Cross Sections for the $O^{16}(\gamma,\pi^+)N^{16}$ Reaction*

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Cross sections for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction were determined by measuring the N^{16} radioactivity produced in water samples that were irradiated with bremsstrahlung of maximum energy varying from 100 to 300 MeV. The observed yields were corrected for contributions from photonuclear reactions involving the O^{17} and O^{18} nuclei present in the targets and for secondary reactions. The resulting cross sections reach a maximum value of 8 μb at 240 MeV. The $O^{16}(\gamma,\pi^+)N^{16}$ cross sections average about 24% of those reported previously for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. These results are in agreement with those expected from the theory outlined by Laing and Moorhouse for reactions of this type assuming surface production of pions and assuming that the transition probabilities depend much more on the total number of states available than on the specific details of the states involved.

I. INTRODUCTION

THIS paper reports the results of some work which is part of a continuing program of the study of photopion production reactions in complex nuclei in which specific final states are involved. A previous paper[1] from this laboratory reported cross sections for the $B^{11}(\gamma,\pi^-)C^{11}$ and the $B^{11}(\gamma,\pi^+)Be^{11}$ reactions. This paper is concerned with the $O^{16}(\gamma,\pi^+)N^{16}$ reaction.

Our interest in reactions of this type stems from a theoretical paper by Laing and Moorhouse[2] in which predictions were made for the cross sections expected for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. They assumed that the primary photoproduction process is a single nucleon process and that the struck nucleon undergoes transitions to discrete states of the product nucleus. The nuclear model used was a simple independent-particle model. The calculations were performed for pion production occurring throughout the entire volume of the nucleus and for pion production being restricted to the nuclear surface. Their calculated cross sections for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction based on surface production of pions agreed quite well with the experimental cross sections reported by Hughes and March[3] and by Dyal and Hummel.[1]

Experimentally the cross sections for the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction[1] were between $\frac{1}{9}$ and $\frac{1}{5}$ of those for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. Although detailed calculations using the Laing and Moorhouse approach had not been made, it was possible to account for the smaller cross sections for the production of Be^{11} by considering the relative number of initial and final states involved in the two cases. The reason that such an approach might be expected to be valid is that the results of the Laing and Moorhouse calculation for the various possible transitions occurring in the $B^{11}(\gamma,\pi^-)C^{11}$ reaction depend more on the total number of states available than on the specific details of the states.[4]

The study of the $O^{16}(\gamma,\pi^+)N^{16}$ reaction being reported here was made in order to see if the cross sections for this reaction can be accounted for in terms of the Laing and Moorhouse approach by consideration of the number of initial and final states involved. The results indicate that the cross sections for this reaction can be understood in these terms.

II. EXPERIMENTAL

The yield curve for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction was determined by measuring the radioactivity of the product nuclei in water samples that were irradiated with bremsstrahlung from the University of Illinois 300-MeV betatron. The N^{16} radioactivity measurements were made by observing the intensity of the 6.13-MeV gamma ray[5] by using scintillation-spectroscopy techniques.

Because of the short half-life of N^{16} (7.4 sec), it was necssary to arrange for rapid transfer of the water samples from the irradiation area to the counting area. This was accomplished by using a flow system that allowed the water to drain from the target holder into a container that was in contact with the face of a 3-$\times$3-in. NaI(Tl) scintillation crystal. The counter setup was located 4 ft below the bremsstrahlung beam and was shielded by a lead and steel housing. The transfer of the sample material was remotely controlled from the betatron control room; this made it possible to begin counting a sample 5 sec after the end of the irradiation.

Conductivity grade water was used as the target material in these experiments. The target container was a 52-ml aluminum chamber that was 2 cm thick. The beam entrance and exit windows of the chamber were made of $\frac{1}{32}$-in.-thick aluminum. This chamber was attached to the flow system in such a way that after

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[1] P. Dyal and J. P. Hummel, Phys. Rev. **127**, 2217 (1962).

[2] E. W. Laing and R. G. Moorhouse, Proc. Phys. Soc. (London) **70**, 629 (1957).

[3] I. S. Hughes and P. V. March, Proc. Phys. Soc. (London) **72**, 259 (1958).

[4] E. W. Laing and R. G. Moorhouse (private communication).

[5] Unless noted otherwise, all decay scheme data were taken from *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C., 1961), NRC 61-5, 6-223.

one 52-ml sample had been irradiated and drained into the counting chamber, the irradiation chamber was refilled from a reservoir by remote control. This made it possible to irradiate and count about 30 samples an hour. The betatron energy range covered in these experiments was from 100 to 300 MeV. Data were taken at 10-MeV intervals over this range with the exception of the range between 130 to 230 MeV in which data were taken every 5 MeV. The number of irradiations made at each energy varied from 60 to 160. All of the irradiations were long enough in duration to saturate the N^{16} activity. In general, all of the irradiations at a given betatron energy were made in succession. However, repeat sets of irradiations were made at most of the betatron energies in order to check the reproducibility of the results. The data from the repeat runs were in satisfactory agreement with the first set of results.

The collimated bremsstrahlung beam was monitored with a calibrated thick-walled copper ionization chamber. The ionization current collected in the chamber was measured with a vibrating reed electrometer circuit which contained an appropriate RC network to correct for the decay of the product radioactivity during the irradiation and eliminate the effects of fluctuations in the bremsstrahlung beam intensity. This chamber has recently been calibrated against a National Bureau of Standards type P2 ionization chamber.[6,7]

The gamma-ray spectra of the irradiated samples were obtained with a Radiation Counter Laboratories 512-channel pulse-height analyzer that was coupled to the 3-×3-in. NaI(Tl) scintillation crystal that was mentioned before. Each sample was ordinarily counted for 35 sec starting 5 sec after the end of the irradiation. The spectra from all of the samples run in succession at the same betatron energy were summed in the analyzer before the data were printed out. A spectrum resulting from 65 irradiations at a betatron operating energy of 250 MeV is shown in Fig. 1. The arrows between channels 150 and 200 indicate the locations of the photopeak and escape peaks of the 6.13-MeV gamma ray from N^{16}. The peaks near channels 70 and 90 are the photopeak of the 2.31-MeV gamma ray and a sum peak of the 2.31-MeV gamma ray and a 0.51-MeV positron-annihilation photon from the decay of O^{14}. The 0.51-MeV photopeak does not appear in the spectrum because the lower level discriminator was set at an energy above it in order to reduce the dead time of the system.

The assignment of the observed peaks between channels 150 and 200 as being due to N^{16} is based on both energy and half-life measurements. The energies were determined by assuming a linear extrapolation of a calibration made by observing the spectra of standard

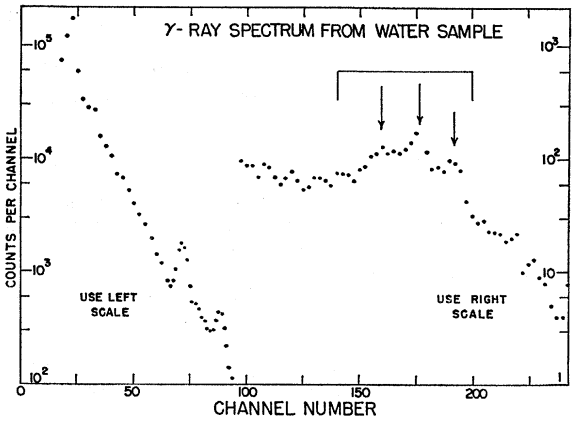

FIG. 1. Gamma-ray spectrum from 65 samples of water that were irradiated with 250-MeV bremsstrahlung. The arrows show the locations of the three peaks assigned to N^{16}. The bracket encloses the region of the spectrum that was integrated to obtain values for the yield curve shown in Fig. 2.

sources. (These standard sources gave calibration data to 2.75 MeV.) The half-life of the events in the region of the spectrum that contains the three peaks assigned to N^{16} was determined in two different ways. One method involved using the scaler-timer mode of operation of the pulse-height analyzer to record the number of counts in that region of the spectrum as a function of the time elapsed since the start of a count. The counting data from eighty irradiations at the same betatron energy (250 MeV) were summed in the analyzer to improve the counting statistics. The observed half-life was 7.3 sec which is in good agreement with the literature value (7.4 sec). The other approach used to determine the half-life of the region of the spectrum of interest was to record the counts for sets of irradiations in which the delay period before the counting was started was 8 sec longer than the normal delay period. These were then compared with the observed counts obtained after the normal delay to estimate the half-life. The half-lives obtained in this way for irradiations done at 210 and 280 MeV were 7.2 and 6.9 sec, respectively, which are in satisfactory agreement with the literature value.

A further check that the portion of the gamma ray spectrum between channels 150 and 200 is due to the 6.13-MeV gamma ray of N^{16} can be made by producing N^{16} in other nuclear reactions. We would expect that N^{16} would be produced in high yield in high-energy bremsstrahlung irradiations of fluorine targets by the $F^{19}(\gamma,2pn)N^{16}$ reaction. Samples of trifluorotoluene were irradiated with high-energy bremsstrahlung (maximum energy varying from 40 to 300 MeV) and counted in the same way as the water samples. The observed gamma-ray spectra from these samples showed the three peaks arising from the 6.13-MeV gamma ray of N^{16} in the same region of the spectrum in which they were observed for the water samples. Decay curve studies showed that their half-life was also 7.4 sec. This observation substantiates the assignment of the observed

[6] J. S. Pruitt and S. R. Domen, Natl. Bur. Std. (U. S.) Monograph 48, (1962).
[7] W. P. Swanson, R. A. Carrigan, Jr., and E. L. Goldwasser, Rev. Sci. Instr. 34, 538 (1963).

radiation in the water samples as being due to N^{16}.

The yield-curve data for the production of N^{16} from the water samples were obtained by summing the region of the spectrum containing the photopeak and escape peaks from the 6.13-MeV gamma ray. (The region that was summed is indicated by the bracket in Fig. 1.) The absolute yield values were obtained from the 6.13-MeV photopeak intensity by correcting for the efficiency of the counting system. This was done by first applying a measured geometry and absorption factor which converted the observed counting rates to the values that would have been observed for point source samples located on the face of the crystal housing. These values were then corrected for the point source counting efficiency by using a calculated photopeak efficiency factor.[8] In converting from the gamma-ray intensity to the N^{16} disintegration rate, the abundance of the 6.13-MeV gamma ray was taken as 68%.[9]

III. RESULTS

The observed yield per monitor unit[10] as a function of the bremsstrahlung maximum energy for the production of N^{16} in water targets is shown in Fig. 2. It is evident there that N^{16} activity is observed below the threshold for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction (151 MeV). This below threshold activity is expected to be due to photonuclear reactions involving the other oxygen isotopes (O^{17} and O^{18}) and secondary nuclear reactions caused by photoneutrons that are produced in the betatron, the beam collimator, and the water target. Although it is difficult to estimate the contribution to this observed yield from each of the possible sources because of the lack of information on photonuclear reaction yields at these energies, an estimate based on the yield trends observed by Edwards and MacMillan[11] for 70-MeV bremsstrahlung indicates that most of the observed yield below 151 MeV is due to the $O^{18}(\gamma,pn)$-N^{16} reaction.

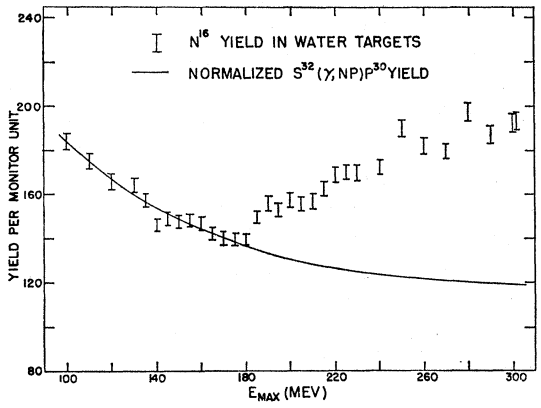

FIG. 2. Yield data (in arbitrary units) for the production of N^{16} in water targets. The solid line is a $S^{32}(\gamma,np)P^{30}$ yield curve that has been normalized to the N^{16} yields below 150 MeV. (Note the suppressed zero on the ordinate scale.)

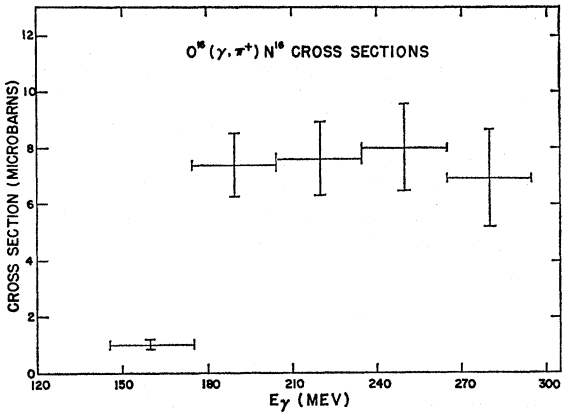

FIG. 3. Cross sections (in units of microbarns) for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction.

Before the cross sections for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction can be calculated from the observed yields, a correction must be made for the contribution to the observed yield above 151 MeV from the reactions responsible for the yield observed below 151 MeV. Since the $O^{18}(\gamma,pn)N^{16}$ reaction appears to be mainly responsible for the interference, this correction could be made by subtracting a yield curve having the same shape or energy dependence as that for the $O^{18}(\gamma,pn)$ reaction and normalized to the yield data below 151 MeV. Because the yield curve for the $O^{18}(\gamma,pn)$ reaction has not been measured, we have made the correction by using a normalized yield curve for the $S^{32}(\gamma,pn)$ reaction which has recently been determined by Van Hise.[12] We expect that there will be little difference between the energy dependences for these two (γ,pn) reactions, especially in the energy region above 100 MeV. The basis for this statement is that the yield curve for the $Ca^{40}(\gamma,pn)K^{38}$ reaction observed recently by Meyer[13] has the same shape as the $S^{32}(\gamma,pn)$ reaction above 100 MeV. The use of this yield curve should also account fairly well for the contributions from other interfering reactions, i.e., the $O^{17}(\gamma,p)N^{16}$ reaction and any secondary reactions. The normalized $S^{32}(\gamma,pn)$ yield curve that was used to correct for the interfering reactions is also shown in Fig. 2.

The yield curve for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction resulting from the subtraction of the normalized $S^{32}(\gamma,pn)$ yield

[8] C. D. Zerby and H. S. Moran, Nucl. Instr. and Methods **14**, 115 (1961).

[9] D. E. Alburger, A. Gallmann, and D. H. Wilkinson, Phys. Rev. **116**, 939 (1959).

[10] The response of the beam monitor is energy dependent. At 120 MeV one monitor unit corresponds to 4.27×10^7 ergs of energy in the bremsstrahlung beam. At 280 MeV the response is 5.62×10^7 ergs per monitor unit. The response varies approximately linearly with the bremsstrahlung maximum energy over this energy range.

[11] L. S. Edwards and F. A. MacMillan, Phys. Rev. **87**, 377 (1952).

[12] J. R. Van Hise, Ph.D. thesis, University of Illinois, Urbana, Illinois, 1963 (unpublished).

[13] R. A. Meyer, Ph.D. thesis, University of Illinois, Urbana, Illinois, 1963 (unpublished).

curve from the N^{16} yield data has been used to calculate cross sections at various photon energies by applying the cross-section analysis method of Penfold and Leiss.[14] These resulting cross-section values for 30-MeV-wide energy bins are shown in Fig. 3. The uncertainties shown there include a 15% contribution for the uncertainty in the factors used to obtain the absolute yield values from the counting data. The integrated cross section from threshold to 300 MeV is 960±160 MeV-μb.

IV. DISCUSSION

The cross sections given in Fig. 3 for the $O^{16}(\gamma,\pi^+)N^{16}$ reaction show the same energy dependence as that observed previously for the $B^{11}(\gamma,\pi^-)C^{11}$ and the $B^{11}(\gamma,\pi^+)Be^{11}$ reactions.[1] The values for the $O^{16}(\gamma,\pi^+)N^{16}$ cross sections average to be 24±4% of those reported for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction and are 1.6±0.3 times those reported for the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction.

As stated previously, the observed cross sections for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction were consistent with theoretical predictions made by Laing and Moorhouse[2] on the basis of the surface production of pions. In their calculation they assumed that the photoproduction process was a single nucleon process in which the struck nucleon undergoes transitions into discrete states of the product nucleus. They used a simple single-particle model to represent the various states involved, and they summed over the possible transitions in which the initial neutron was in the $1p_{3/2}$ shell and in which the final state in C^{11} was stable against particle emission (i.e., for $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ states for the final proton). They did calculations for both production throughout the entire nucleus and for production only on the nuclear surface. The results for volume production were about a factor of 6 greater than those for surface production. Their results for surface production were in good agreement with the experimental results[1,3] except at energies close to threshold where the neglect of small energy differences in their calculations makes them very approximate.

The Laing and Moorhouse calculations can be extended rather easily to account for the smallness of the $O^{16}(\gamma,\pi^+)N^{16}$ cross sections as compared to those for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. The extension is based on the observation that the probabilities for the various possible transitions calculated by Laing and Moorhouse depended more on the number of states available than on the specific details of the states involved.[4] This suggests that cross sections for similar reactions could be predicted by using the $B^{11}(\gamma,\pi^-)C^{11}$ results and correcting for the differences in the number of initial and final states involved. The much smaller cross sections for the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction compared to those for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction were explained in this way as being due to the much smaller number of final states in Be^{11} that are stable to particle emission.[1]

In making the extension to the $O^{16}(\gamma,\pi^+)N^{16}$ reaction we note that the known levels in N^{16} that are stable against the emission of nucleons can be accounted for in shell-model terms by configurations involving a $1p_{1/2}$ proton coupling with $1d_{5/2}$ and $2s_{1/2}$ neutrons.[15,16] This leads to the following differences between the $O^{16}(\gamma,\pi^+)N^{16}$ reaction and the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. First, the number of final states available is much smaller in the N^{16} case in which the final neutron can have only $1d_{5/2}$ or $2s_{1/2}$ assignments compared to the C^{11} case in which the final proton could be in $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, or $1d_{3/2}$ levels. Considering the $(2j+1)$ degeneracies involved, we would count 8 final states in the N^{16} case and 15 in the C^{11} case.[17] The second effect is that in the O^{16} reaction we can use only the two $1p_{1/2}$ protons for the initial particles because pion production involving a $1p_{3/2}$ proton would lead to N^{16} nuclei having a vacancy in the $1p_{3/2}$ proton shell. These nuclei would presumably be unstable to nucleon emission. Thus, we count two initially available protons in the $O^{16}(\gamma,\pi^+)N^{16}$ case compared to the four $1p_{3/2}$ neutrons initially available in the case of the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. Thus, using the relative number of initial and final states, we estimate the ratio of the cross sections for the $O^{16}(\gamma,\pi^+)N^{16}$ and $B^{11}(\gamma,\pi^-)C^{11}$ reactions to be

$$\frac{\sigma_{O^{16}(\gamma,\pi^+)N^{16}}}{\sigma_{B^{11}(\gamma,\pi^-)C^{11}}}=\frac{2}{4}\times\frac{8}{15}=0.27.$$

This agrees with the 0.24±0.04 value for the ratio that was observed experimentally.

A similar type of comparison can be made between the $O^{16}(\gamma,\pi^+)N^{16}$ and the $B^{11}(\gamma,\pi^+)Be^{11}$ reactions. The initially available protons for the photoproduction process would be the two $1p_{1/2}$ protons in the O^{16} case and the three $1p_{3/2}$ protons in the B^{11} case. For the number of final states for N^{16}, we use the eight outlined above. For Be^{11}, we note that there are two known levels that are stable against nucleon emission which are probably the $2s_{1/2}$ and the $1p_{1/2}$ levels.[18,19] This gives four final states in the Be^{11} case. The expected cross section ratio thus becomes

$$\frac{\sigma_{O^{16}(\gamma,\pi^+)N^{16}}}{\sigma_{B^{11}(\gamma,\pi^+)Be^{11}}}=\frac{2}{3}\times\frac{8}{4}=1.33.$$

[14] A. S. Penfold and J. E. Leiss, Phys. Rev. **114**, 1332 (1959).

[15] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[16] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) A242, 57 (1957).

[17] Only one of the $1p_{3/2}$ states is counted in the C^{11} case since the other three were already occupied by protons in B^{11}.

[18] I. Talmi and I. Unna, Phys. Rev. Letters **4**, 469 (1960).

[19] D. J. Pullen, A. E. Litherland, S. Hinds, and R. Middleton, Nucl. Phys. **36**, 1 (1962).

This agrees favorably with the value of 1.6±0.3 which was observed experimentally.

It thus appears that the cross sections for these reactions can be understood in terms of the Laing and Moorhouse approach with the added assumption that the number of initial and final states involved is more important than their detailed nature. So far all of the reactions studied have involved nuclei that are closely related in that they have quite similar mass numbers. It would be of interest to see if this behavior is found for similar reactions involving other nuclei in different regions of the periodic table.

ACKNOWLEDGMENTS

We would like to acknowledge the contribution made by the operating and engineering staff of the 300-MeV betatron facility in making the irradiations possible. The cross sections reported here were calculated from the yield-curve data with the aid of an IBM-7094 computer which was operated by the University of Illinois Digital Computer Laboratory and was supported by a grant from the National Science Foundation. One of us (WBW) held a National Science Foundation predoctoral fellowship during part of the time that this project was worked on.

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Study of the $Ca^{40}(d,p)Ca^{41}$ Ground State Reaction at $E_d = 14.3$ MeV*

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The proton polarization from the $Ca^{40}(d,p)Ca^{41}$ ground-state (g.s.) reaction has been measured in the angular range from 15° to 90° at a mean deuteron energy of 14.3 MeV. The $Ca^{40}(d,d)Ca^{40}$ and the $Ca^{40}(d,p)Ca^{41}$ g.s. differential cross sections were determined at the same bombarding energy and within the same angular range. A preliminary analysis of the data in terms of the distorted-wave Born approximation theory is presented. Most calculations were performed in the zero-range approximation with local optical potentials, but including the effects of nonlocality in the approximation of Perey. The inclusion of finite range improved the fit to the (d,p) cross sections but had little effect on the polarization. Although a good fit to the polarization data has not been obtained, it is clear that a spin-orbit term is needed in the deuteron optical potential, and furthermore, the indications are that the imaginary part of the spin-orbit potential has to be positive or zero.

I. INTRODUCTION

ONE-nucleon transfer reactions have, in recent years, become a very powerful tool in nuclear spectroscopy. These reactions are usually analyzed in terms of the distorted-wave Born approximation (DWBA),[1] which accounts very well for the shape of the differential cross section, particulary at forward angles. This permits in general an unambiguous l-value assignment to the observed level. The absolute cross section, as predicted by the theory however, is rather sensitive to the parameters entering the calculations, and it is well known that the absolute values of the spectroscopic factors extracted from a DWBA analysis can be in error by as much as 50%. There are also some doubts about the treatment of the nuclear interior; sometimes the agreement with experimental data is improved if a somewhat arbitrary lower cutoff (radius) is employed in the evaluation of the radial integral of the transition amplitude. In light of this situation a very extensive experimental and theoretical study of the $Ca^{40}(d,p)Ca^{41}$ and the $Ca^{40}(d,d)Ca^{40}$ reactions has recently been performed in the energy range between 7 and 12 MeV.[2,3]

Ca^{40} is a suitable target nucleus to be used as a "calibration point" of the DWBA theory, since the structures of Ca^{40} and Ca^{41} are quite well understood in terms of the shell model and the spectroscopic factors

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† On leave of absence from the Nobel Institute of Physics, Stockholm, Sweden.

[1] For the basic theory see, for instance, W. Tobocman, *Theory of Direct Nuclear Reactions*, (Oxford University Press, New York, 1961); N. Austern, *Fast Neutron Physics II*, edited by J. B. Marion and J. L. Fowler, (Interscience Publishers, Inc., New York, 1963). For a reference list to applications of the theory, see Ref. 3.

[2] R. H. Bassel, R. M. Drisko, G. R. Satchler, L. L. Lee, J. P. Schiffer, and B. Zeidman, Phys. Rev. **136**, B960 (1964).

[3] L. L. Lee, J. P. Schiffer, B. Zeidman, G. R. Satchler, R. M. Drisko, and R. H. Bassel, Phys. Rev. **136**, B971 (1964).