Cross section and analyzing power measurements for the (p,d) reaction on ^{16}O and ^{40}Ca at 200 MeV

R. Abegg, D. A. Hutcheon, and C. A. Miller
TRIUMF, Vancouver, British Columbia, Canada V6T 2A3

L. Antonuk,* J. M. Cameron,† G. Gaillard,‡ J. M. Greben,§ P. Kitching, R. P. Liljestrand,**
W. J. McDonald, W. C. Olsen, and G. M. Stinson
Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2J1

J. Tinsley††
Physics Department, University of Oregon, Eugene, Oregon 97403

P. D. Kunz
University of Colorado, Boulder, Colorado 80309
(Received 25 April 1988)

Cross sections and analyzing powers for the reactions $^{16}O(\vec{p},d)^{15}O$ and $^{40}Ca(\vec{p},d)^{39}Ca$ at $T_p=200$ MeV have been measured for the $\frac{1}{2}^-$ (0 MeV) and $\frac{3}{2}^-$ (6.18 MeV) levels in ^{15}O and for the $\frac{3}{2}^+$ (0 MeV) and $\frac{1}{2}^+$ (2.47 MeV) levels in ^{39}Ca. The angular ranges covered are $3° \leq \theta_{c.m.} \leq 47°$ and $4° \leq \theta_{c.m.} \leq 21°$, respectively, for the two reactions. Exact finite range distorted-wave Born approximation calculations are in poor agreement with the measured angular distributions of cross sections and analyzing powers. The angular distributions of the cross sections are featureless and decrease exponentially with increasing scattering angle.

I. INTRODUCTION

At low projectile energies, pickup and stripping reactions have long been used to determine the angular momentum (l) of the transition and the spin-parity (J^π) of the final state by comparing the angular distributions of differential cross section (σ) and analyzing power (A_y) with distorted-wave Born approximation (DWBA) calculations.[1] At higher energies the specific features of A_y are, however, poorly reproduced even by exact finite range (EFR) DWBA calculations.[2,3] Cross section measurements of (p,d) reactions above about 100 MeV incident proton energy reveal angular distributions with an exponential decrease with increasing scattering angle. This shape is essentially independent of the l transfer of the transition. For example, DWBA calculations for $^{13}C(\vec{p},d)^{12}C$ to the ground state and 4.94 MeV levels in ^{12}C at 200 and 400 MeV (Ref. 2) do not reproduce the pronounced structure of the analyzing power, and fail to reproduce the smooth exponential decrease of the cross section with angle. Varying the deuteron optical potential parameters for the $T_p=400$ MeV study did not lead to even crude agreement with the angular distribution of the cross section. A more critical look at the comparison of the EFR DWBA and measurement at 200 as well as at 400 MeV would lead one to the conclusion that the calculations cannot reproduce the angular distributions of either the cross sections or analyzing powers. At 400 MeV the situation is more complex due to Δ effects and contributions such as $NN \rightarrow \pi d$ that may play an important role. At 200 MeV such contributions are not important, and therefore 200 MeV data provide a critical test of the DWBA.

In order to try to understand the disconcerting fact that the EFR DWBA cannot reproduce data[2] at 200 MeV on $^{13}C(\vec{p},d)^{12}C$, we have extended the study of pickup reactions to ^{16}O and ^{40}Ca targets. Cross sections and analyzing powers were measured for transitions to the ground states and excited states in ^{15}O and ^{39}Ca.

II. EXPERIMENTAL PROCEDURE

A 200 MeV achromatic, polarized proton beam from the TRIUMF cyclotron was incident on targets of 151.1 mg/cm^2 thick H_2O or 50.3 mg/cm^2 thick natural Ca. The water was contained in a planar cell[4] with thin windows of Kapton. The reaction products were momentum analyzed in a 1.6 GeV/c medium resolution magnetic spectrometer consisting of a quadrupole magnet followed by a dipole providing a 60° bend. Time-of-flight and energy loss measurements allowed a clean separation of the deuterons from protons and tritons. The energy resolution of about 1.2 MeV (FWHM) was sufficient to resolve the ground states from the dominant excited states. In ^{39}Ca the 2.47 MeV level is unresolved from the 2.80 MeV ($\frac{7}{2}^-$) state which could contribute to the yield. The oxygen data were taken with a water target, using an empty target for background measurements. The beam current and polarization were continuously monitored using a previously calibrated in-beam polarimeter.[4]

III. EXPERIMENTAL RESULTS

The angular distributions of the cross section for the (p,d) reactions on ^{16}O and ^{40}Ca to the ground states and excited states in ^{15}O (Fig. 1) and ^{39}Ca (Fig. 2) are rather featureless and decrease exponentially with increasing

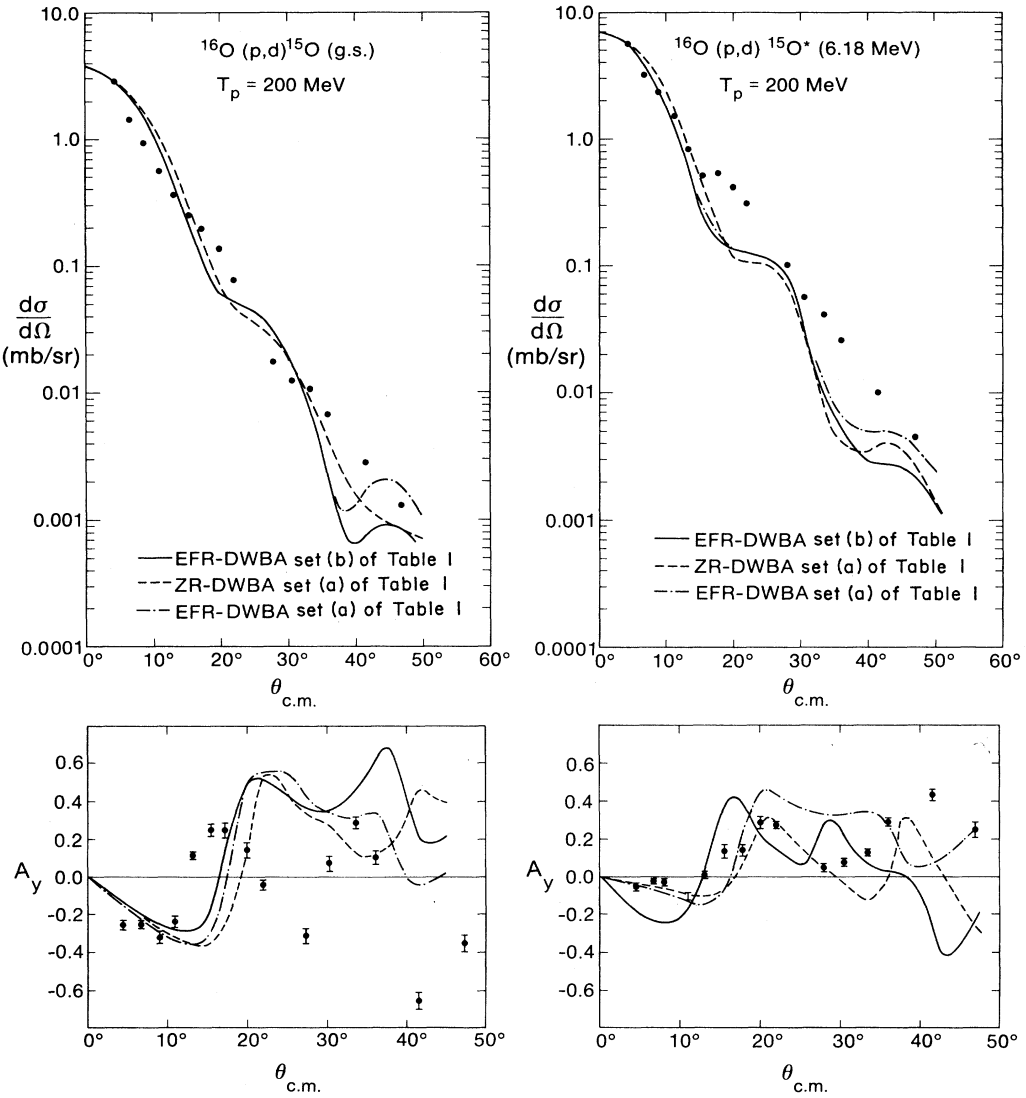

FIG. 1. Angular distribution of differential cross sections (top) and analyzing powers (bottom) for the ground state transition (left) and the transition to the excited state (right) in ^{15}O. The EFR DWBA curve using set (a) is identical to the EFR DWBA calculation using set (b) except where shown.

scattering angle. As has been observed with other targets, the angular distributions of the analyzing powers exhibit strong oscillations. The statistical errors are shown only when they are larger than the dot size. The systematic errors are estimated to be less than 10%, with the exception of the transition to the 2.47 MeV level in ^{39}Ca, where they could be as high as 20%.

IV. ANALYSIS AND DISCUSSION

Optical potential parameters for the proton channels of the ^{16}O$(p,d)^{15}$O and ^{40}Ca$(p,d)^{39}$Ca reactions for zero range (ZR) and exact finite range (EFR) DWBA calculations were obtained by extrapolating the values from Ref. 5 from 135 to 200 MeV using their equations. The deuteron potential was calculated by first extrapolating the proton parameters to half the deuteron energy and then utilizing the adiabatic folding approach of Wales and Johnson[6] [set (a), Table I]. At an energy of 200 MeV a large fraction of the breakup is in relative D and F waves rather than S and D waves. It is therefore possible that the adiabatic approach becomes questionable at these energies. The ZR and EFR DWBA calculations were carried out using DWUCK4 and DWUCK5 (Ref. 7), respectively. The Reid soft-core potential was used to generate the deuteron internal wave function and S and D waves were added coherently. The neutron form factors were calculated such that the binding energies were correct. We have also compared these calculations to predictions using recent deuteron channel parameters for ^{58}Ni$(\vec{d},d)^{58}$Ni (Ref. 8) and ^{16}O$(\vec{d},d)^{16}$O (Ref. 9) at 200 MeV as summarized in set (b) of Table I.

The Perey form of the nonlocality correction which is valid at lower energies is not justified at intermediate energies. The central potential which is used in this form is small and gives a much smaller correction in this energy range than does the equivalent Schrödinger reduction of the Dirac model.[11] In the formulation of the Dirac model the reduction factor for the local equivalent wave func-

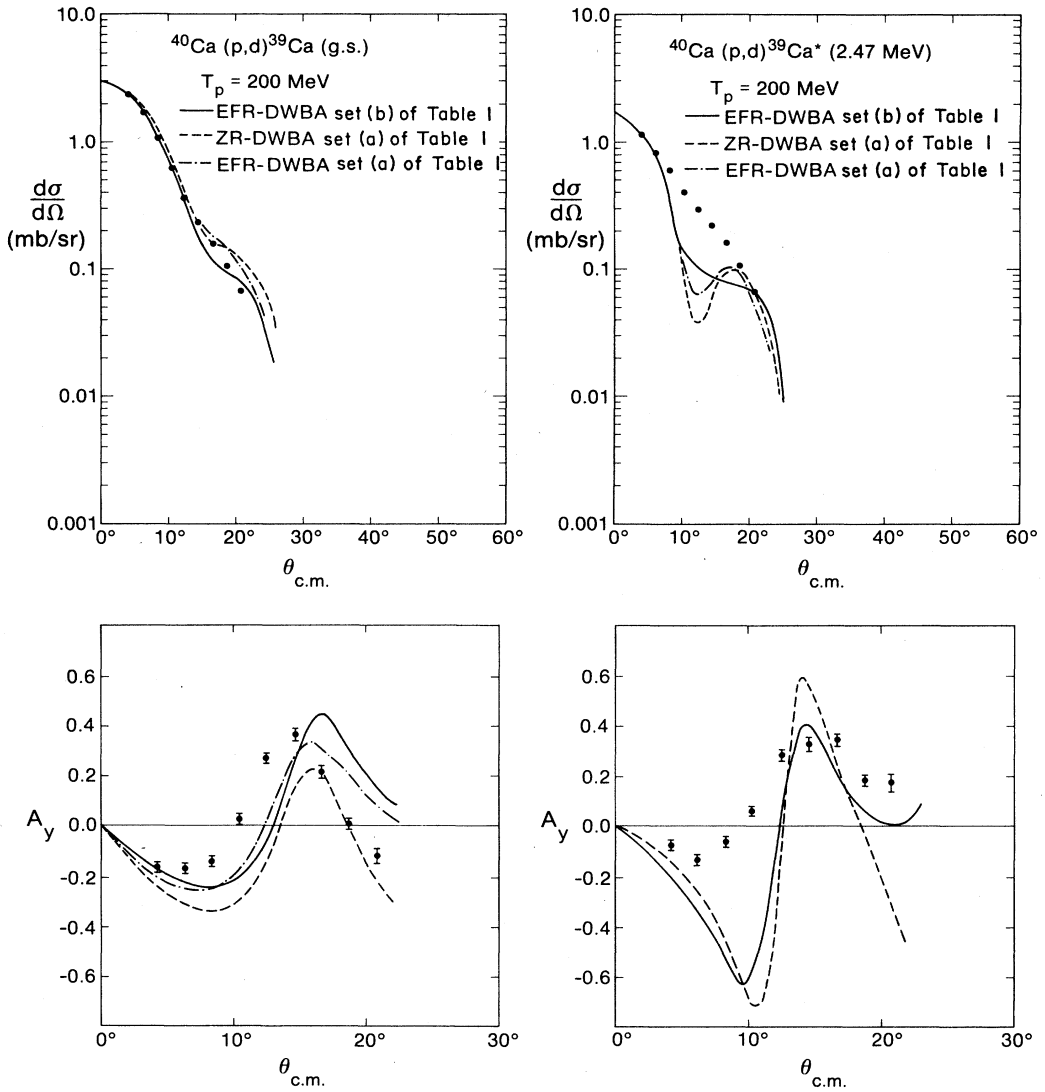

FIG. 2. Angular distributions of differential cross sections (top) and analyzing powers (bottom) for the ground state transition (left) and the transition to the first excited state (right) in ^{39}Ca. The EFR DWBA calculations using set (b) are indistinguishable from the ZR calculation for the excited state transition. The dotted lines are the results of the incoherent superposition of the calculated cross sections of the 2.47 MeV and 2.80 MeV levels.

tion is based upon the Darwin term. In the pseudoscalar theory for the one pion exchange potential (OPEP) this suppression factor is exactly canceled by the medium corrections,[12] for the transition operator. However, in the preferred[13] pseudovector derivative coupling theory for OPEP, the medium correction is very small,[14,15] and a suppression factor similar to the Darwin factor survives. A close approximation to this factor is based upon the one arising from the Darwin term

$$f(r)=\exp\tfrac{1}{2}w_{so} .$$

In the Dirac model notation we can express w_{so} as

$$w_{so}=\ln\{[E+mc^2-V(r)+S(r)]/(E+mc^2)\} ,$$

where $V(r)$ an $S(r)$ are the vector and scalar potentials, respectively, and E is the total energy of the projectile. Using the definition in DWUCK5 the spin-orbit potential is related to w_{so} by

$$V_{so}=-\frac{\hbar^2}{M}\frac{1}{r}\frac{d}{dr}w_{so} .$$

Hence, given the spin-orbit potential V_{so} it is straightforward to reconstruct the nonlocal factor by a numerical integration

$$f(r)=\exp\tfrac{1}{2}\frac{m}{\hbar^2}\int_r^\infty V_{so}(r')dr' .$$

This expression is used in a recently modified version of DWUCK5 (Ref. 16) to calculate the nonlocality corrections for our cases. The corrections were found to be insignificant.

This suppression factor does not take into account other effects such as the explicit energy dependence of the

TABLE I. Optical potential parameters. The complex potential has Woods-Saxon form and is parametrized as in Ref. 10. The Coulomb potential results from a uniformly charged sphere of radius $r_c = 1.3 A^{1/3}$ fm.

Reaction	Channel	V (MeV)	r (fm)	a (fm)	W_s (MeV)	r_I (fm)	a_I (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	W_{so} (MeV)	r_{so} (fm)	A_{so} (fm)	r_c (fm)
$^{16}O(p,d)^{15}O$	p	9.44	1.41	0.60	18.72	1.03	0.68	3.77	0.88	0.63	−2.66	0.94	0.49	1.2
	(a) d_1	34.61	1.32	0.68	13.60	1.49	0.57	3.97	1.00	0.42				1.3
	(b) d_2	45.92	1.13	0.89	23.72	1.37	0.74	5.62	0.88	0.65				1.3
$^{40}Ca(p,d)^{39}Ca$	p	14.7	1.33	0.74	16.56	1.17	0.82	2.29	1.02	0.60	−2.35	1.00	0.62	1.2
	(a) d_1	50.63	1.22	0.73	13.16	1.42	0.59	4.64	1.02	0.60	−0.97	1.00	0.62	1.3
$^{58}Ni(\vec{d},d)$	(b) d_2	41.60	1.24	0.82	13.3	1.45	0.69	3.90	1.08	0.77				1.3

vector and scalar potentials and the ranges of the nucleon-nucleon potentials.

For ^{16}O, all predictions of the angular distributions of the cross sections are similar in shape and result only in different extracted spectroscopic factors (summarized in Table II). Comparison of the predicted and observed cross sections reveals the following: (1) the oscillations in predicted angular distributions are more pronounced than those of the data, and (2) such oscillations as do exist in the data appear shifted in angle with respect to those of the DWBA calculations. These discrepancies may indicate an incorrect weighting by our DWBA model of the contributions from large and small impact parameters. The required $l=1$ angular momentum transfer favors small impact parameters, but the strong absorption favors the larger ones of the nuclear surface. Finite range effects do not play a role, nor is there great sensitivity to the choice of optical model parameters. The analyzing powers at forward angles are large and negative for the ground state ($j=l-\frac{1}{2}$ pickup), but near zero for the excited state ($j=l+\frac{1}{2}$). Such behavior has previously been noted in $^{13}C(\vec{p},d)^{12}C$ at 200 MeV (Ref. 2) and $^{24}Mg(\vec{p},d)^{23}Mg$ at 150 MeV (Ref. 3). The predicted analyzing power angular distributions disagree with the data over the full angular range.

The spectroscopic factors (Table II) were extracted by normalizing to the observed cross section at the most forward angle. In view of the failure to predict the angular distributions, especially for the $^{16}O(p,d)^{15}O$(g.s.) transition, these spectroscopic factors should be treated with some caution.

TABLE II. Summary of spectroscopic factors. (a) refers to deuteron potential set (a) of Table I; (b) refers to the deuteron potential set (b); ZR refers to spectroscopic factors obtained from the zero range calculations.

Transition	E_x (MeV)	J^π	C^2S (a)	C^2S (b)	C^2S ZR	Ref.
$^{16}O(p,d)^{15}O$	0	$\frac{1}{2}^-$	1.00	1.43	0.59	1.46[a]
$^{16}O(p,d)^{15}O^*$	6.18	$\frac{3}{2}^-$	1.67	2.41	1.15	1.62[a]
$^{40}Ca(p,d)^{39}Ca$	0	$\frac{3}{2}^+$	1.96	1.41	1.34	2.58[a]
$^{40}Ca(p,d)^{39}Ca^*$	2.47	$\frac{1}{2}^+$	0.48	1.20	0.56	0.60[a]
$^{40}Ca(p,d)^{39}Ca^*$	2.80	$\frac{7}{2}^-$	0.20			0.25[a]

[a]References 17 and 18.

A coupled channel calculation (using CHUCK2) was carried out for the excited state in ^{15}O via the 3^- state in ^{16}O using a deformation parameter $\beta=0.25$. In this collective model calculation the deuteron D state was not included, but the full sum rule for the transfer was observed. This calculation showed insignificant coupled channel contributions.

For the $^{40}Ca(\vec{p},d)^{39}Ca$(g.s.) transition all calculations reproduce the angular distribution of the cross section fairly well. This is surprising in view of the fact that the parameters for the deuteron potential were taken from 200 MeV $^{58}Ni(\vec{d},d)$ and no scaling with energy was performed, nor was the mass difference taken into account (except for the radius parameters). The extracted spectroscopic factors from EFR calculations are in fair agreement with published values obtained at lower energies. Our experiment could not resolve the 2.47 MeV ($\frac{1}{2}^+$) state from that at 2.80 MeV ($\frac{7}{2}^-$). Even though the latter has a small spectroscopic factor, it is an $l_n=3$ pickup which is favored over the $l_n=0$ of the 2.47 MeV level. In the analysis the spectroscopic factors from Ref. 18 together with set (a) of optical potential parameters (Table I) were used to calculate in exact finite range the contributions to the yield of the two transitions. The partial cross sections for each spin state were added incoherently and renormalized at forward angles to obtain the spectroscopic factors in Table II. It is seen (Fig. 2, dotted line) that the contribution from the $\frac{7}{2}^-$ transition fills in the dip in the calculated cross section from the 2.47 MeV level and dampens the analyzing power oscillations. The $l_n=1$ state at 3.02 MeV in ^{39}Ca has a small spectroscopic factor in the range 0.01 and 0.04 and is therefore thought not to contribute to the yield. The calculated contribution of this transition was insignificant.

V. CONCLUSIONS

We find that the angular distributions of the cross sections for the pickup reactions $^{16}O(p,d)$ and $^{40}Ca(p,d)$ at 200 MeV to the ground states and excited states in the residual nuclei are featureless and fall off exponentially with increasing scattering angle. This shape is reproduced by the exact finite range DWBA calculation (Fig. 2) only for the ground state transition in $^{40}Ca(p,d)^{39}Ca$.

The extracted spectroscopic factors are in fair agreement with published values, although with some uncertainty in the case of $^{16}O(p,d)^{15}O$ due to the difference between the shapes of observed and calculated angular distributions. The predictions of the angular distributions of the analyzing powers when compared to data do not indicate a clear preference of the exact finite range calculations over the zero range predictions. It has been suggested[19] that increasing the proton channel spin-orbit potential [obtained from Kerman, McManus, and Thaler (KMT)] to create the oscillations necessary to fit elastic scattering data results in good accord between DWBA and experiment at $T_p = 500$ MeV. In our approach we have used values that do describe elastic scattering correctly, so we do not have the freedom to arbitrarily increase the spin-orbit term. The results indicate that the failure of the DWBA, which was observed earlier at 150 MeV for ^{24}Mg (Ref. 3), and at 200 MeV for ^{13}C (Ref. 2) extends to ^{16}O at 200 MeV, but becomes less significant for larger nuclei, like ^{40}Ca. The failure of the conventional DWBA at intermediate energies for the lighter nuclei could have various causes. The recent success of Dirac approaches at higher energies[20] may suggest that the nonrelativistic treatment of the distorted waves and bound-state wave functions is at fault. However, lacking a consistent relativistic theory of (p,d) reactions, it is difficult to verify this conjecture. For example, there is little virtue in modifying the proton optical potentials as suggested by the Dirac approach (like the wine bottle shape), when one does not at the same time include the consequences of relativistic formulations for the deuteron optical potential. Since in this study even variations in the deuteron optical potential do not change the results dramatically, the observed discrepancy between theoretical and experimental results suggests a breakdown of the DWBA itself, rather than a problem in input. Modifications of the DWBA at intermediate energies have recently been considered in the context of a microscopic distorted-wave series.[21] Significant deviations from the standard DWBA were observed; however, no uniform agreement with intermediate energy data was (yet) accomplished. We conclude that further theoretical studies are necessary to establish the causes of the failure of the conventional DWBA theory to reproduce the present and previous $(\vec{p},d)$ data.

ACKNOWLEDGMENTS

One of the authors (R.A.) would like to thank Dr. A. Moalem, Bersheba University of the Negev, for fruitful and valuable discussions. This work was supported in part by the Natural Sciences and Engineering Council of Canada.

*Present address: The University of Michigan Medical Center, Department of Radiation Oncology, Ann Arbor, MI 48109.
†Present address: IUCF, Bloomington, IN 47405.
‡Present address: Université de Geneve, Department de Physique Nucléaire et Corpusculaire, CH-1211 Geneve 4, Switzerland.
§Present address: Theoretical Physics Division, CSIR/NR/MS, P.O. Box 395 Pretoria 0001, South Africa.
**Present address: EG&G Los Alamos, P.O. Box 809, 1100 4th Street, Los Alamos, NM 87544.
††Present address: Arizona State University, Tempe, AZ 85287.

[1]S. E. Vigdor, R. D. Rathmell, H. S. Liers, and W. Haeberli, Nucl. Phys. **A210**, 70 (1973); B. Mayer, J. Gasset, J. L. Escudie, and H. Kamitsubo, *ibid.* **A177**, 205 (1971; N. S. Chant, P. S. Fisher, and D. K. Scott, *ibid.* **A99**, 669 (1967).
[2]R. P. Liljestrand, J. M. Cameron, D. A. Hutcheon, W. J. McDonald, R. Macdonald, C. A. Miller, W. C. Olsen, J. J. Kraushaar, J. R. Shepard, J. G. Rogers, J. T. Tinsley, and C. E. Stronach, Phys. Lett. **99B**, 311 (1981), and references therein.
[3]D. W. Miller, J. D. Brown, D. L. Friesel, W. W. Jacobs, W. P. Jones, H. Nann, P. Pichardo, J. Q. Yang, P. W. F. Alons, and J. J. Kraushaar, Phys. Rev. C **33**, 22 (1986), and references therein.
[4]P. Kitching, C. A. Miller, W. C. Olsen, D. A. Hutcheon, W. J. McDonald, and A. W. Stetz, Nucl. Phys. **A340**, 423 (1980).
[5]P. Schwandt, H. O. Meyer, W. W. Jacobs, A. D. Bacher, S. E. Vigdor, M. D. Kaitchuck, and T. R. Donoghue, Phys. Rev. C **26**, 55 (1982).
[6]G. L. Wales and R. C. Johnson, Nucl. Phys. **A274**, 168 (1976).
[7]DWUCK4, DWUCK5; P. D. Kunz, University of Colorado, Boulder, CO 80309.
[8]Ngyen van Sen, J. Arvieux, Ye Yanlin, G. Gaillard, B. Bonin, A. Boudard, G. Bruge, J. C. Lugol, R. Babinet, T. Hasegawa, F. Soga, J. M. Cameron, G. C. Neilson, and D. M. Sheppard, Phys. Lett. **156B**, 185 (1985).
[9]Ngyen van Sen, Ye Yanlin, J. Arvieux, G. Gaillard, B. Bonin, A. Boudard, G. Bruge, J. C. Lugol, T. Hasegawa, F. Soga, L. E. Antonuk, J. M. Cameron, S. T. Lam, G. C. Neilson, G. Roy, D. M. Sheppard, and R. Babinet, Nucl. Phys. **A464**, 717 (1987).
[10]P. Schwandt and W. Haeberli, Nucl. Phys. **A110**, 585 (1968).
[11]B. C. Clark, R. L. Mercer, and P. Schwandt, Phys. Lett. **122B**, 211 (1983).
[12]E. D. Cooper, A. O. Gattone, and M. H. Macfarlane, J. Phys. G **9**, L131 (1983).
[13]B. D. Serot and J. D. Walecka, *Advances in Nuclear Physics* (Plenum, New York, 1986), Vol. 16, p. 4.
[14]E. D. Cooper, A. O. Gattone, and M. H. Macfarlane, Phys. Lett. **130B**, 359 (1983).
[15]P. D. Kunz and E. Rost (unpublished).
[16]DWUCK5, P. D. Kunz, University of Colorado, Boulder, CO 80309.
[17]D. Bachelier, M. Bernas, I. Brissaud, C. Détraz, and P. Radvanyi, Nucl. Phys. **A126**, 60 (1969).
[18]I. S. Towner, Nucl. Phys. **A126**, 97 (1969).
[19]H. Ohnuma, F. Irom, B. Aas, M. Haji-Saeid, G. J. Igo, G. Pauletta, A. K. Rahbar, A. T. M. Wang, C. A. Whitten, Jr., M. M. Gazzaly, J. B. McClelland, and T. Hasegawa, Phys. Lett. **147B**, 253 (1984).
[20]J. A. McNeil, J. R. Shepard, and S. J. Wallace, Phys. Rev. Lett. **50**, 1439 (1983).
[21]J. M. Greben, Phys. Rev. C **29**, 381 (1984).