CONF-9005233--4

Talk presented at the Second International Conference on Medium- and High-Energy Nuclear Physics, Taiwan, May 14-18, 1990

CONF-9005233--4

DE91 000607

# PION DOUBLE CHARGE EXCHANGE SCATTERING ABOVE THE DELTA RESONANCE

George R. Burleson
Department of Physics
New Mexico State University
Las Cruces, NM 88003, U.S.A.

FG04-88ER40403



Data are presented on pion-nucleus double-charge-exchange scattering at energies between 300 and 500 MeV, the highest energies measured so far, together with a review of results at lower energies. The small-angle excitation functions disagree with predictions based on a six-quark cluster model and on an optical model consistent with single-charge-exchange scattering at these energies, but they are consistent with a distorted-wave calculation. Data on $f_{7/2}$-shell nuclei are in partial agreement with a two-amplitude model which is successful at lower energies. In order to achieve good understanding of this process at these energies, more work, both experimental and theoretical, is needed.

## INTRODUCTION

A major program of experimental measurements of pion-nucleus double-charge-exchange (DCX) scattering began at the high-intensity accelerators a little more than ten years ago. Most of the research has been carried out at the LAMPF accelerator in Los Alamos, New Mexico, using various beam channels and spectrometer systems. Much theoretical study has been carried out in parallel with this work. Some of the general questions addressed include descriptions of the reaction mechanisms, the sensitivity to nuclear structure, and the relation of DCX to elastic and single-charge-exchange (SCX) scattering. The results of this work have been discussed extensively at two workshops held at LAMPF, one in 1985,[1] and a recent one in August, 1989.[2] At these workshops there have been lively discussions and spirited controversy, with the result that some useful understanding of DCX has been achieved, though some prominent features of the data are still not understood. Most of the results I present here are discussed in more detail in the proceedings of those workshops.

The DCX process is particularly interesting because it involves two nucleons in leading order, whereas for most nuclear reactions double scattering is a second-order correction. Theoretical investigations of pion-nucleus reaction mechanisms generally relate DCX to other interactions involving pions and nuclei, such as elastic and inelastic scattering, SCX to discrete states, and absorption. (Note that absorption is also a two-nucleon process, but one which involves a much larger energy transfer.) Optical-model studies of DCX, together with other processes, have achieved good fits to large data sets, but the interpretation of the fitted parameters is generally not clear. Calculations involving sequential scattering processes and excitation of nucleon isobars have also achieved some success, but many problems remain. Theoretical studies of DCX have also given some information on nuclear structure, including nuclear wave functions, nucleon-nucleon correlations, and the relative strengths of transitions between analog and nonanalog intermediate states.

From an experimental point of view, what is needed for DCX measurements is an intense pion beam (greater than $10^7$ pions/sec), a spectrometer with fairly good resolution (1–2 MeV or better), a sweeping magnet located near the target to prevent the incident beam from entering the spectrometer at small angles, a Cherenkov counter to veto electrons at small angles, and a great deal of running time (a data rate of 1 count/hour is generally considered very good, and one count/day is generally a lower limit).

## REVIEW OF PREVIOUS RESULTS

The purpose of this talk is to present recent results on DCX at the highest energies measured so far. In order to appreciate these, however, they must be related to the results at lower energies, so I will first review those briefly.

Because of the nature of the pion-nucleon interaction, it is natural to speak of three energy regions for the existing data. The most prominent feature of the pion-nucleon interaction below about 1 GeV is the broad peak corresponding to the $\Delta(1232)$ resonance, which lies in the 100–300 MeV region. Here the nucleus is generally black to pions, the collision length is short (about 0.3 fm at 180 MeV) and the pions interact mostly in the nuclear surface. At energies above and below this region the pion penetrates further into the nucleus, but not into the deep interior; such a penetration should give more sensitivity to nucleon-nucleon correlations, for example. This suggests that the DCX interaction at the higher energies may be more similar to that at low energies than over the resonance. In the 300–500 MeV energy region of the data of this talk, the pion-nucleon total cross section is relatively flat and the reaction is not resonance-dominated, since it lies between the $\Delta(1232)$ and the $N^*(1440)$. Another important difference in these energy regions lies in the strength of the expansion parameter for a multiple-scattering series. Estimates[3] of the ratio of the second-order optical potential to the first-order term give $\sim 0.1$ at 160 MeV and $\sim 0.04$ at 500 MeV, which indicates that a multiple-scattering calculation should be more convergent at the higher energies. The different characteristics of these regions from the point of view of DCX are illustrated in Fig. 1, which shows the small-angle excitation functions for DCX on $^{14}C$ and $^{18}O$ up to $\sim 500$ MeV, as well as the $0^0$ SCX cross sections for $^{14}C$; these are all for transitions to analog states.[7]

### Resonance Energies (100–300 MeV)

The characteristics of DCX scattering at resonance energies were summarized at the second Workshop by Zumbro.[8] As shown in Fig. 1, the small-angle excitation functions for transitions to analog states generally pass through a minimum at resonance, as might be expected for a process with small probabil-

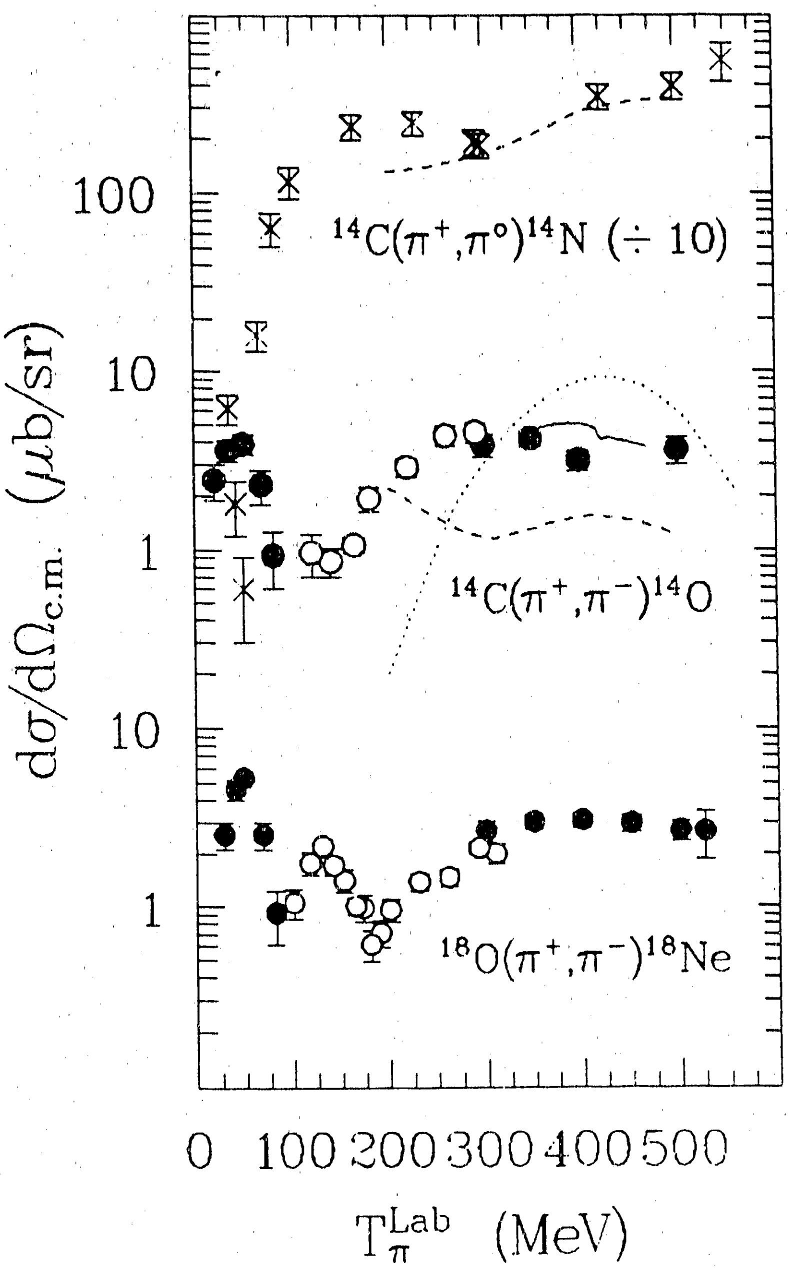


**Fig. 1** The small-angle cross sections for SCX scattering to analog states from $^{14}C$ (crosses) and for DCX scattering to analog states from $^{14}C$ and $^{18}O$ (circles, indicating the three energy regions discussed in the text). The theoretical curves are from ref. 4 (dotted curve), ref. 5 (dashed curve), and ref. 6 (solid curve).

ity that is in competition with other reactions having greater probability. An example of the angular distributions is shown in Fig. 2 for $^{18}O$. Here we see a minimum which remains fixed at one momentum transfer below about 200 MeV and moves to a larger momentum transfer at the higher energies. The minimum at the higher momentum transfer is diffractive, in that it reflects the nuclear size, whereas the one at the smaller momentum transfer is not. The A-dependence of the cross sections is expected to be the product of several terms, including (number of neutrons available for the first scattering), (number of neutrons available for the second scattering), (square of an amplitude), and (nuclear radius). For analog transitions, this gives

$$d\sigma/d\Omega \sim (N-Z)(N-Z-1)|1/A^2|^2(A^{2/3}) \sim (N-Z)(N-Z-1)A^{-10/3},$$

which has been found to be generally true.

For transitions to nonanalog states, the cross sections are about the same order of magnitude as those to analog states, which was initially a surprise, since they were expected to be considerably smaller. The small-angle excitation functions pass through a peak at resonace, in contrast to the behavior of the analog transitions (which brings into question the idea above about competing processes). The shape is generally well represented by a Breit-Wigner curve. The angular distributions resemble those in Fig. 2, but they are all diffractive. The A-dependence is given by

$$d\sigma/d\Omega \sim (N)^2|1/A|^2(A^{2/3}) \sim A^{-4/3},$$

(with $N \sim A$), as might be expected from the above.

Theoretical explanations of DCX at these energies have been discussed in refs. 1 and 2. The mechanisms believed to be the principal ones are shown in Fig. 3. The diagram on the left corresponds to sequential scattering; it has been shown to explain the rise of the small-angle excitation function for energies above 200 MeV, as well as the diffractive angular distributions there. The diagram on the right corresponds to the so-called delta interaction (DINT) mechanism, which has been successful in explaining the behavior of nonanalog transitions. Other possible contributions are shown in Fig. 4, the so-called meson exchange

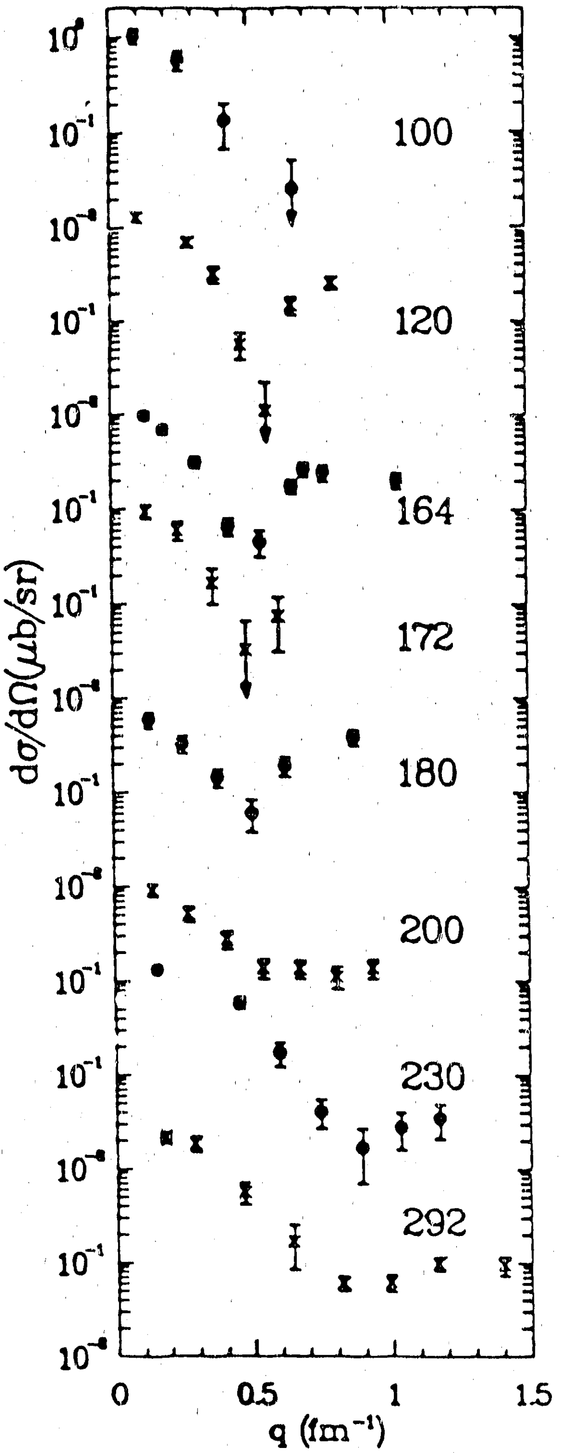


**Fig. 2**. Angular distributions for DCX scattering on $^{18}O$ at energies between 100 and 292 MeV (taken from ref. 8).

currents. These are not believed to give major contributions to DCX at these energies, since the two diagrams appear to cancel each other; they may be important below and above the resonance, however.

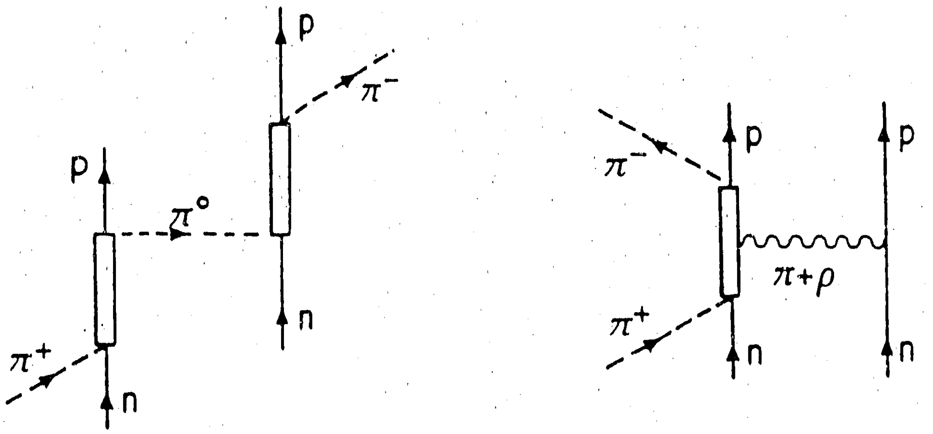


**Fig. 3.** Diagrams for DCX mechanisms. Left: sequential scattering; right, delta interaction (DINT).

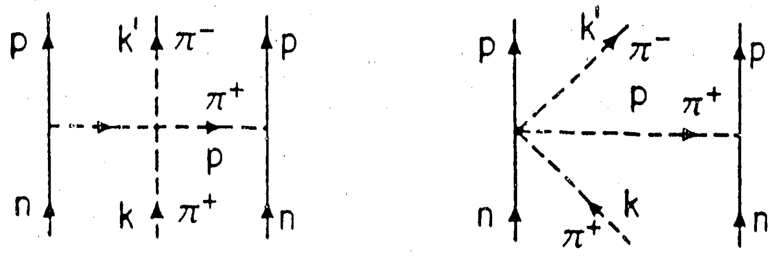


**Fig. 4.** Diagrams of meson exchange currents as DCX mechanisms. Left, interaction with the cloud of virtual pions exchanged between nucleons; right, contact term.

We should note that there are two prominent features of the data in this energy region for which no good explanation has been found. One is the forward minimum of the angular distributions between 100 and 200 MeV, and the other is the general shape of the excitation functions in this same energy region, including the additional peak in the $^{18}$O excitation function seen in Fig. 1. A combination of the two diagrams in Fig. 3 was found not to be successful in explaining these effects,[10] for example, which indicates that there are important mechanisms in the DCX process that have not yet been identified.

**Low Energies (10–100 MeV)**

A summary of the characteristics of DCX at these energies was given at the second Workshop by Leitch.[11] As shown in Fig. 1, the small-angle excitation functions for analog transitions generally pass through a peak at $\sim$ 50 MeV, whereas SCX passes through a minimum, for all nuclei. A forward minimum is seen in the fundamental $\pi^-$p charge exchange process as well, which results from an interference between s and p partial waves. This suggests a transparency of the nuclear medium at these energies, which is rather surprising. The angular distributions are forward-peaked for nuclei with $T = 1$ and 2, but they are fairly flat for those with $T > 2$. The most interesting feature of the A-dependence is seen for the calcium isotopes (which has been found at other energies as well, as discussed below). According to the $(N - Z)(N - Z - 1)$ dependence, we would expect cross section ratios of 6 for $^{44}$Ca/$^{42}$Ca and 28 for $^{48}$Ca/$^{42}$Ca, whereas what is found is $\sim$ 1/2 and $\sim$ 1, respectively.

The question of the reason for the forward maximum in DCX angular distributions at $\sim$ 50 MeV, as constrasted with the forward minumum for SCX angular distributions, was discussed extensively at the first LAMPF workshop.[1] An interesting suggestion was made by Miller that it could be a signature of a six-quark cluster in the nucleus, but it was shown that this behavior could result from less exotic mechanisms as well. These included the $\Delta$-hole model (Karapiperis), multiple scattering (Gibbs, et al), and a sequential scattering model (Bleszynski and Glauber). One common feature of most of these ideas is that what seems to be seen is some kind of a short-range nucleon-nucleon effect, which is equivalent to transitions through intermediate nonanalog states. For example, the valence neutrons in $^{42}$Ca are strongly correlated, producing a forward distribution, whereas those in $^{48}$Ca are not, which leads to a flat distribution.

A detailed explanation of the behavior of cross sections for the calcium isotopes was given by Auerbach, et al,[12] in terms of two amplitudes. One of these (labeled A) corresponds to transitions through analog states as a long-range process, and the other (labeled B) corresponds to transitions through nonanalog states as a short-range process. Using shell-model wave functions, simple predictions could be made for DCX cross sections both to analog states and to residual ground states for nuclei within a single shell. In a simplified version of the shell model known as the seniority model, the predictions for nuclei in the $f_{7/2}$ shell for the analog state (DIAS) and ground state (g.s.) can be written

$$d\sigma/d\Omega(DIAS) = \frac{n(n-1)}{2}|A + XBe^{i\phi}|^2$$

$$d\sigma/d\Omega(g.s.) = \frac{n(n-1)}{2}|YB|^2,$$

where

$$X = \frac{(5-n)}{3(n-1)}$$

$$Y = \frac{4\sqrt{(n-1)(10-n)}}{9(n-1)},$$

and $n = (N - Z)$. Fits of the data on the $f_{7/2}$-shell nuclei to this model, with shell-model wave functions, have been generally very successful,[13] and the ratio of $|B|/|A|$ was found to be about 3.5, consistent with the value originally estimated.[12]

## THE HIGH-ENERGY RESULTS (300–500 MeV)

The data I present here constitute the only measurements of DCX at energies above the Δ resonance. They were taken at LAMPF over a period of about three years by a collaboration including Texas, LAMPF, New Mexico State, Pennsylvania, and Colorado. * This work required a fairly extensive modification of the $P^3$ channel and the Large Aperture Spectrometer (LAS). Some of

* The participants were A. Williams, K. Johnson, G. Kharimanis, C. Fred Moore, S. Mordechai, and H. Ward, University of Texas; L. Agnew, L. Atencio, H. Baer, J. McGill, C. Morris, and S. Schilling, LAMPF; G. Burleson, K. Dhuga, J. Faucett, G. Kyle, and M. Rawool, NMSU; M. Burlein, H. T. Fortune, E. Insko, R. Ivie, J. O'Donnell, J. Silk, D. Smith, and J. Zumbro, University of Pennsylvania; and D. Oakley, University of Colorado.

the results have been published,[14] and others were summarized at the second LAMPF Workshop.[15]

For analog transitions, the small-angle excitation functions for all nuclei measured ($^{14}$C to $^{80}$Se) are flat, as indicated in Fig. 1. Only one angular distribution has been measured, that for $^{18}$O at 400 MeV, which is shown in Fig. 5. The A-dependence (for $14 \leq A \leq 208$) is generally consistent with $(N-Z)(N-Z-1)A^{-7/3}$, suggesting that the interaction is somewhat weaker than at resonance energies, as might be expected from the smaller pion-nucleon total cross sections. Nonanalog transitions have not been very well explored yet, but the small-angle cross sections for $^{16}$O appear also to be flat and those for the ground states of $T > 1$ nuclei appear to be surprisingly small, as discussed below. Another unexpected effect is that the nonanalog continuum around the analog peaks for $T > 1$ nuclei is seen to decrease with energy,[15] a feature that is important from an experimental point of view, since it causes the peaks to be more prominent.

There are as yet no explicit calculations for nonanalog trnsitions at these energies, nor for angular distributions. The excitation functions in Fig. 1 are compared with several predictions, however. One of these is the six-quark cluster model of Miller,[4] which predicts a peak that is not observed. Another is due to Parnell and Ernst,[5] based on a first-order optical potential with no free parameters which assumes sequential scattering through the intermediate analog state and contains s, p, and d waves, but omits pion absorption. As shown in Fig. 1, their SCX prediction is consistent with the data, but their prediction for DCX is about a factor of three too small. Another prediction shown is due to Haider and Liu,[6] which is consistent with the $^{14}$C data. This is a distorted-wave calculation, which was made in the context of the possibility of a bound state of an $\eta^0$ in a nucleus, the signature of which is indicated by the wiggle in the curve. (At larger momentum transfer a much more pronounced wiggle is predicted.)

We have two sets of data that we have compared with the two-amplitude model of ref. 6. These include small-angle cross sections for $^{42,44,48}$Ca at energies between 300 and 500 MeV and for $^{46,50}$Ti, $^{52}$Cr, and $^{54}$Fe at 450 MeV. We have fitted these data to this model, using correction factors for shell-model wave

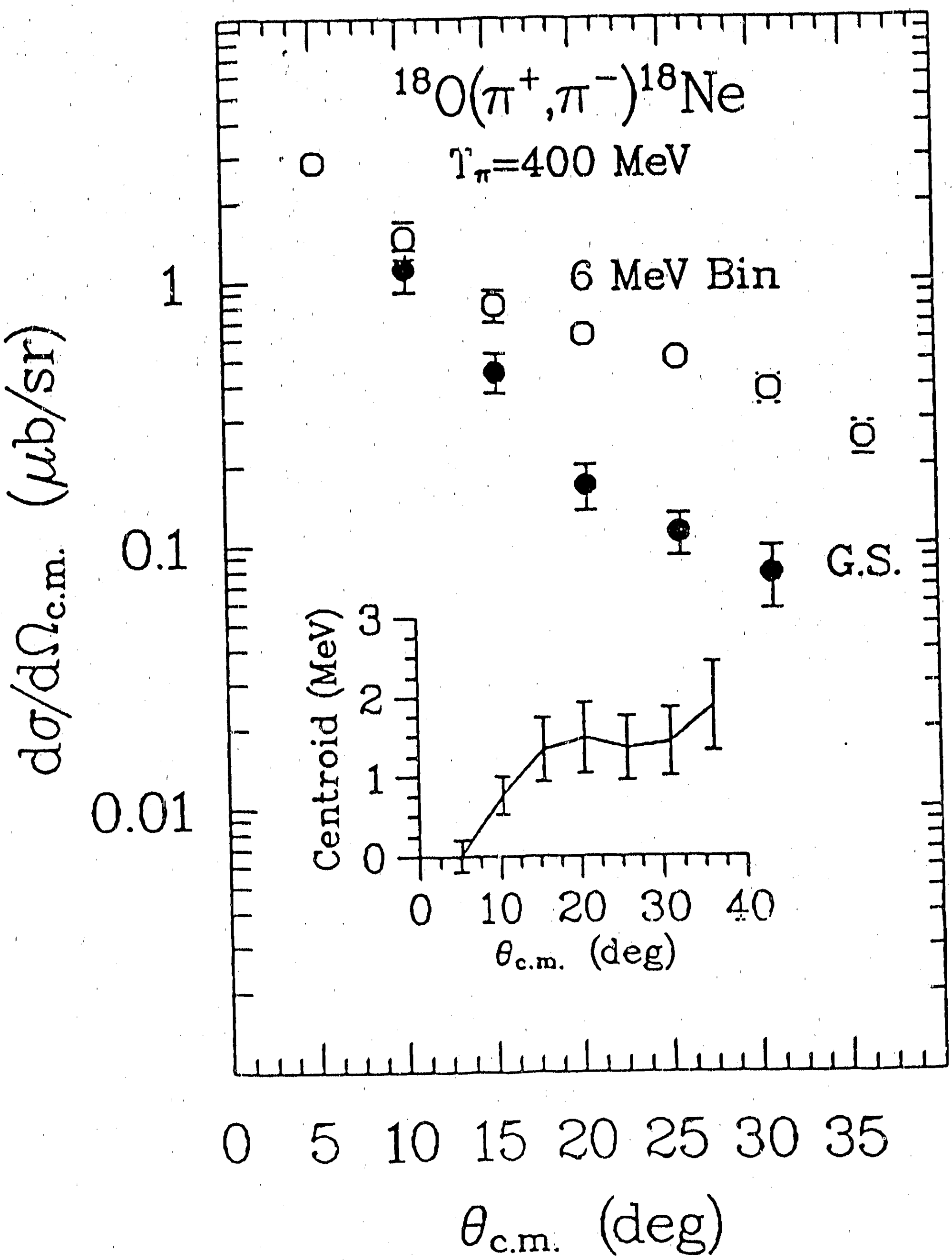


**Fig. 5.** The measured angular distribution at 400 MeV for DCX scattering from $^{18}O$ to states up to 6 MeV (open circles). The filled circles represent the estimated cross sections for the ground state. The inset figure shown the change in the centroid of the 0–6 MeV bin as a function of angle.

functions and for distortion effects given us by Gibbs.[16] The general conclusions presented here do not depend on these corrections, however.

For the Ca data, we find that we cannot fit both the DIAS and the ground-state transitions, because the experimental ground-state cross sections are too small. For example, if we average the data between 400 and 500 MeV and fit the DIAS cross sections only, we find that the experimental ground-state cross sections fall below the predicted value by 9 standard deviations for $^{44}$Ca and 12 standard deviations for $^{48}$Ca. The values of $|B|/|A|$ resulting from the DIAS fits as a function of energy are shown in Fig. 6, compared with prediction of Gibbs.[16] The agreement here is good, which suggests that there appears to be some validity to the model, aside from the ground-state problem.

When we compare this model with the full set of 450 MeV data described above, we find that the cross sections for the DIAS transitions in $^{50}$Ti and $^{52}$Cr are consistent with those of the calcium isotopes, but we still have the ground-state problem, in that the cross sections for these nuclei are also too small to fit. With the other two nuclei another two problem appears, however. We cannot fit the cross sections for all the $T = 1$ nuclei; we have to omit either the ($^{46}$Ti,$^{54}$Fe) pair or $^{42}$Ca. Omitting $^{46}$Ti and $^{54}$Fe gives a value of $|B|/|A|$ consistent with that shown in Fig. 6, and omitting $^{42}$Ca gives a good fit, but with $|B|/|A|$ of $\sim$ 0.60, inconsistent with the results shown in Fig. 6 (but again the ground-state cross sections cannot be fitted).

The impression that all of this gives is that high-energy DCX may not be as similar to low-energy DCX as might be expected, and that more study, both experimental and theoretical, is needed. Some experimental work that has been proposed includes measurements of angular distributions on both $T = 1$ and $T > 2$ nuclei, to see whether there are differences similar to what is seen at low energy, to take more data on nonanalog transitions in order to study their behavior further, and to search for the $\eta^0$ bound state suggested by Haider and Liu. We hope that more theoretical work will be done as well.

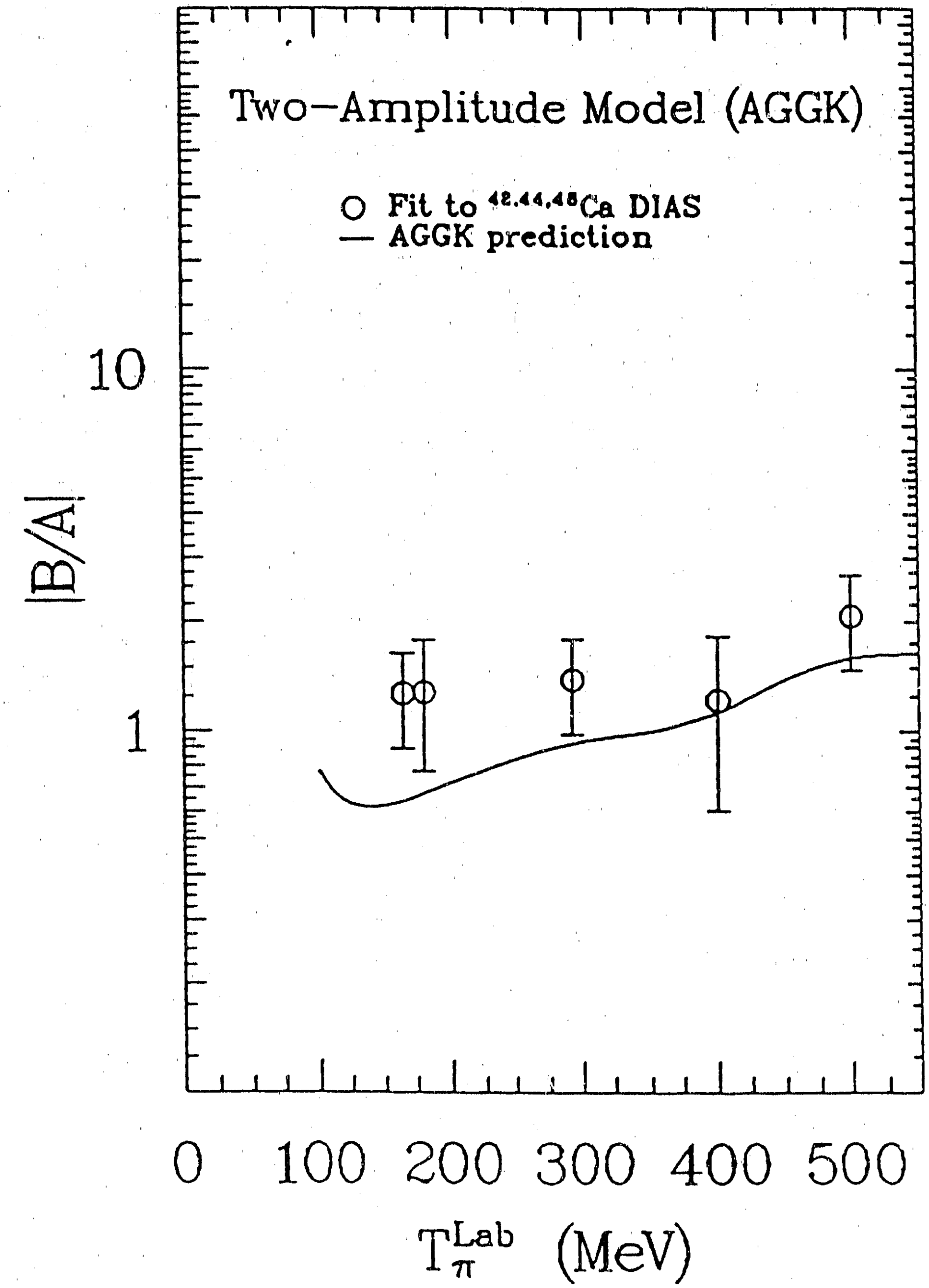


**Fig. 6.** Values of the ratio $|B|/|A|$ as a function of energy, from fits of the model of ref. 11 to forward-angle cross sections for DCX from $^{42,44,48}Ca$ to analog states. The curve is a prediction of Gibbs for this ratio, based on ref. 11.

## ACKNOWLEDGEMENTS

This work has been supported by the U.S. Department of Energy, the National Science Foundation, and the Robert A. Welsh Foundation.

## REFERENCES

1. Proceedings of the *LAMPF Workshop on Pion Double Charge Exchange*, Los Alamos, NM, January, 1985 (Los Alamos National Laboratory Report LA-10550-C, 1985).

2. Proceedings of the *Second LAMPF Workshop on Pion Double Charge Exchange*, Los Alamos, NM, August, 1989 (to be published by World Scientific Publishing Company).

3. D. Ernst, Proceedings of the *Conference on Pion-Nucleus Physics: Future Directions and New Facilities at LAMPF*, Los Alamos, NM, 1988 (AIP Conference Proceedings No. 163; Am. Inst. of Phys. New York (1988), p. 513).

4. G. A. Miller, Phys. Rev. C **35**, 377 (1987).

5. G. E. Parnell, Ph.D. dissertation, Texas A & M University (1987), unpublished; D. J. Ernst and G. E. Parnell, private communication.

6. Q. Haider and L. C. Liu, Phys. Rev. C **36**, 1636 (1987).

7. A compilation of DCX data is found in the Ph.D. dissertation of R. Gilman, University of Pennsylvania, 1985 (Los Alamos National Laboratory Report LA-10524-T, 1985).

8. J. D. Zumbro, ref. 2.

9. P. A. Seidl, *et al*, Phys. Lett. **154B**, 255 (1995).

10. M. Johnson, presented at this conference.

11. M. J. Leitch, ref. 2.

12. N. Auerbach, W. R. Gibbs, J. N. Ginocchio, and W. B. Kaufmann, Phys. Rev. C **38**, 1277 (1988).

13. Z. Weinfeld, *et al*, Phys. Lett. **238B**, 33 (1990).

14. A. L. Williams, *et al*, Phys. Lett. **216B**, 11 (1989), and to be published.

15. G. Burleson, ref. 2.

16. W. R. Gibbs private communication.

# END

# DATE FILMED

10 / 24 / 90