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TWO-NUCLEON TRANSFER REACTIONS INDUCED BY POLARIZED PROTONS*

J. C. Hardy, A. D. Bacher, G. R. Plattner†, J. A. Macdonald and R. G. Sextro

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

June 1970

Abstract:

The (p,t) and (p, ^{3}He) reactions on ^{16}O and ^{15}N targets have been studied using 43.8 MeV polarized protons. The observed cross sections and asymmetries for most states are well reproduced by DWBA calculations. However, of the five L = 2(S=0) transitions observed, two exhibit asymmetries which disagree markedly with the other three and with DWBA predictions. Thus asymmetries in two-nucleon transfer reactions do not always appear to be simply characteristic of the transferred quantum numbers.

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The two-nucleon transfer reactions, (p,t) and (p, ^{3}He), have been used in the past not only to determine spins, parities and isospins of nuclear energy levels[1] but also to investigate wave functions for the states involved.[2,3] Such studies have always used unpolarized projectiles. We present here a report on the first detailed examination of asymmetries produced in reactions initiated by polarized protons; of particular interest is whether these asymmetries are characteristic of the quantum numbers of the transferred nucleons. The only previously published report of (p,t) and (p, ^{3}He) reactions using polarized protons[4] showed the similarity of the asymmetries in transitions to analogue final states--a result which our data confirms.

We have investigated the (p,t) and (p, ^{3}He) reactions on ^{16}O and ^{15}N gas targets. The reactions were initiated by 43.8 MeV protons from the Berkeley 88-inch cyclotron and the recently installed polarized-ion source.[5] The external beam of 30-50 nA, with polarization $|P| \simeq 0.75$, had an energy spread of $\approx$ 100 keV. Emitted particles were detected in two $\Delta E - E$ counter telescopes positioned symmetrically on opposite sides of the incident beam. Standard particle-identification techniques[6] were used to separate the reaction products; an overall energy resolution of $\approx$ 150 keV was obtained. Since the direction of the incident beam polarization could be reversed at the ion source, the procedure described in Ref. 7 was used to extract the analyzing power,[8] $A(\theta)$, from the measurements, thereby minimizing effects caused by instrumental asymmetries. The beam polarization was monitored continuously with a ^{4}He polarimeter calibrated from recent p-^{4}He polarization measurements.[9]

In general, at forward angles ($\theta_{lab} \leqslant 60°$) the angular distributions of differential cross sections for (p,t) and (p, ^{3}He) reactions are characteristic of the transferred orbital angular momentum L and are reasonably-well reproduced by calculations which use the distorted-wave Born approximation (DWBA). If the reaction may proceed by more than one set of transferred quantum numbers (L, S and J), the process is described by the coherent sum of transition amplitudes characterized by the same J but different values of L and S. The extent of the interference between these amplitudes depends upon the strength of spin-orbit coupling in the entrance and exit channels, the sum becoming incoherent in the absence of such coupling. It has been suggested that previously reported inconsistencies in the ratio of cross sections for certain mirror transitions[10] might be due to particularly strong interference of this type.

In our experiment, the observed asymmetry of the reaction products, as

parameterized by the analyzing power $A(\theta)$, is expected to be very sensitive to the strength of spin-orbit coupling and the interference effects arising from it. Sixteen transitions were observed of which eleven corresponded to unique sets of transferred quantum numbers. Since all L-values, $L \leqslant 3$, were represented, it was hoped that these unique transitions might define characteristic shapes for angular distributions of the analyzing power so that the ability of the DWBA calculations to reproduce them could be tested. If these simple cases were successfully reproduced, then interference effects could be studied for the other transitions which involve superpositions of amplitudes for as many as four sets of transferred quantum numbers. Initially, the most interesting cases were the mirror (p,t) and (p, ^{3}He) reactions leading to the $5/2^-$ states at 7.38 MeV in ^{13}N and 7.55 MeV in ^{13}C for which an unexpectedly small (p, ^{3}He) cross section had previously been reported.[10]

The detailed results of this experiment and its analysis will be published later.[11] However, a very striking result has emerged which prompts us to write this letter. Five (p,t) transitions were observed for which the transferred quantum numbers are L=2 and S=0. Although these quantum numbers are the same for all five cases, the measured analyzing powers do <u>not</u> have the same angular distributions. They appear instead to be of two distinct types, one which agrees well with DWBA calculations (we shall refer to this as the "normal" type) and one which does not ("anomalous" type). This is particularly surprising in light of the success we have had in reproducing the shapes of the analyzing-power angular distributions for transitions with other L-values, and in fitting cross sections for all transitions, <u>including</u> the "anomalous" ones.

The observed cross-section angular distributions for the five, L=2, (p,t) transitions[12] are shown in Fig. 1 together with the distribution for the L=0 ground state transition, ^{16}O(p,t)^{14}O. Measured analyzing powers for the same

transitions appear in Fig. 2. The DWBA calculations whose results appear in both figures utilized optical model parameters taken from elastic scattering data which, for the protons, included polarization measurements. (Specifically, the proton parameters for oxygen were from 43.1 MeV scattering[13] on ^{16}O, while those for nitrogen came from 40 MeV scattering[14] on ^{12}C; the mass-3 parameters were obtained from ^{3}He elastic scattering on ^{12}C at 30 MeV[15] and ^{14}N at 29 MeV[16] respectively.) The results of two separate calculations are shown with each angular distribution. They differ only in the choice of the form factor used to describe the radial wave function of the transferred nucleons; both assume a zero-range interaction.[17] The solid line is the result of using harmonic oscillator wave functions for the transferred nucleons, transforming to relative and center-of-mass coordinates, and matching at some large radius in the cm system to a Hankel function which produces an asymptotic form corresponding to the known two-nucleon binding energy.[18] The dashed line represents the results of calculations which use Woods-Saxon wave functions for both particles;[19] those shown assume each particle is bound by half the total binding energy, with a Thomas spin-orbit factor, $\lambda_{SO} = 25$.

The wave functions used to describe the initial and final nuclear states involved only 1p-shell configurations with spectroscopic amplitudes taken from the work of Cohen and Kurath.[20] Since only one 2^+ state with this configuration is predicted to occur below 10 MeV in ^{14}O, the same wave functions were used for the three 2^+ states observed in that nucleus. The effects of sd-shell configuration-mixing will be discussed subsequently.

The agreement between calculation and experiment is seen to be good for the differential cross section data in Fig. 1, and there is also reasonable success in fitting those observed transitions which are not shown. Similar agreement is

seen in Fig. 2 for the L=0 and "normal" L=2 transitions; and again this is typical of the fits for all of the unique transitions. This success makes the disagreement with the analyzing powers for the "anomalous" L=2 transitions all the more striking. It must be emphasized that this is not simply a disagreement with theory but that there is a significant discrepancy--virtually opposite phase in their analyzing powers--observed between transitions in the same nucleus which are characterized by the same transferred quantum numbers.

In attempting to understand the "anomalous" transitions, we have examined whether it is possible to reproduce their analyzing powers by making the following variations in the calculations:

i) Optical-model parameters. It is possible by varying the geometrical parameters to make minor improvements to the analyzing-power predictions for the "anomalous" transitions but this was always found to be at the expense of worsening the agreement to the cross-section data. Since the agreement for other transitions deteriorates at the same time, it seems unlikely that such variations could ever generate the dramatic change necessary to simultaneously fit all of the L=2 transitions.

ii) Bound-state parameters. The calculated analyzing powers were found to be insensitive to all reasonable variations in those parameters describing the radial wave functions of the transferred nucleons; this included the strength function for the harmonic oscillator wave functions and the individual binding energies used with the Woods-Saxon well.

iii) Nuclear wave functions. For the states at high excitation energy significant sd-shell components are expected in the final-state wave functions. Although the states with "anomalous" transitions are relatively low in excitation, a study of the effects of such admixtures was made. It indicated that the

amplitude of the oscillations in the angular distribution of analyzing powers was dependent upon the predominant configuration in the wave functions but that the positions of maxima and minima remained unchanged. Thus, no improvement in the fitting of "anomalous" transitions could be effected. One improvement to a "normal" L=2 transition might, however, be noted: the differential cross section to the state at 9.72 MeV in ^{14}O was reproduced more reliably at forward angles when transfer from the sd-shell was assumed.

It does not appear possible within the context of the simple DWBA to explain both types of L=2 transitons. Based on the ^{15}N data, it is tempting to postulate coupling to the spin of the residual nucleus, since the two final states in ^{13}N differ in that respect ($3/2^-$ and $5/2^-$). However no such explanation could apply to the three 2^+ states in ^{14}O. Dependence on the L-S coupling of the transferred nucleons cannot play a significant role either since the transferred nucleons in the (p,t) reaction must have predominantly S=0. The explanation may lie in the use of a more realistic interaction potential than the delta function assumed in calculations of the type followed here, or it may lie in a more complicated reaction mechanism--i.e. two-step, knock-out, etc. But, for these refinements to be effective, the basic terms which we have considered must be reduced considerably in the "anomalous" transitions relative to the "normal" ones. In ^{13}N, where p-shell wave functions adequately account for the number of states observed, the relative magnitudes of the ground, $3/2^-$ and $5/2^-$ states are reliably predicted by our calculations. Thus, there is no a priori indication that the normally dominant processes should be reduced or forbidden for the "anomalous" transitions.

Without a better understanding of those transitions characterized by a unique set of transferred quantum numbers, any attempt to explain the more complicated (p, ^3He) transitions must be treated with caution. The analyzing powers for three

states populated in the (p, ^{3}He) reaction are shown in Fig. 3. The transition to the state at 7.03 MeV in ^{14}N is described by L=2 (but S=1) and appears to be of the "normal" type; the others are more complex, but involve L=2 components. Although the state at 3.68 MeV in ^{13}C is the mirror of the 3.51 MeV state in ^{13}N which is fed by an "anomalous" (p,t) transition, the trend of the data, at least at forward angles, is adequately reproduced by the DWBA calculations. On the other hand, the (p, ^{3}He) transition to the state at 7.55 MeV in ^{13}C corresponds to a "normal" (p,t) transition to ^{13}N; however, its analyzing power is not well reproduced and is small at all observed angles, in contrast to most other strong transitions. Thus, it appears that the inconsistent cross-section ratio previously noted for this state may well be due to a strong cancellation between the amplitudes involved. Whether this cancellation can be reproduced by changes in the model wave function, or whether it depends upon an understanding of the "anomalous" transitions is presently being investigated.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Present address: University of Basel, Basel, Switzerland.

1. e.g. J. Cerny and R. H. Pehl, Phys. Rev. Letters 12, 619 (1964); H. Brunnader, J. C. Hardy and J. Cerny, Nucl. Phys. A137, 487 (1969).
2. e.g. D. G. Fleming, J. Cerny, C. C. Maples and N. K. Glendenning, Phys. Rev. 166, 1012 (1968).
3. I. S. Towner and J. C. Hardy, Advan. Phys. 18, 401 (1969).
4. J. M. Nelson, N. S. Chant and P. S. Fisher, Phys. Letters 31B, 445 (1970).
5. D. J. Clark, A. U. Luccio, F. Resmini and H. Meiner, University of California Lawrence Radiation Laboratory Report, UCRL-18934, unpublished.
6. F. S. Goulding, D. A. Landis, J. Cerny and R. H. Pehl, Nucl. Instr. Methods

31, 1 (1964).

7. G. R. Plattner, T. B. Clegg and L. G. Keller, Nucl. Phys. A111, 481 (1968).

8. In simple terms, $A(\theta)$ is related to directly measurable quantities by the equation

$$\sigma(\theta)_{\text{pol. beam}} = \sigma(\theta)_{\text{unpol. beam}} (1 + P_{\text{beam}} \cdot A(\theta)),$$

where P_{beam} is the component of the incident beam-polarization perpendicular to the reaction plane. The analyzing power, $A(\theta)$, is equal to the proton polarization which would be observed in the inverse reaction initiated by unpolarized particles. Their signs are defined in accordance with the Basel convention (Helv. Phys. Acta Suppl. 6, 436 (1961)).

9. G. R. Plattner, A. D. Bacher, H. E. Conzett, D. J. Clark, H. Grunder and W. F. Tivol, Bull. Am. Phys. Soc. 15, 519 (1970), and private communication.

10. D. G. Fleming, J. Cerny and N. K. Glendenning, Phys. Rev. 165, 1153 (1968).

11. J. C. Hardy, A. D. Bacher, G. R. Plattner, J. A. Macdonald and R. G. Sextro, to be published.

12. These L-values are determined from independent spin and parity assignments for the final states. [See the reviews by F. Ajzenberg-Selove, Lemon Aid Preprints, LAP-76 and LAP-82.] The (2^+) assignment to the 9.72 MeV level in ^{14}O is from D. G. Fleming, J. C. Hardy and J. Cerny, to be published; since it is a "normal" transition, its uncertainty does not affect any of the arguments given here.

13. W. T. H. Van Oers and J. M. Cameron, Phys. Rev. 184, 1061 (1969), and private communication. In order to improve the details of the fits to our cross-section data we have increased the imaginary well-depth in these parameters. This is not uncommon in such light nuclei (see for example L. A. Kull and E. Kashy, Phys. Rev. 167, 963 (1968)) and has little effect on the predicted analyzing powers.

14. L. N. Blumberg, E. E. Gross, A. van der Woude, A. Zucker and R. H. Bassel, Phys. Rev. 147, 812 (1966).

15. Private communication from N. F. Mangelson quoted in Ref. 2. Recent polarization measurements of ^{3}He scattered from ^{12}C at 20 MeV (W. S. McEver et al., Phys. Rev. Letters 24, 1123 (1970)) indicate the need for a spin-orbit potential of ≈ 4 MeV. No such potential was used in our analysis; however, its effects were checked and found not to influence our conclusions.

16. J. C. Hiebert, E. Newman and R. H. Bassel, Phys. Rev. 154, 899 (1967).

17. All DWBA calculations reported here used the program DWUCK written by P. D. Kunz. The modifications to include the harmonic oscillator form factor and coherent summation were made by us.

18. N. K. Glendenning, Phys. Rev. 137, B102 (1965).

19. B. F. Bayman and A. Kalleo, Phys. Rev. 156, 1121 (1967).

20. S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).

FIGURE CAPTIONS

Fig. 1. Differential cross sections for some transitions from the reactions ^{16}O(p,t)^{14}O (labelled a) and ^{15}N(p,t)^{13}N (labelled b). Each transition is denoted by the spin and parity of its initial and final states, and the excitation energy of the latter. The results of DWBA calculations are shown with each angular distribution; the solid line corresponds to the use of harmonic oscillator wave functions for the transferred nucleons, while the dashed line indicates Woods-Saxon wave functions were used.

Fig. 2. Angular distributions of analyzing powers for the same transitions as in Fig. 1. The curves and labels have the same significance.

Fig. 3. Angular distributions of analyzing powers for three transitions from the reactions a) $^{16}O(p, {}^{3}He)^{14}N$ and b) $^{15}N(p, {}^{3}He)^{13}C$. The calculations shown used harmonic oscillator wave functions for the transferred nucleons. In addition to the excitation energy of the final states, each transition is marked with its contributing sets of transferred quantum numbers (L S J). The initial- and final-state spins for these transitions are: 7.03 MeV ($0^+ \rightarrow 2^+$), 3.68 MeV ($1/2^- \rightarrow 3/2^-$), and 7.55 MeV ($1/2^- \rightarrow 5/2^-$).

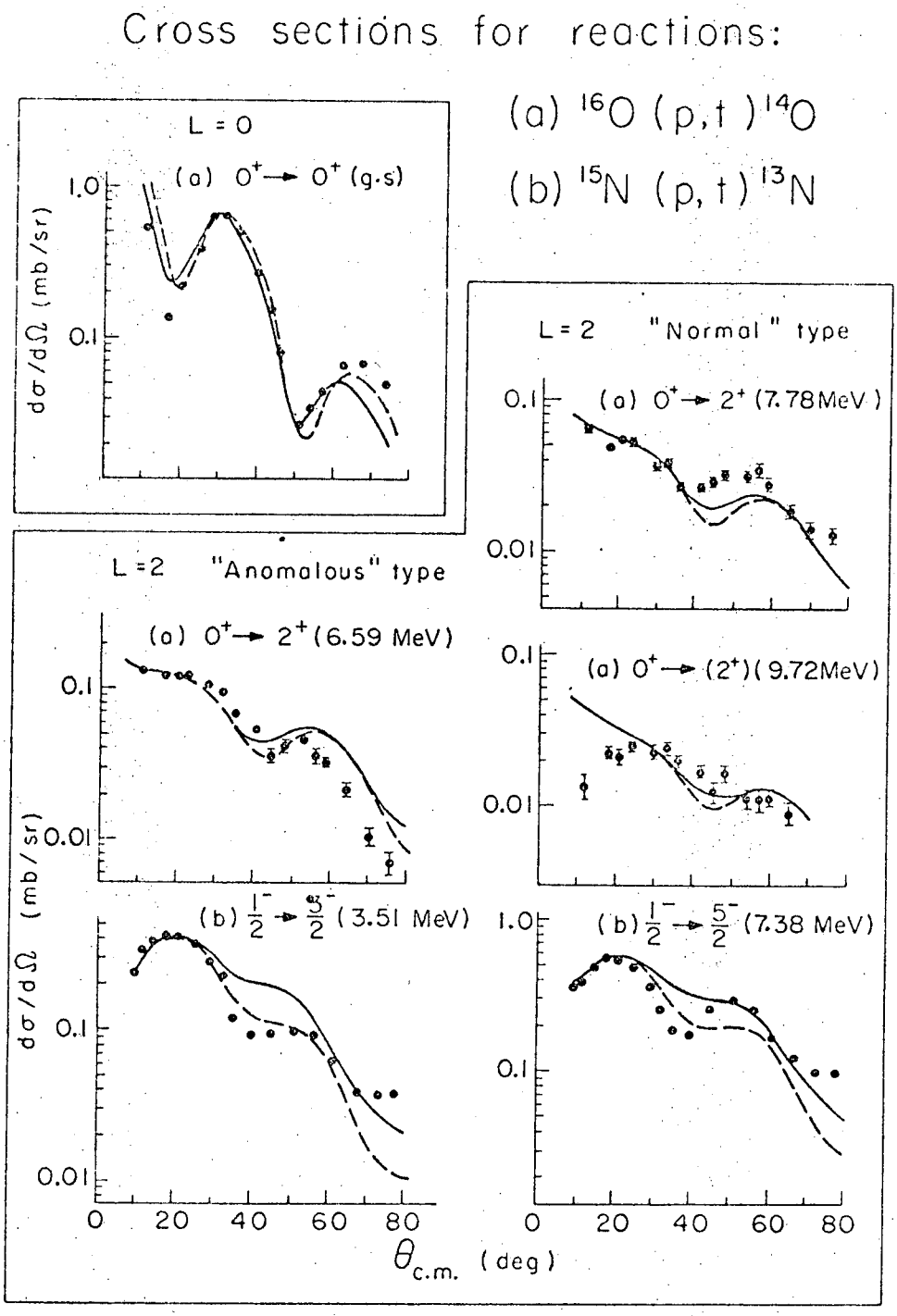

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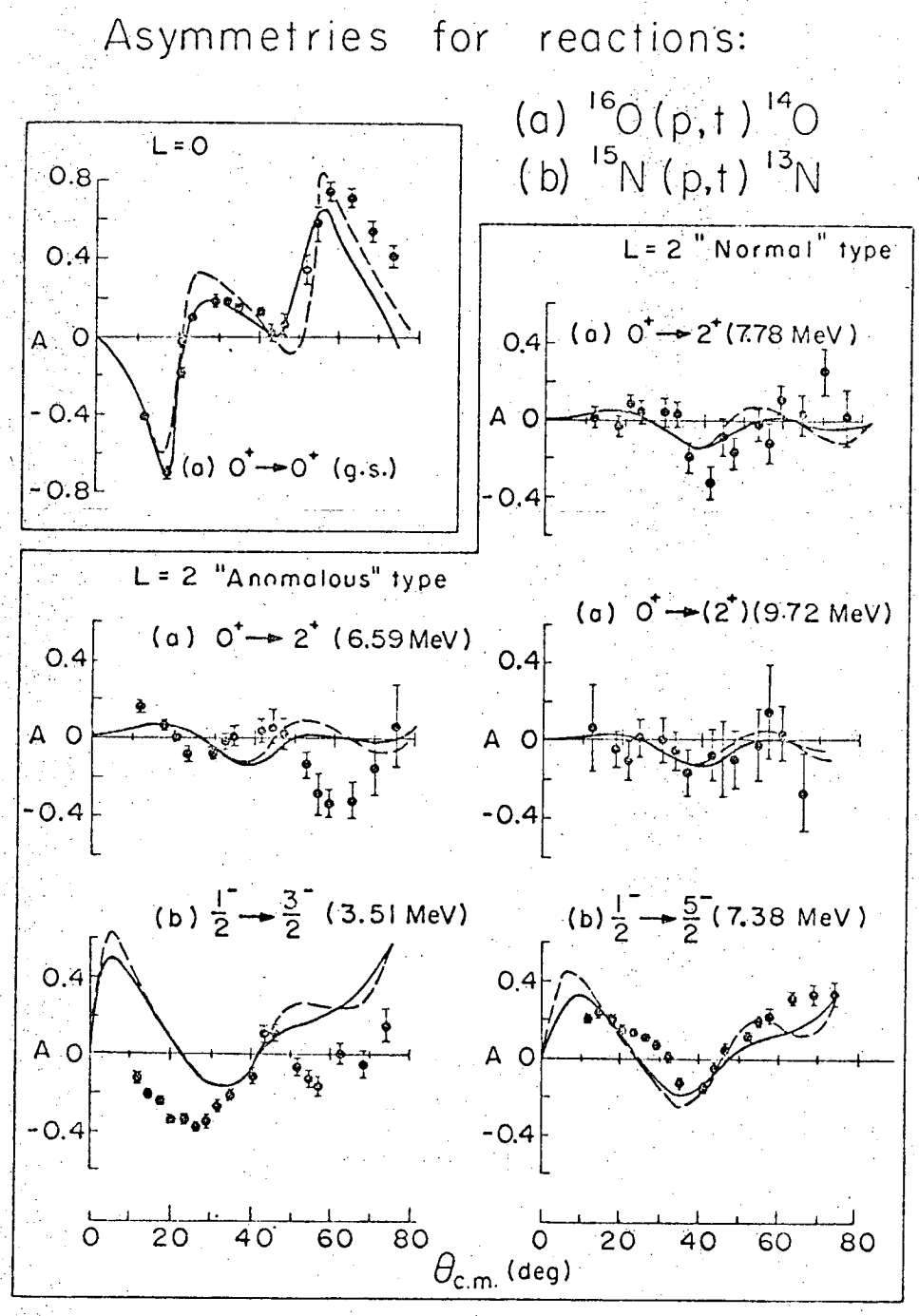
Fig. 1



XBL706-3059

Fig. 2

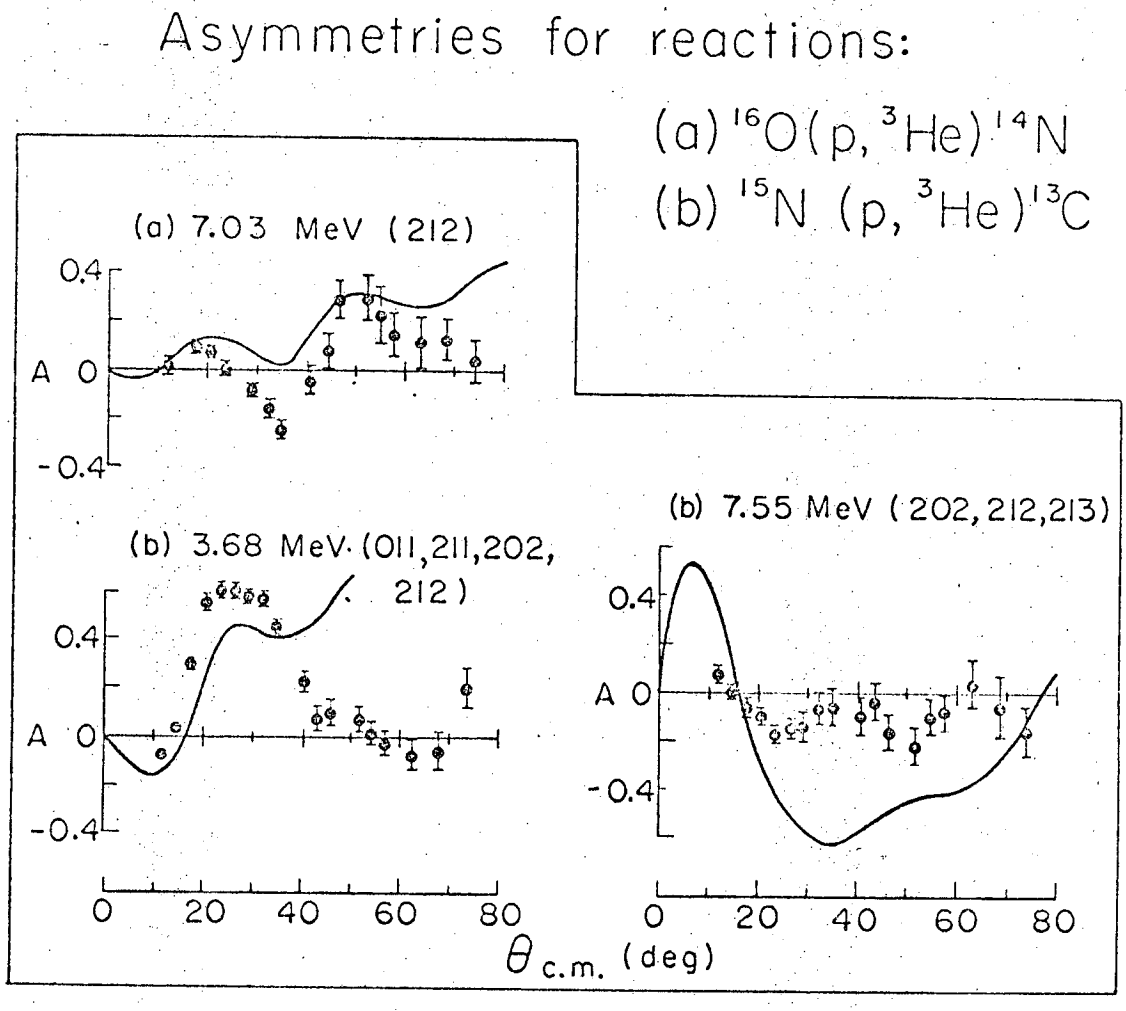


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Fig. 3

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