,n) reactions.

In a sense heavy ion reactions are complementary to nucleon induced reactions in that the larger absorption means that these reactions selectively sample the nuclear surface. This may be particularly advantageous when the transition density contains a node, as for the spin-isovector-monopole transition--the cross section should be relatively larger for heavy ion reactions, since contributions from the exterior and interior regions of the nucleus will not cancel.

There are also advantages on the experimental side. Reactions in both the β^+ and β^- direction are available with charged particles in the ingoing and outgoing channels. This will permit high resolution measurements using the spectrographs now operating at GANIL and under construction at the NSCL (MSU) which have energy resolutions of 2×10^{-4}. If the reactions are good spin probes at low energies, as (^{6}Li,^{6}He) is at 150 MeV, then resolutions of 30 keV or so should be possible. Such resolution will be particularly useful for studies of spin strength whenever it is important to resolve transitions to individual levels.

However, making use of these potential advantages requires that the reaction mechanism is understood and that it is simple so there is a strong correlation between the observed cross sections and the relevant matrix elements. This paper is devoted to tests of the reaction mechanism for the (^{6}Li,^{6}He) and (^{12}C,^{12}N). Both of these reactions have the desirable property that only the ground state of the product is particle stable, so the spectrum is not further complicated by projectile excitation peaks. Because the spin strength which couples ^{6}Li and ^{6}He is an order of magnitude larger than that which couples ^{12}C and ^{12}N, we expect that the (^{6}Li,^{6}He) reaction will be one-step in nature at a significantly lower energy than (^{12}C, ^{12}N). We have therefore concentrated most attention on the former reaction, with only a preliminary investigation of the latter.

There is a significant literature on heavy ion induced charge exchange reactions. However, with the exception of that described by Ellegaard at this Workshop, none has been at energies where one anticipates that the one-step mechanism should dominate. References to this (lower energy) work will not be given here, but can be found in Refs. (1) and (2).

EXPERIMENTS

The experiments described here have been carried out at the NSCL (Michigan State University), using beams from the K500 superconducting cyclotron and the S320 spectrograph. This spectrograph has relatively low resolution and is especially useful for giant resonance studies where bending power and spectral cleanliness are more important than resolution. Resolutions of about 1/600 were obtained, adequate for the work described here. We studied (^{6}Li,^{6}He) on targets of ^{7}Li, ^{12}C and ^{14}C at 14, 25 and 35 MeV per nucleon. In addition, ^{26}Mg and ^{90}Zr data were taken at 35 MeV/nucleon and for ^{90}Zr, also at 25 MeV/nucleon. The ^{12}C(^{12}C, ^{12}N)^{12}B reaction was studied at 35 MeV/nucleon. Spectra from (^{6}Li, ^{6}He) at 35 MeV/nucleon are shown in Fig. 1.

TESTS OF REACTION MECHANISMS

The tests we have carried out are of three principal types:

1) Comparisons of the ratio of cross sections to states in a given nucleus for which the ratio of GT strengths, B(GT), is known from ß decay. This comparison should be independent of many model uncertainties, but may not be sufficient to establish that the reaction is one-step in nature, since successive transfer reactions may also be proportional to GT strength in some cases (3).
2) Comparison with DWBA calculations to extract values of $V_{\sigma\tau}$ which can then be compared with results from (p,n) reactions.
3) Comparison of the dependence of cross section on B(GT) for a variety of nuclei. This comparison is particularly valuable because the observed correlation, if linear as is observed for intermediate energy (p,n) reactions (5), can serve as a calibration for the probe. One could read from this calibration the B(GT) associated with the cross section for an unknown transition. We devote most attention to this comparison.

Ratios of Cross Sections

The $^{14}C(^{6}Li, ^{6}He)^{14}N$ reaction leading to three states of ^{14}N is of particular interest. The 1^+ ground state transition has a B(GT) value, obtained from ß decay, of about 10^{-6} of that for the strong 3.95 MeV 1^+ level. For (^{6}Li, ^{6}He), the ratios obtained at a momentum transfer q = 100 MeV/c are 0.21, 0.15 and 0.11 at 14, 25 and 35 MeV/nucleon, respectively. Previous work (4) at 10 MeV/nucleon gives 0.3. While the observed decrease is encouraging, this test is not conclusive because higher multipoles (L=2) and tensor forces are known to contribute to this reaction, and do not follow the same selection rules as does ß decay. A better measure of the contribution of two-step processes is the ratio of the cross section for the 2.31 MeV 0^+ isobaric analog state (IAS) to that for the 3.95 MeV state: the $0^+ \rightarrow 0^+$ IAS transition can be mediated only by the non-local part of the exchange interaction in a one-step process and this is expected to be small near 0^o. This ratio observed is 0.1, 0.08, 0.05 and 0.05 at 10, 14, 25 and 35 Mev/nucleon, respectively, again suggesting that multistep processes are a factor of two smaller at the higher energies. A measure of the suppression of $\Delta S = 0$ amplitudes can be obtained by comparing this ratio with the value of 0.8 observed (6) for the $^{14}C(p,n)$ reaction at 35 MeV--this corresponds to a suppression of $\Delta S = 0$ strength by a factor of 16.

A similar test compares the ratio of the small-angle cross sections for the $^7Li(^6Li, ^6He)^7Be$ reaction leading to the two lowest states of ^7Be. The ratio of B(GT) for these states obtained from β decay is 1.18; the values obtained from $(^6Li, ^6He)$ at 2.5^o are 1.78±0.05, 1.34±0.07, and 1.08±0.06 at 14, 25 and 35 MeV/nucleon. Only at 35 MeV/nucleon is the observed ratio in agreement with that expected.

In summary, these results support the conclusion that the $(^6Li, ^6He)$ reaction is dominated by one-step processes at 35 (and possibly 25) MeV/nucleon.

Comparisons with DWBA

In this section we compare the observed cross sections and the results of Distorted Wave Born Approximation calculations, with the aim of determining whether a one-step description of the reaction is reasonable. The fitting parameters in this comparison are the strengths of the various parts of the two body interaction mediating the transition. If the transition is indeed one-step in nature, then we expect that the deduced interaction strengths will be comparable to those obtained from studies of nucleon induced reactions or deduced from theoretical studies.

Unfortunately, we do not expect to obtain a precise description of the observed cross section since the state of the art of available codes does not yet permit one to make calculations without further approximations beyond the DWBA. For example, in the $(^6Li, ^6He)$ calculations described below, exchange is included for the central part of the interaction, but not for the tensor part. In the case of the (^{12}C, ^{12}N) only the central direct amplitude is included. In addition optical model potentials are often not available for the precise energies and/or targets of the present measurements and we have had to make do with what is available in the literature.

The calculations for (^{6}Li, ^{6}He) were performed with a modified version of the code DWUCK (7) which allows for the finite size of the projectile system and includes central $V_{\sigma\tau}$(direct and exchange) and tensor (direct) terms in the interaction. The central interaction had a 1.0 fm range Yukawa form and the tensor interaction a $r^2\times$Yukawa form. Optical potentials obtained (8) from 156 MeV ^{6}Li scattering data were used. Further details for the (^{6}Li, ^{6}He) and ^{12}C(^{12}C, ^{12}N)^{12}B calculations are given in Refs. (2) and (1), respectively. Results for the ^{14}C(^{6}Li, ^{6}He)^{14}N reaction are shown in Fig. 2. We note that the calculations overpredict the cross section at small angles; this appears to be a general feature of the reaction at intermediate energies. In addition, a significant tensor interaction is necessary to fit the data. The values of interactions obtained by adjusting the central and tensor interactions to best fit the angular distributions for $\theta > 3^o$ are shown in Table 1. The values of the central interaction can be compared to the value of $V_{\sigma\tau} = 11.7 \pm 1.7$ MeV obtained (9) from (p,n) and (p,p') studies at similar MeV/nucleon. Given the approximations made, it is reasonable to conclude that the one-step DWBA calculation reproduces the magnitude and that one-step processes are dominant in the (^{6}Li, ^{6}He) reaction at 25 MeV/nucleon and above.

The results for the ^{12}C(^{12}C, ^{12}N)^{12}B reaction differ significantly (1). The interaction required to fit the data is $V_{\sigma\tau} \sim 30$ MeV, indicating that the cross section is about ten times larger than expected on the basis of one-step calculations and that the reaction must be dominantly two step in nature. We shall return to this result later.

(^{6}Li, ^{6}He) Cross Sections vs B(GT)

We have chosen to make this comparison at a momentum transfer of qR/R(^{14}C)=100 MeV/c, where q is the momentum transfer and R/R(^{14}C) is the sum of the projectile and target radii, divided by that for ^{6}Li+^{14}C. This point is at the second diffraction maximum and was chosen, in preference to smaller angles, because DWBA calculations fit the cross section in this angular region and in order to provide some flexibility in matching q among the different reactions. The results are shown in Fig. 3. There is a high degree of proportionality for all final states observed at 25 and 35 MeV/nucleon (at 14 MeV/nucleon the data are too limited for such a comparison, but, based on the tests described earlier, we doubt whether the reaction is one-step at this energy).

The results shown here appear to establish a calibration curve which permits the use of the (^{6}Li, ^{6}He) reaction to determine the value of B(GT) for an unknown transition from its measured cross section.

WHEN IS THE (^{12}C,^{12}N) REACTION ONE-STEP?

As noted above, the ^{12}C(^{12}C, ^{12}N)^{12}B reaction at 35 MeV/nucleon is dominated by two-step processes. However, one expects that the dominant two-step process, sequential transfer, will become less important as the bombarding energy increases. This follows from the decrease of transfer cross sections with increasing energy which in turn is a consequence of the decreasing overlap of the projectile and target momentum distributions (10). Here we attempt to answer the question: at what energy is the reaction dominated by one-step processes so that it can be used for spectroscopic investigations? Our particular interest in this point follows from the fact that many of the most interesting questions in spin physics involve transitions in the β^+ direction.

The technique is as follows. We calculate the energy variation of the one-step charge exchange process with the result shown in Fig. 4: the cross section first increases with bombarding energy and then reaches a plateau above about 35 MeV/nucleon (in this figure the value of $V_{\sigma\tau}$ is taken to be 11.7 MeV). Intuitively, one expects that the cross section for a sequential transfer process (e.g. $^{12}C \rightarrow {}^{13}N \rightarrow {}^{12}N$) is proportional to the product of the cross sections for the two transfer events. Adapting a model introduced by Madsen (11) for transitions leading to the IAS, we then assume that the sequential transfer cross section is $\sigma_{seq} \sim \sigma_1\sigma_2/\sqrt{E}$. The transfer cross sections are calculated using a finite range transfer code (SATURN-MARS (12)) and the above equation then yields the energy dependence of the sequential transfer process. This is also shown in Fig. 4 where σ_{seq} is normalized to our cross section measurement at 35 MeV/nucleon. We see that the one-step process should begin to dominate at about 50 MeV/nucleon. This is well above the energy of 25 MeV/nucleon at which (^6Li, ^6He) is found to be one-step, presumably because the projectile-ejectile transition strength is about a factor of ten smaller for $^{12}C \rightarrow {}^{12}N$. If the $^{12}C \rightarrow {}^{12}N$ strength were as large as that for $^6Li \rightarrow {}^6He$, then the one-step curve would be raised by a factor of ten, leading to one-step dominance by 35 MeV/nucleon. The present estimate is not very precise: effects of exchange, which would increase $\sigma_{one\text{-}step}$, have not been taken into account, nor may all sequential transfer routes have the same energy dependence as shown on Fig. 4. Nevertheless, it appears that one-step processes should dominate at energies readily available at GANIL and MSU Phase II.

MOMENTUM TRANSFER AND THE NATURE OF CHARGE EXCHANGE SPECTRA

The spectrum for ^{90}Zr(^6Li, ^6He) shown in Fig. 5 differs from forward angle spectra for high energy (p,n) reactions, in that the giant GT excitation near E_x=8.7 MeV appears to ride on a significant "background". The giant GT strength seen is as expected. The cross section for the 8.7 MeV peak, above the background drawn, is 4.0 times that for the 2.3 MeV peak, consistent with the ratio of 4.6±0.7 seen (13) in (p,n) reactions at 120 MeV. Since the 2.3 MeV cross section lies on the calibration line of Fig. 3, it appears that (^6Li, ^6He) provides a good measure of the giant GT strength.

It may be that the observed difference in background is related to the different momentum transfer q. In Fig. 6 we see that the value of q for various reactions on the same target depends on the bombarding energy <u>in MeV/nucleon</u>. Thus the value of q for the spectrum of Fig. 5 is comparable to that in 35 MeV proton induced charge exchange; indeed, the spectrum of Fig. 5 closely resembles the discovery spectrum (14) for the giant GT resonance taken at E_p=45 MeV. Another comparison might be with 120 MeV (p,n) results at 11^o for which qR is about the same as that in Fig. 5. At this value of qR, both L=1 and L=2 amplitudes are expected to contribute to the spectrum and it seems likely that the GT strength will ride on a background of higher multipoles. It is also possible that two-step processes contribute at the higher values of E_x.

A NEW SPIN PROBE FOR THE τ_z CHANNEL

Inelastic proton scattering has been a powerful technique for examining spin strength ("M1" transitions) in nuclei. At energies above 150 MeV, the interaction $V_{\sigma\tau}$ is sufficiently strong compared to the isoscalar interaction that 1^+ states are prominent at small angles, although for most medium and heavy nuclei they ride on a significant background at all angles and are hidden by the tail of the elastic peak at the most forward angles. The uncertainty in the strength of the isoscalar interaction V_σ also contributes to the uncertainty in the extracted strength. The (^{6}Li,^{6}Li',γ) reaction, where ^{6}Li is initially left in its 3.56 MeV 0^+ T=1 state, and the decayed ^{6}Li and the decay γ are detected in coincidence, may be superior to (p,p') in several respects. The quantum numbers of the ^{6}Li transition involved (1^+T=0 → 0^+T=1) guarantee that ΔS=ΔT=1 (no isoscalar contribution to 1^+ states and no isovector, non-spin-transfer background) and the coincident γ detection should eliminate the elastic tail. Since there are no other particle stable states in ^{6}Li and the decay γ ray is essentially isotropic, (^{6}Li,^{6}Li',γ) is the most favorable reaction for the application of this technique. A preliminary experiment has been approved for the NSCL.

SUMMARY AND CONCLUSIONS

We conclude that heavy ion charge exchange reactions may play a useful role in spin physics, especially for transitions where high resolution or higher multipole transitions are of prime interest. We have shown that the $(^{6}\mathrm{Li},{}^{6}\mathrm{He})$ reaction is one-step in nature above about 25 MeV/nucleon and have established a linear calibration curve relating cross section and GT strength. The $(^{12}\mathrm{C},\ {}^{12}\mathrm{N})$ reaction is found to be dominated by two-step reactions at 35 MeV/nucleon, but estimates indicate that the one-step process should dominate above about 50 MeV/nucleon.

It is suggested that the $(^{6}\mathrm{Li},\ {}^{6}\mathrm{Li}'\ \gamma)$ reaction, with coincident detection of ^{6}Li and the decay gamma ray, may probe isovector spin strength better than high energy (p,p') because of the elimination of the isoscalar contribution and the elastic tail.

ACKNOWLEDGMENTS

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REFERENCES

(1) J.S. Winfield, N. Anantaraman, S.M. Austin, L.H. Harwood, J. van der Plicht, H.-L. Wu and A.F. Zeller, Phys. Rev. C33 (1986) 1333.

(2) N. Anantaraman, J.S. Winfield, S.M. Austin, A. Galonsky, J. van der Plicht, C.C. Chang, G. Ciangaru and S. Gales, Michigan State University Cyclotron Laboratory preprint no. MSUCL-565; submitted to Phys. Rev. Lett.

(3) W.R. Wharton and P.T. Debevec, Phys. Rev. C11 (1975) 1963.

(4) C.D. Goodman, W.R. Wharton and D.C. Hensley, Phys. Lett. 64B, (1976) 417.

(5) C.D. Goodman, C.A. Goulding, M.B. Greenfield, J. Rapaport, D.E. Bainum, C.C. Foster, W.G. Love and F. Petrovich, Phys. Rev. Lett. 44 (1980) 1755.

(6) T.N. Taddeucci, R.R. Doering, A. Galonsky, and S.M. Austin, Phys. Rev. C29 (1984) 764.

(7) G. Ciangaru, R.L. McGrath and F.E. Cecil, Nucl. Phys. A380 (1982) 147.

(8) J. Cook, H.J. Gils, H. Rebel, Z. Majka and H. Klewe-Nebenius, Nucl. Phys. A388 (1982) 173.

(9) S.M. Austin, The (p,n) Reaction and the Nucleon-Nucleon Force, edited by C.D. Goodman et al. (Plenum, New York, 1980), p. 203.

(10) W. von Oertzen, Phys. Lett. 151B (1985) 95.

(11) V.A. Madsen and V.R. Brown, The (p,n) Reaction and the Nucleon-Nucleon Force, edited by C.D. Goodman et al. (Plenum, New York, 1980) p. 433.

(12) T. Tamura and K.S. Low, Comp. Phys. Commun. 8 (1974) 349.

(13) D.E. Bainum, J. Rapaport, C.D. Goodman, D.J. Horen, C.C. Foster, M.B. Greenfield and C.A. Goulding, Phys. Rev. Lett. 44 (1980) 1751.

(14) R.R. Doering, A. Galonsky, D.M. Patterson and G.F. Bertsch, Phys. Rev. Lett. 35 (1975) 1691.

Table 1. Values of effective interactions deduced from the (^{6}Li,^{6}He) reaction.

Final state	E/A (MeV)	$V_{\sigma\tau}$ (a) (MeV)	$V_{Ten}/V_{\sigma\tau}$ (b)
^{12}N 0.00 MeV	35	6	0.17
^{14}N 3.95 MeV	35	14	0.135
^{14}N 3.95 MeV	25	12	0.135 c)
^{14}N 3.95 MeV	14	23	0.135 c)
^{26}Al 1.06 MeV	35	15	0.16

a) For 1.0 fm range Yukawa interaction.

b) For $r^2\times$Yukawa tensor interaction. See Ref. (7) for details.

c) Tensor/central ratio not varied to optimize fit to the data.

FIGURE CAPTIONS

Fig. 1 -- Spectra measured at θ_{lab}=3.5° for the (^{6}Li,^{6}He) reaction at 210 MeV on targets of ^{7}Li, ^{12}C, ^{14}C, ^{26}Mg, and ^{90}Zr.

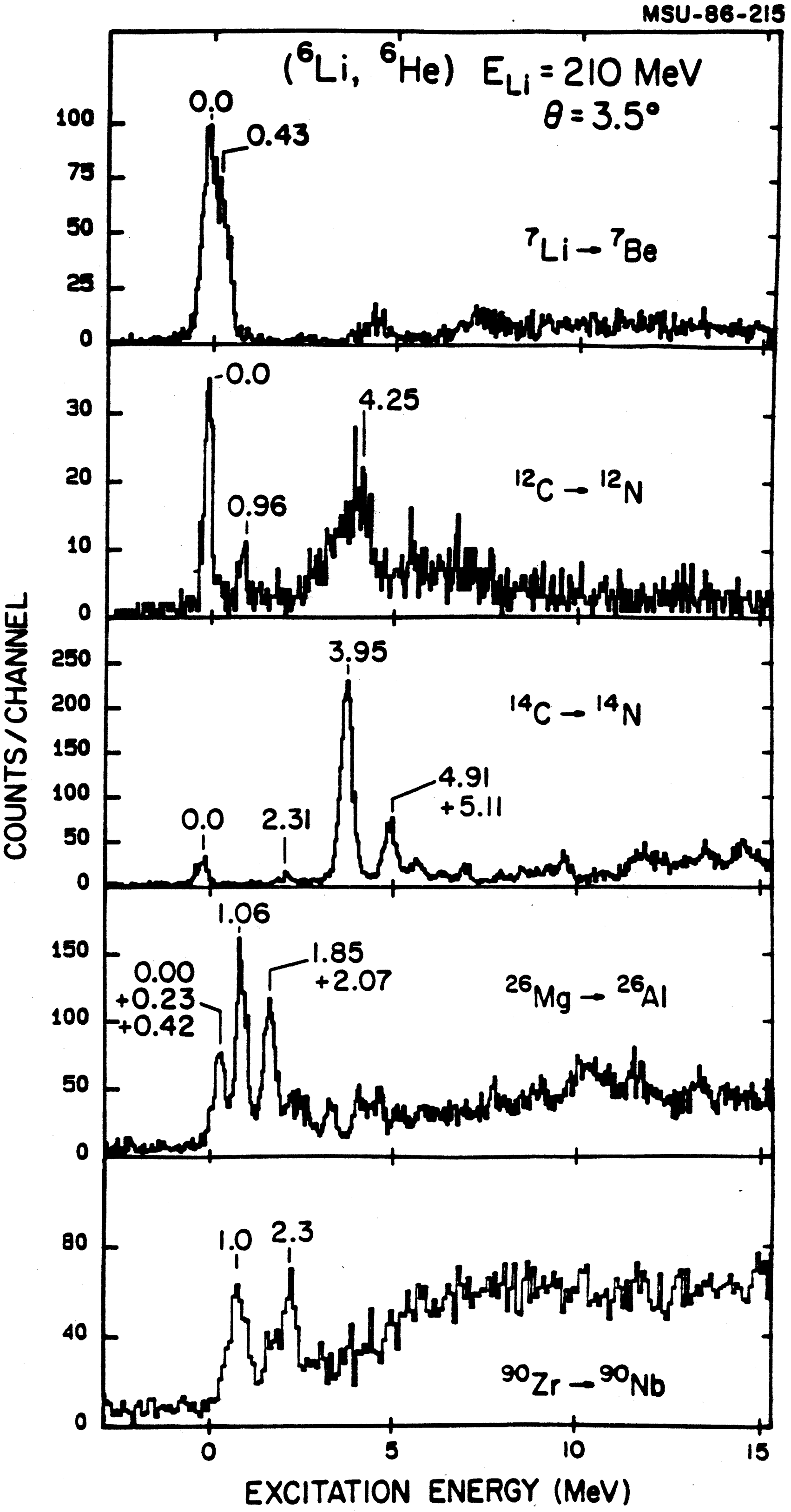
Fig. 2 -- Angular distributions for the ^{14}C(^{6}Li,^{6}He)^{14}N reaction at E(^{6}Li) = 14, 25, and 35 MeV/nucleon leading to the 3.95 MeV 1^+ level of ^{14}N. The solid curves are microscopic DWBA predictions, (with direct, exchange and tensor terms included) and are normalized to the data (excluding $\theta_{c.m.} <$ 3° for E(^{6}Li) = 35 MeV/nucleon) to yield the empirical strength of the interaction. The dashed curve is a calculation with only the direct and exchange terms of the interaction included.

Fig. 3 -- Plot of cross sections at qR/R(^{14}C) = 100 MeV/c for various GT transitions induced by (^{6}Li,^{6}He) at 25 and 35 MeV/nucleon. The final states, with excitation energies in MeV, are: ^{14}N(3.95), ^{90}Nb(2.3), ^{12}N(0.0), ^{7}Be(0.0 and 0.43), and ^{26}Al(1.06 and 1.85).

Fig. 4 -- Energy dependence of σ_{seq} and σ_{1step} for ^{12}C(^{12}C,^{12}N)^{12}B, as estimated from DWBA calculations. The normalization of σ_{seq} was determined from the experimental cross section (represented by the point) for the reaction to the ground state of ^{12}B at 35 MeV/nucleon, with the assumption that this is dominated by sequential transfer processes.

Fig. 5 -- Spectrum for ^{90}Zr(^{6}Li,^{6}He)^{90}Nb at 35 MeV/nucleon and θ_{lab}=2.9°. The dashed line is a background drawn by hand to represent contribution from processes other than one-step, L=0.

Fig. 6 -- The energy dependence of linear momentum transfer (q) for the charge exchange reaction on ^{208}Pb induced by p, ^{3}He, and ^{6}Li projectiles. The q-transfer essentially scales with energy/nucleon, apart from some small offsets due to the different Q-values of the reactions.



HEAVY ION REACTIONS AS SPIN PROBES
Fig. 1

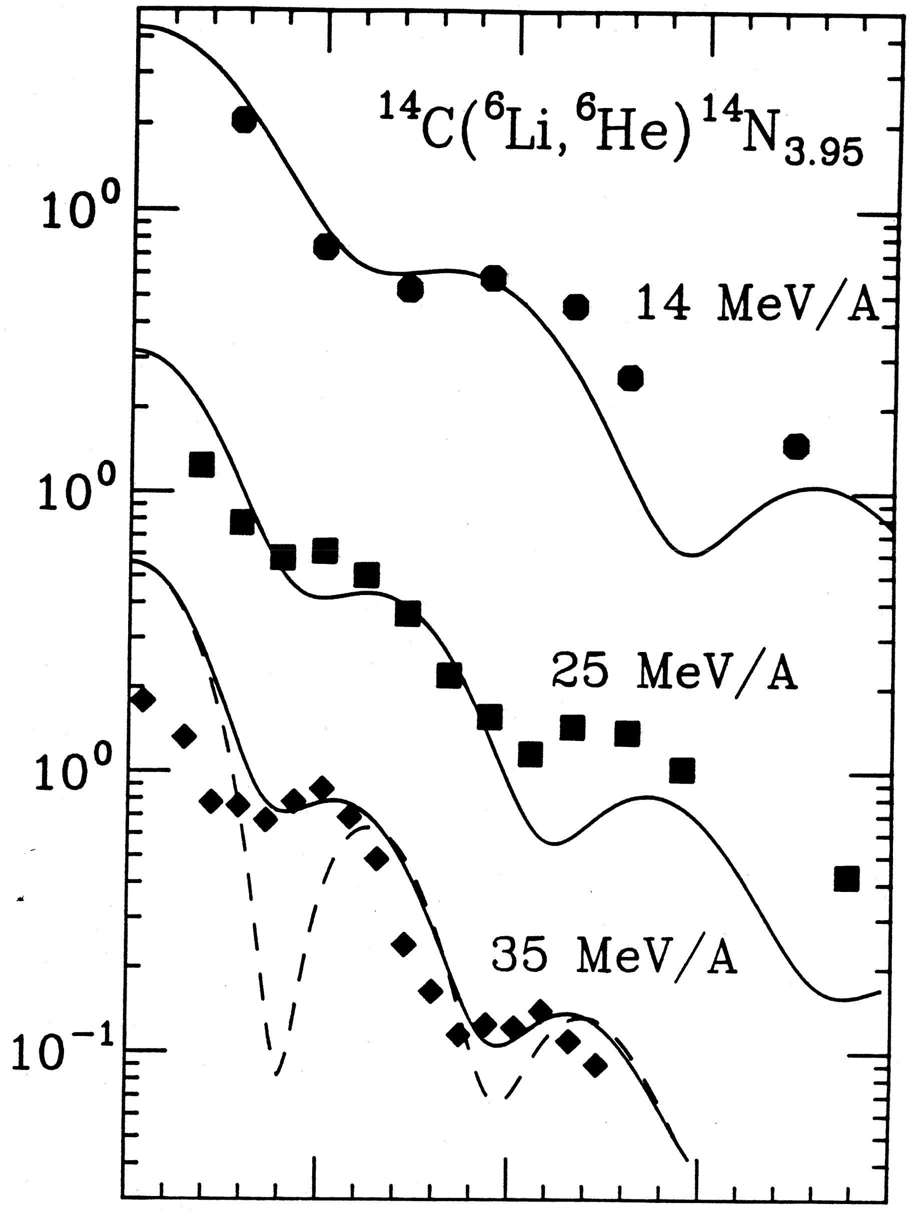


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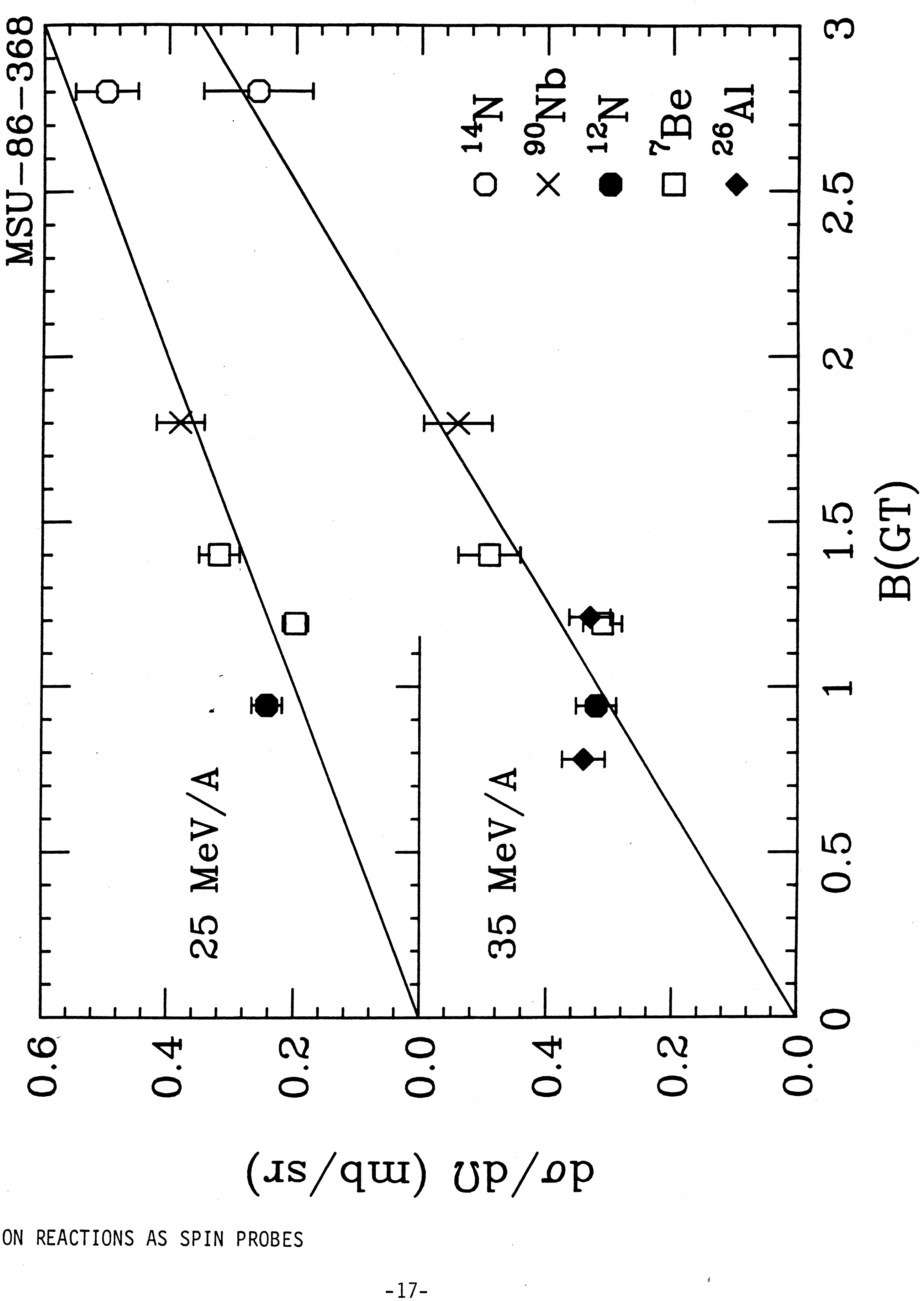
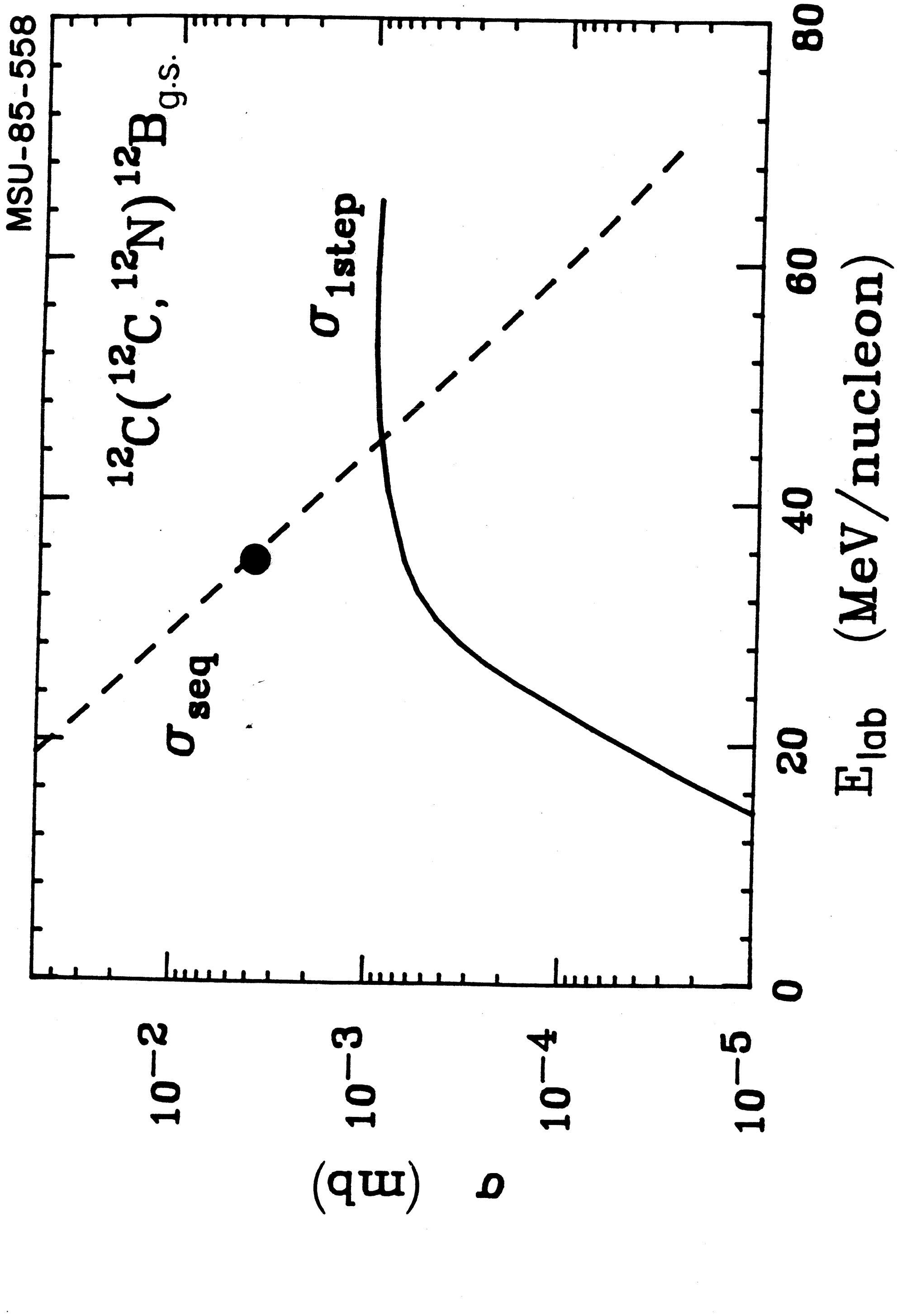
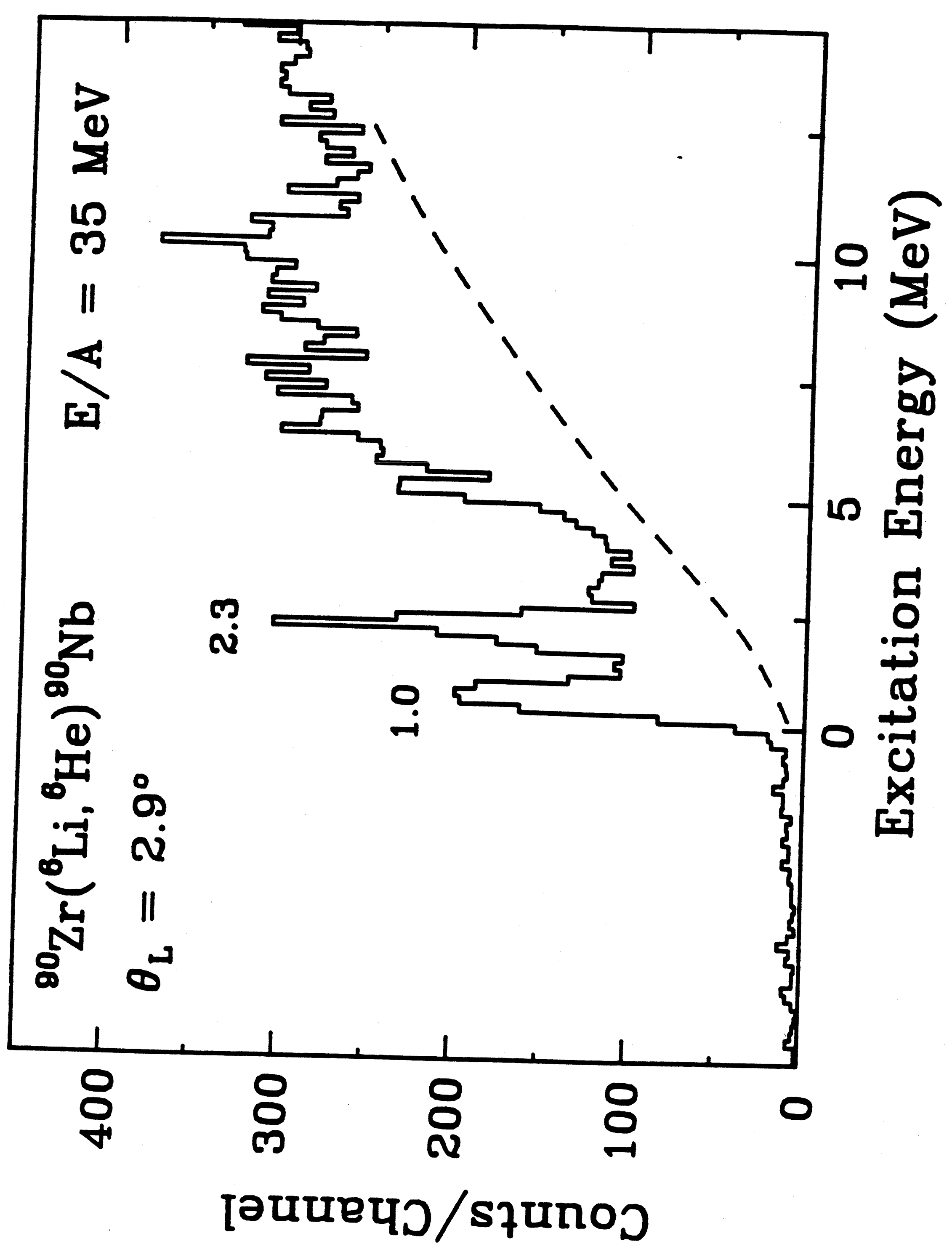
Fig. 2



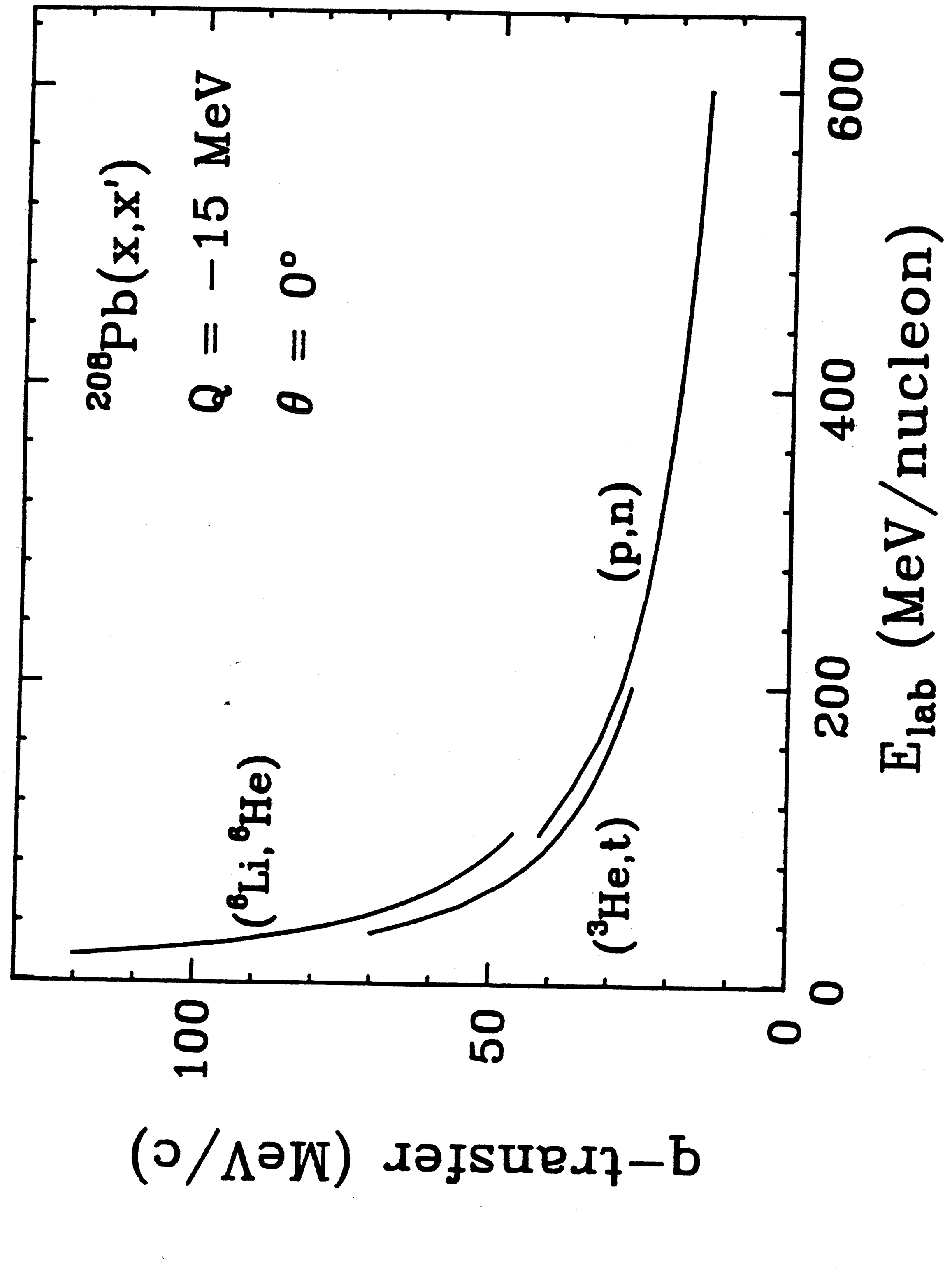
HEAVY ION REACTIONS AS SPIN PROBES
Fig. 3



HEAVY ION REACTIONS AS SPIN PROBES
Fig. 4



HEAVY ION REACTIONS AS SPIN PROBES
Fig. 5



HEAVY ION REACTIONS AS SPIN PROBES
Fig. 6

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28 October 1986

Dr. Peter Jackson
TRIUMF

Dear Peter:

Enclosed is my contribution for the Proceedings of the Isovector Workshop. I'm sorry it's been delayed, but I didn't return to MSU immediately after the Vancouver meeting. I greatly appreciated the opportunity to talk about our heavy ion charge exchange work and thank you both for the opportunity to do so and for running an extremely interesting workshop.

If you need anything further, please let me know.

I'd appreciate it if you would put me on the mailing lists for Triumf work on isovector excitations, both charge exchange and (p,p').

Sincerely,

Sam

Sam M. Austin
Co-Director

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INTRODUCTION

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In a sense heavy ion reactions are complementary to nucleon induced reactions in that the larger absorption means that these reactions selectively sample the nuclear surface. This may be particularly advantageous when the transition density contains a node, as for the spin-isovector-monopole transition--the cross section should be relatively larger for heavy ion reactions, since contributions from the exterior and interior regions of the nucleus will not cancel.

There are also advantages on the experimental side. Reactions in both the β^+ and β^- direction are available with charged particles in the ingoing and outgoing channels. This will permit high resolution measurements using the spectrographs now operating at GANIL and under construction at the NSCL (MSU) which have energy resolutions of 2×10^{-4}. If the reactions are good spin probes at low energies, as (^{6}Li,^{6}He) is at 150 MeV, then resolutions of 30 keV or so should be possible. Such resolution will be particularly useful for studies of spin strength whenever it is important to resolve transitions to individual levels.

However, making use of these potential advantages requires that the reaction mechanism is understood and that it is simple so there is a strong correlation between the observed cross sections and the relevant matrix elements. This paper is devoted to tests of the reaction mechanism for the (^{6}Li,^{6}He) and (^{12}C,^{12}N). Both of these reactions have the desirable property that only the ground state of the product is particle stable, so the spectrum is not further complicated by projectile excitation peaks. Because the spin strength which couples ^{6}Li and ^{6}He is an order of magnitude larger than that which couples ^{12}C and ^{12}N, we expect that the (^{6}Li,^{6}He) reaction will be one-step in nature at a significantly lower energy than (^{12}C, ^{12}N). We have therefore concentrated most attention on the former reaction, with only a preliminary investigation of the latter.

There is a significant literature on heavy ion induced charge exchange reactions. However, with the exception of that described by Ellegaard at this Workshop, none has been at energies where one anticipates that the one-step mechanism should dominate. References to this (lower energy) work will not be given here, but can be found in Refs. (1) and (2).

EXPERIMENTS

The experiments described here have been carried out at the NSCL (Michigan State University), using beams from the K500 superconducting cyclotron and the S320 spectrograph. This spectrograph has relatively low resolution and is especially useful for giant resonance studies where bending power and spectral cleanliness are more important than resolution. Resolutions of about 1/600 were obtained, adequate for the work described here. We studied (^{6}Li,^{6}He) on targets of ^{7}Li, ^{12}C and ^{14}C at 14, 25 and 35 MeV per nucleon. In addition, ^{26}Mg and ^{90}Zr data were taken at 35 MeV/nucleon and for ^{90}Zr, also at 25 MeV/nucleon. The ^{12}C(^{12}C, ^{12}N)^{12}B reaction was studied at 35 MeV/nucleon. Spectra from (^{6}Li, ^{6}He) at 35 MeV/nucleon are shown in Fig. 1.

TESTS OF REACTION MECHANISMS

The tests we have carried out are of three principal types:

1) Comparisons of the ratio of cross sections to states in a given nucleus for which the ratio of GT strengths, B(GT), is known from β decay. This comparison should be independent of many model uncertainties, but may not be sufficient to establish that the reaction is one-step in nature, since successive transfer reactions may also be proportional to GT strength in some cases (3).
2) Comparison with DWBA calculations to extract values of $V_{\sigma\tau}$ which can then be compared with results from (p,n) reactions.
3) Comparison of the dependence of cross section on B(GT) for a variety of nuclei. This comparison is particularly valuable because the observed correlation, if linear as is observed for intermediate energy (p,n) reactions (5), can serve as a calibration for the probe. One could read from this calibration the B(GT) associated with the cross section for an unknown transition. We devote most attention to this comparison.

Ratios of Cross Sections

The $^{14}C(^{6}Li, ^{6}He)^{14}N$ reaction leading to three states of ^{14}N is of particular interest. The 1^{+} ground state transition has a B(GT) value, obtained from β decay, of about 10^{-6} of that for the strong 3.95 MeV 1^{+} level. For (^{6}Li, ^{6}He), the ratios obtained at a momentum transfer q = 100 MeV/c are 0.21, 0.15 and 0.11 at 14, 25 and 35 MeV/nucleon, respectively. Previous work (4) at 10 MeV/nucleon gives 0.3. While the observed decrease is encouraging, this test is not conclusive because higher multipoles (L=2) and tensor forces are known to contribute to this reaction, and do not follow the same selection rules as does β decay. A better measure of the contribution of two-step processes is the ratio of the cross section for the 2.31 MeV 0^{+} isobaric analog state (IAS) to that for the 3.95 MeV state: the $0^{+} \rightarrow 0^{+}$ IAS transition can be mediated only by the non-local part of the exchange interaction in a one-step process and this is expected to be small near 0^{o}. This ratio observed is 0.1, 0.08, 0.05 and 0.05 at 10, 14, 25 and 35 Mev/nucleon, respectively, again suggesting that multistep processes are a factor of two smaller at the higher energies. A measure of the suppression of $\Delta S = 0$ amplitudes can be obtained by comparing this ratio with the value of 0.8 observed (6) for the $^{14}C(p,n)$ reaction at 35 MeV--this corresponds to a suppression of $\Delta S = 0$ strength by a factor of 16.

A similar test compares the ratio of the small-angle cross sections for the $^7Li(^6Li, ^6He)^7Be$ reaction leading to the two lowest states of ^7Be. The ratio of B(GT) for these states obtained from β decay is 1.18; the values obtained from (^6Li, ^6He) at 2.5^o are 1.78±0.05, 1.34±0.07, and 1.08±0.06 at 14, 25 and 35 MeV/nucleon. Only at 35 MeV/nucleon is the observed ratio in agreement with that expected.

In summary, these results support the conclusion that the (^6Li, ^6He) reaction is dominated by one-step processes at 35 (and possibly 25) MeV/nucleon.

Comparisons with DWBA

In this section we compare the observed cross sections and the results of Distorted Wave Born Approximation calculations, with the aim of determining whether a one-step description of the reaction is reasonable. The fitting parameters in this comparison are the strengths of the various parts of the two body interaction mediating the transition. If the transition is indeed one-step in nature, then we expect that the deduced interaction strengths will be comparable to those obtained from studies of nucleon induced reactions or deduced from theoretical studies.

Unfortunately, we do not expect to obtain a precise description of the observed cross section since the state of the art of available codes does not yet permit one to make calculations without further approximations beyond the DWBA. For example, in the (^6Li, ^6He) calculations described below, exchange is included for the central part of the interaction, but not for the tensor part. In the case of the (^{12}C, ^{12}N) only the central direct amplitude is included. In addition optical model potentials are often not available for the precise energies and/or targets of the present measurements and we have had to make do with what is available in the literature.

The calculations for (^{6}Li, ^{6}He) were performed with a modified version of the code DWUCK (7) which allows for the finite size of the projectile system and includes central $V_{\sigma\tau}$ (direct and exchange) and tensor (direct) terms in the interaction. The central interaction had a 1.0 fm range Yukawa form and the tensor interaction a r^2×Yukawa form. Optical potentials obtained (8) from 156 MeV ^{6}Li scattering data were used. Further details for the (^{6}Li, ^{6}He) and ^{12}C(^{12}C, ^{12}N)^{12}B calculations are given in Refs. (2) and (1), respectively. Results for the ^{14}C(^{6}Li, ^{6}He)^{14}N reaction are shown in Fig. 2. We note that the calculations overpredict the cross section at small angles; this appears to be a general feature of the reaction at intermediate energies. In addition, a significant tensor interaction is necessary to fit the data. The values of interactions obtained by adjusting the central and tensor interactions to best fit the angular distributions for $\theta > 3^{\circ}$ are shown in Table 1. The values of the central interaction can be compared to the value of $V_{\sigma\tau} = 11.7 \pm 1.7$ MeV obtained (9) from (p,n) and (p,p') studies at similar MeV/nucleon. Given the approximations made, it is reasonable to conclude that the one-step DWBA calculation reproduces the magnitude and that one-step processes are dominant in the (^{6}Li, ^{6}He) reaction at 25 MeV/nucleon and above.

The results for the ^{12}C(^{12}C, ^{12}N)^{12}B reaction differ significantly (1). The interaction required to fit the data is $V_{\sigma\tau} \sim 30$ MeV, indicating that the cross section is about ten times larger than expected on the basis of one-step calculations and that the reaction must be dominantly two step in nature. We shall return to this result later.

(^{6}Li, ^{6}He) Cross Sections vs B(GT)

We have chosen to make this comparison at a momentum transfer of qR/R(^{14}C)=100 MeV/c, where q is the momentum transfer and R/R(^{14}C) is the sum of the projectile and target radii, divided by that for ^{6}Li+^{14}C. This point is at the second diffraction maximum and was chosen, in preference to smaller angles, because DWBA calculations fit the cross section in this angular region and in order to provide some flexibility in matching q among the different reactions. The results are shown in Fig. 3. There is a high degree of proportionality for all final states observed at 25 and 35 MeV/nucleon (at 14 MeV/nucleon the data are too limited for such a comparison, but, based on the tests described earlier, we doubt whether the reaction is one-step at this energy).

The results shown here appear to establish a calibration curve which permits the use of the (^{6}Li, ^{6}He) reaction to determine the value of B(GT) for an unknown transition from its measured cross section.

WHEN IS THE (^{12}C,^{12}N) REACTION ONE-STEP?

As noted above, the ^{12}C(^{12}C, ^{12}N)^{12}B reaction at 35 MeV/nucleon is dominated by two-step processes. However, one expects that the dominant two-step process, sequential transfer, will become less important as the bombarding energy increases. This follows from the decrease of transfer cross sections with increasing energy which in turn is a consequence of the decreasing overlap of the projectile and target momentum distributions (10). Here we attempt to answer the question: at what energy is the reaction dominated by one-step processes so that it can be used for spectroscopic investigations? Our particular interest in this point follows from the fact that many of the most interesting questions in spin physics involve transitions in the β^{+} direction.

The technique is as follows. We calculate the energy variation of the one-step charge exchange process with the result shown in Fig. 4: the cross section first increases with bombarding energy and then reaches a plateau above about 35 MeV/nucleon (in this figure the value of $V_{\sigma\tau}$ is taken to be 11.7 MeV). Intuitively, one expects that the cross section for a sequential transfer process (e.g. $^{12}C \rightarrow {}^{13}N \rightarrow {}^{12}N$) is proportional to the product of the cross sections for the two transfer events. Adapting a model introduced by Madsen (11) for transitions leading to the IAS, we then assume that the sequential transfer cross section is $\sigma_{seq} \sim \sigma_1\sigma_2/\sqrt{E}$. The transfer cross sections are calculated using a finite range transfer code (SATURN-MARS (12)) and the above equation then yields the energy dependence of the sequential transfer process. This is also shown in Fig. 4 where σ_{seq} is normalized to our cross section measurement at 35 MeV/nucleon. We see that the one-step process should begin to dominate at about 50 MeV/nucleon. This is well above the energy of 25 MeV/nucleon at which (^6Li, ^6He) is found to be one-step, presumably because the projectile-ejectile transition strength is about a factor of ten smaller for $^{12}C \rightarrow {}^{12}N$. If the $^{12}C \rightarrow {}^{12}N$ strength were as large as that for $^6Li \rightarrow {}^6He$, then the one-step curve would be raised by a factor of ten, leading to one-step dominance by 35 MeV/nucleon. The present estimate is not very precise: effects of exchange, which would increase $\sigma_{one\text{-}step}$, have not been taken into account, nor may all sequential transfer routes have the same energy dependence as shown on Fig. 4. Nevertheless, it appears that one-step processes should dominate at energies readily available at GANIL and MSU Phase II.

MOMENTUM TRANSFER AND THE NATURE OF CHARGE EXCHANGE SPECTRA

The spectrum for ^{90}Zr(^6Li, ^6He) shown in Fig. 5 differs from forward angle spectra for high energy (p,n) reactions, in that the giant GT excitation near E_x=8.7 MeV appears to ride on a significant "background". The giant GT strength seen is as expected. The cross section for the 8.7 MeV peak, above the background drawn, is 4.0 times that for the 2.3 MeV peak, consistent with the ratio of 4.6±0.7 seen (13) in (p,n) reactions at 120 MeV. Since the 2.3 MeV cross section lies on the calibration line of Fig. 3, it appears that (^6Li, ^6He) provides a good measure of the giant GT strength.

It may be that the observed difference in background is related to the different momentum transfer q. In Fig. 6 we see that the value of q for various reactions on the same target depends on the bombarding energy in MeV/nucleon. Thus the value of q for the spectrum of Fig. 5 is comparable to that in 35 MeV proton induced charge exchange; indeed, the spectrum of Fig. 5 closely resembles the discovery spectrum (14) for the giant GT resonance taken at E_p=45 MeV. Another comparison might be with 120 MeV (p,n) results at 11° for which qR is about the same as that in Fig. 5. At this value of qR, both L=1 and L=2 amplitudes are expected to contribute to the spectrum and it seems likely that the GT strength will ride on a background of higher multipoles. It is also possible that two-step processes contribute at the higher values of E_x.

A NEW SPIN PROBE FOR THE τ_z CHANNEL

Inelastic proton scattering has been a powerful technique for examining spin strength ("M1" transitions) in nuclei. At energies above 150 MeV, the interaction $V_{\sigma\tau}$ is sufficiently strong compared to the isoscalar interaction that 1^+ states are prominent at small angles, although for most medium and heavy nuclei they ride on a significant background at all angles and are hidden by the tail of the elastic peak at the most forward angles. The uncertainty in the strength of the isoscalar interaction V_σ also contributes to the uncertainty in the extracted strength. The (^{6}Li,^{6}Li',γ) reaction, where ^{6}Li is initially left in its 3.56 MeV 0^+ T=1 state, and the decayed ^{6}Li and the decay γ are detected in coincidence, may be superior to (p,p') in several respects. The quantum numbers of the ^{6}Li transition involved (1^+T=0 → 0^+T=1) guarantee that $\Delta S=\Delta T=1$ (no isoscalar contribution to 1^+ states and no isovector, non-spin-transfer background) and the coincident γ detection should eliminate the elastic tail. Since there are no other particle stable states in ^{6}Li and the decay γ ray is essentially isotropic, (^{6}Li,^{6}Li',γ) is the most favorable reaction for the application of this technique. A preliminary experiment has been approved for the NSCL.

SUMMARY AND CONCLUSIONS

We conclude that heavy ion charge exchange reactions may play a useful role in spin physics, especially for transitions where high resolution or higher multipole transitions are of prime interest. We have shown that the (^{6}Li,^{6}He) reaction is one-step in nature above about 25 MeV/nucleon and have established a linear calibration curve relating cross section and GT strength. The (^{12}C, ^{12}N) reaction is found to be dominated by two-step reactions at 35 MeV/nucleon, but estimates indicate that the one-step process should dominate above about 50 MeV/nucleon.

It is suggested that the (^{6}Li, ^{6}Li' γ) reaction, with coincident detection of ^{6}Li and the decay gamma ray, may probe isovector spin strength better than high energy (p,p') because of the elimination of the isoscalar contribution and the elastic tail.

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REFERENCES

(1) J.S. Winfield, N. Anantaraman, S.M. Austin, L.H. Harwood, J. van der Plicht, H.-L. Wu and A.F. Zeller, Phys. Rev. C33 (1986) 1333.

(2) N. Anantaraman, J.S. Winfield, S.M. Austin, A. Galonsky, J. van der Plicht, C.C. Chang, G. Ciangaru and S. Gales, Michigan State University Cyclotron Laboratory preprint no. MSUCL-565; submitted to Phys. Rev. Lett.

(3) W.R. Wharton and P.T. Debevec, Phys. Rev. C11 (1975) 1963.

(4) C.D. Goodman, W.R. Wharton and D.C. Hensley, Phys. Lett. 64B, (1976) 417.

(5) C.D. Goodman, C.A. Goulding, M.B. Greenfield, J. Rapaport, D.E. Bainum, C.C. Foster, W.G. Love and F. Petrovich, Phys. Rev. Lett. 44 (1980) 1755.

(6) T.N. Taddeucci, R.R. Doering, A. Galonsky, and S.M. Austin, Phys. Rev. C29 (1984) 764.

(7) G. Ciangaru, R.L. McGrath and F.E. Cecil, Nucl. Phys. A380 (1982) 147.

(8) J. Cook, H.J. Gils, H. Rebel, Z. Majka and H. Klewe-Nebenius, Nucl. Phys. A388 (1982) 173.

(9) S.M. Austin, The (p,n) Reaction and the Nucleon-Nucleon Force, edited by C.D. Goodman et al. (Plenum, New York, 1980), p. 203.

(10) W. von Oertzen, Phys. Lett. 151B (1985) 95.

(11) V.A. Madsen and V.R. Brown, The (p,n) Reaction and the Nucleon-Nucleon Force, edited by C.D. Goodman et al. (Plenum, New York, 1980) p. 433.

(12) T. Tamura and K.S. Low, Comp. Phys. Commun. 8 (1974) 349.

(13) D.E. Bainum, J. Rapaport, C.D. Goodman, D.J. Horen, C.C. Foster, M.B. Greenfield and C.A. Goulding, Phys. Rev. Lett. 44 (1980) 1751.

(14) R.R. Doering, A. Galonsky, D.M. Patterson and G.F. Bertsch, Phys. Rev. Lett. 35 (1975) 1691.

Table 1. Values of effective interactions deduced from the (^{6}Li,^{6}He) reaction.

Final state	E/A (MeV)	$V_{\sigma\tau}$ (a) (MeV)	$V_{Ten}/V_{\sigma\tau}$ (b)
^{12}N 0.00 MeV	35	6	0.17
^{14}N 3.95 MeV	35	14	0.135
^{14}N 3.95 MeV	25	12	0.135 c)
^{14}N 3.95 MeV	14	23	0.135 c)
^{26}Al 1.06 MeV	35	15	0.16

a) For 1.0 fm range Yukawa interaction.

b) For r^2×Yukawa tensor interaction. See Ref. (7) for details.

c) Tensor/central ratio not varied to optimize fit to the data.

FIGURE CAPTIONS

Fig. 1 -- Spectra measured at $\theta_{lab}=3.5°$ for the ($^6Li,^6He$) reaction at 210 MeV on targets of ^7Li, ^{12}C, ^{14}C, ^{26}Mg, and ^{90}Zr.

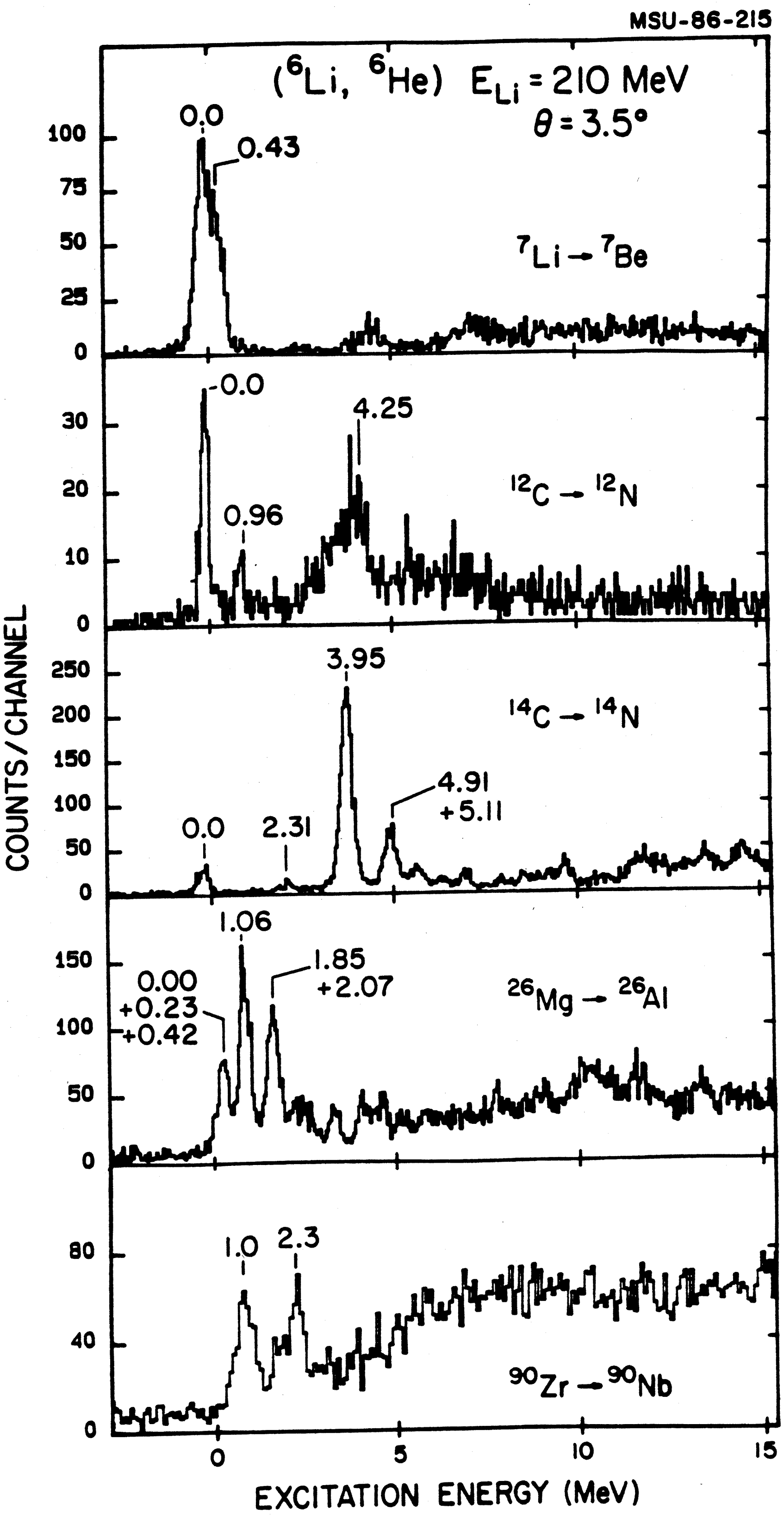
Fig. 2 -- Angular distributions for the $^{14}C(^6Li,^6He)^{14}N$ reaction at E(^6Li) = 14, 25, and 35 MeV/nucleon leading to the 3.95 MeV 1^+ level of ^{14}N. The solid curves are microscopic DWBA predictions, (with direct, exchange and tensor terms included) and are normalized to the data (excluding $\theta_{c.m.} <$ 3° for E(^6Li) = 35 MeV/nucleon) to yield the empirical strength of the interaction. The dashed curve is a calculation with only the direct and exchange terms of the interaction included.

Fig. 3 -- Plot of cross sections at qR/R(^{14}C) = 100 MeV/c for various GT transitions induced by ($^6Li,^6He$) at 25 and 35 MeV/nucleon. The final states, with excitation energies in MeV, are: ^{14}N(3.95), ^{90}Nb(2.3), ^{12}N(0.0), ^7Be(0.0 and 0.43), and ^{26}Al(1.06 and 1.85).

Fig. 4 -- Energy dependence of σ_{seq} and σ_{1step} for $^{12}C(^{12}C,^{12}N)^{12}B$, as estimated from DWBA calculations. The normalization of σ_{seq} was determined from the experimental cross section (represented by the point) for the reaction to the ground state of ^{12}B at 35 MeV/nucleon, with the assumption that this is dominated by sequential transfer processes.

Fig. 5 -- Spectrum for $^{90}Zr(^6Li,^6He)^{90}Nb$ at 35 MeV/nucleon and $\theta_{lab}=2.9°$. The dashed line is a background drawn by hand to represent contribution from processes other than one-step, L=0.

Fig. 6 -- The energy dependence of linear momentum transfer (q) for the charge exchange reaction on ^{208}Pb induced by p, ^{3}He, and ^{6}Li projectiles. The q-transfer essentially scales with energy/nucleon, apart from some small offsets due to the different Q-values of the reactions.



HEAVY ION REACTIONS AS SPIN PROBES
Fig. 1

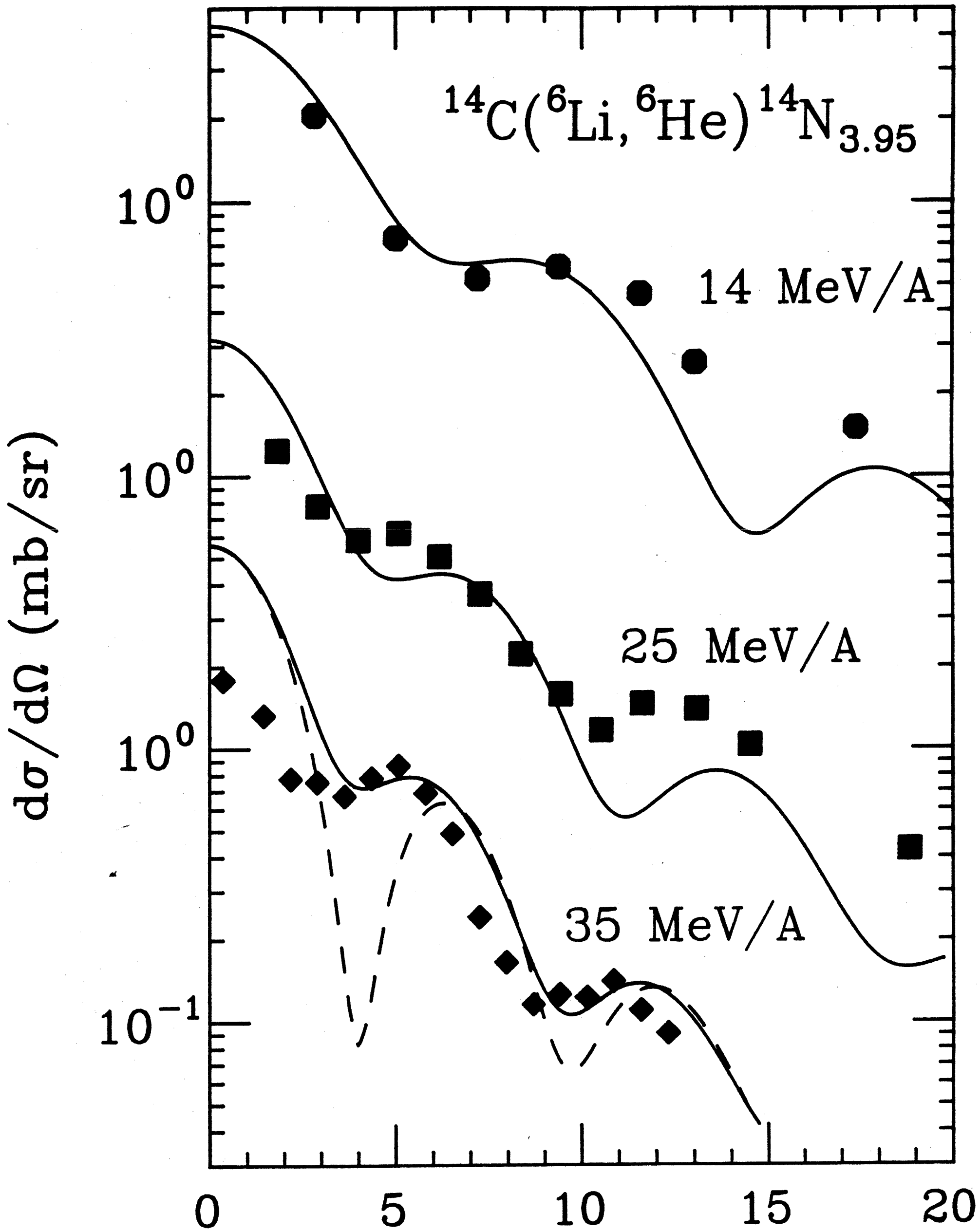


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Fig. 2

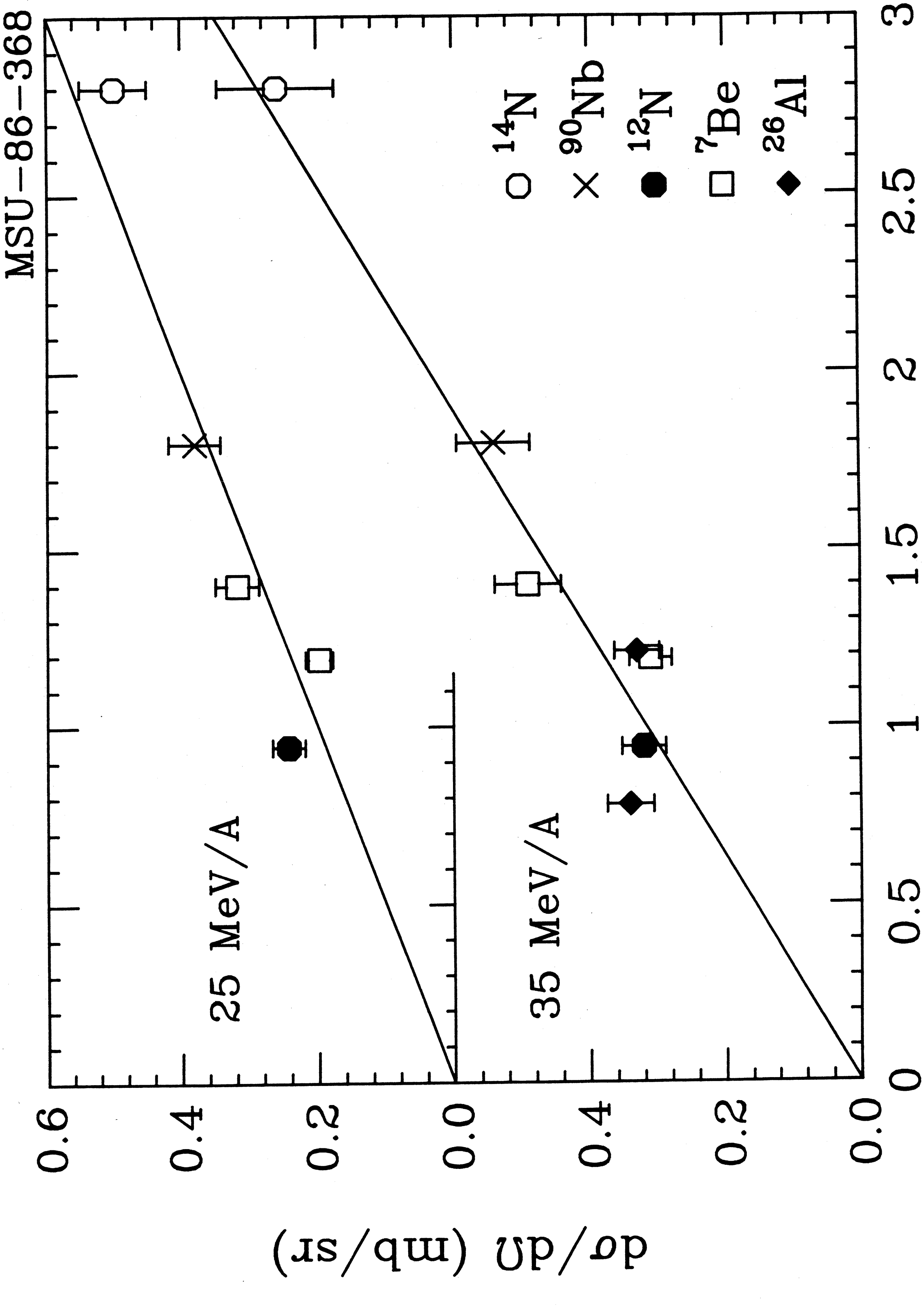

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Fig. 3

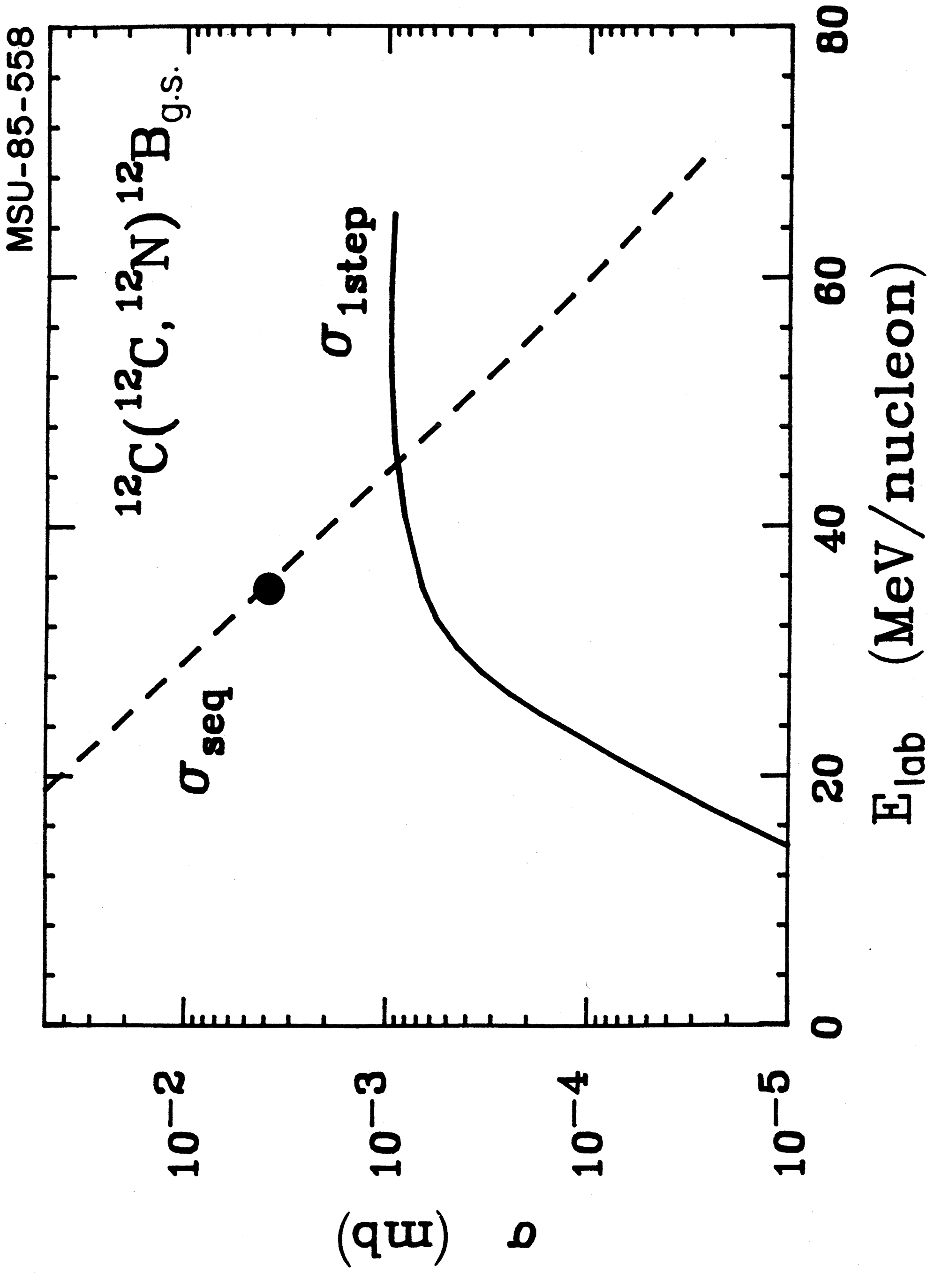

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Fig. 4

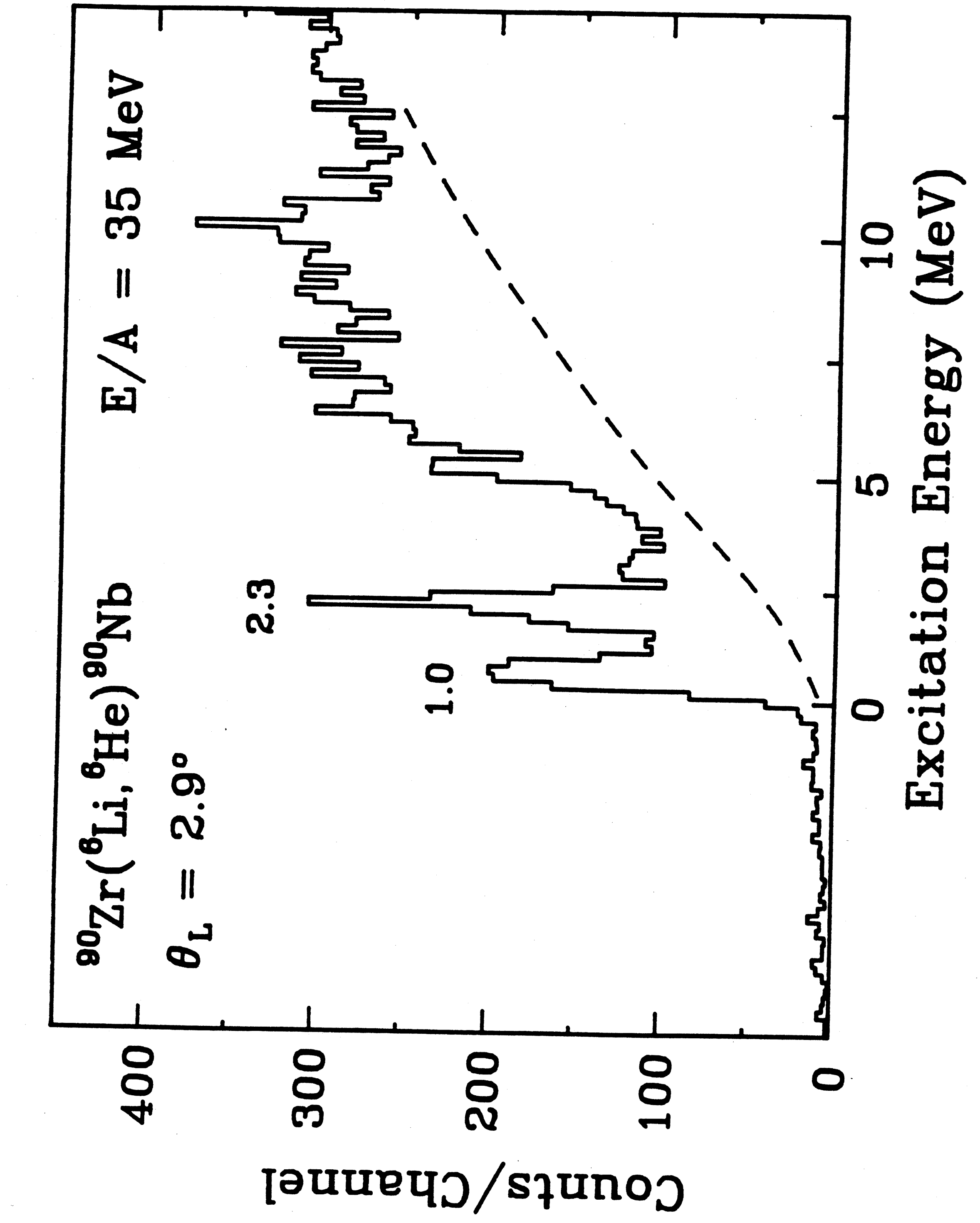

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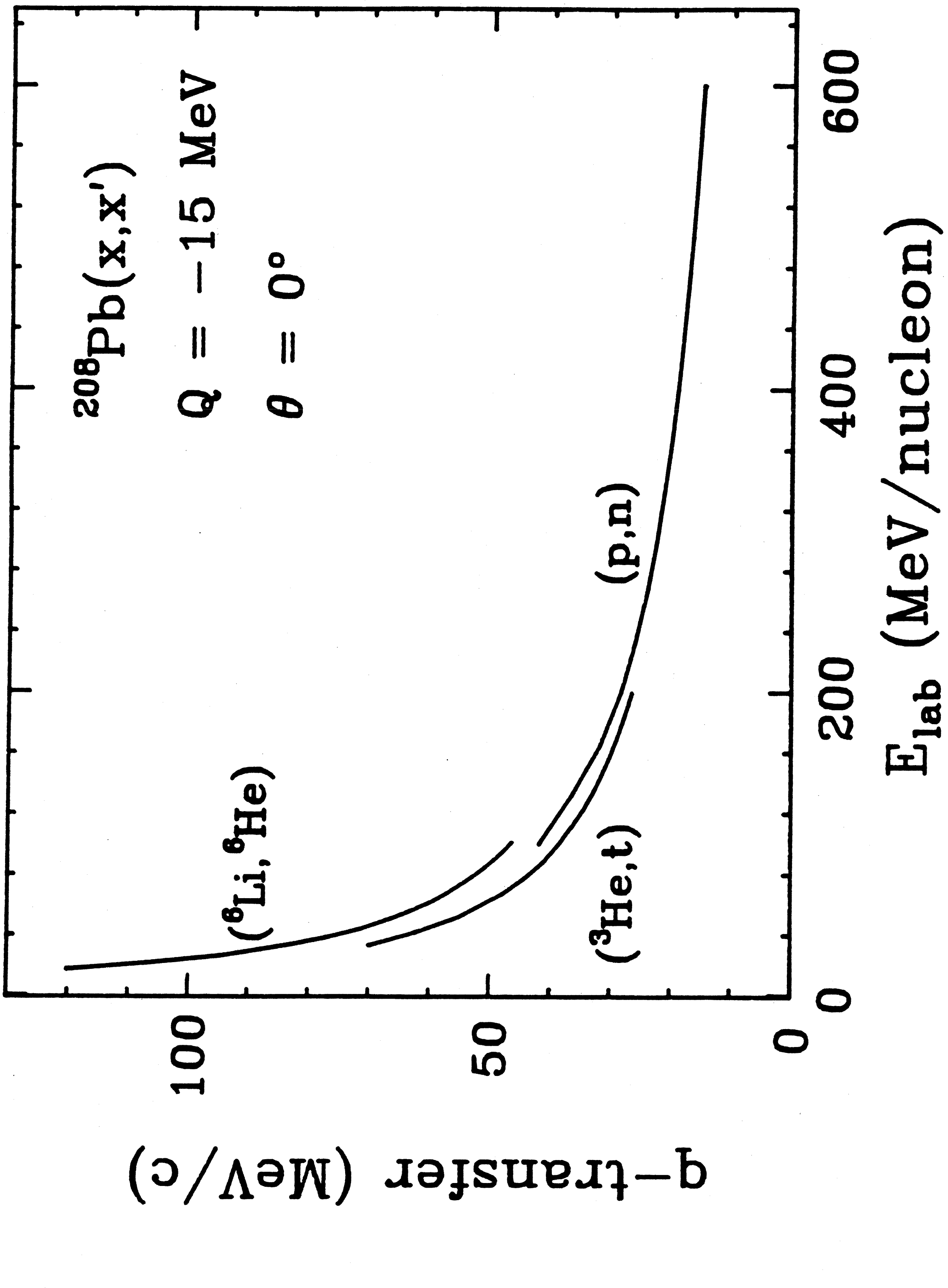
Fig. 5



HEAVY ION REACTIONS AS SPIN PROBES
Fig. 6