^{26}Mg($^{6}\vec{\text{Li}}$,^{7}Li)^{25}Mg reaction at 60 MeV

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Angular distributions of differential cross section and vector analyzing power have been measured for the ^{26}Mg($^{6}\vec{\text{Li}}$,^{7}Li)^{25}Mg reaction at 60 MeV bombarding energy. Finite-range distorted-wave Born approximation calculations were found to reproduce much of the structure of the data, although the predictions were approximately 3° out of phase with the data. Finite-range coupled-channels Born approximation calculations including inelastic excitations in ^{6}Li and ^{7}Li, using coupling schemes derived from elastic scattering analyses, modified the predictions only slightly and did not remove the phase discrepancy.

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I. INTRODUCTION

Observables for the elastic and inelastic scattering of polarized heavy ions are known to be highly sensitive to couplings in the projectile [1]. However, despite the fact that several polarized heavy ion sources have been developed worldwide, no studies have been published of the (^{6}Li,^{7}Li) reaction initiated by polarized ^{6}Li [1]. Studies of the (^{6}Li,^{7}Li) reaction with unpolarized ^{6}Li are also rare.

A greater body of work exists for the (^{7}Li,^{6}Li) reaction with polarized ^{7}Li, where finite-range distorted-wave Born approximation (FRDWBA) and coupled-channels Born approximation (CCBA) studies have been performed. Turkiewicz *et al.* found that calculations of differential cross sections and analyzing powers for the ^{26}Mg($^{7}\vec{\text{Li}}$,^{6}Li)^{27}Mg reaction were highly sensitive to couplings in the projectile [2]. With neutron transfer assumed to take place only from the ground state of ^{7}Li, the inclusion of reorientation of the ^{7}Li ground state and coupling between the ground state and the first excited state of ^{7}Li at 0.478 MeV produced only a slight improvement to the description of the data yielded by a simple FRDWBA calculation. However, the data were adequately described when neutron transfer was included from the first excited state of ^{7}Li, in addition to that from the ground state. Karban *et al.* performed a similar analysis of data for the ^{54}Fe($^{7}\vec{\text{Li}}$,^{6}Li)^{55}Fe reaction and reported that FRDWBA calculations were sufficient to describe vector analyzing power data for the ground and first excited states of ^{55}Fe [3]. However, they also reported that the introduction of inelastic couplings in ^{7}Li was necessary to reproduce their T_{20} and T_{21} data. Karban *et al.* also analyzed data for the ^{54}Fe($^{7}\vec{\text{Li}}$,^{6}He)^{55}Co reaction [4] and obtained a good description of the data with CCBA calculations including inelastic couplings in ^{7}Li.

II. EXPERIMENT

The experiment was performed using the polarized heavy ion source [5] and tandem Van de Graaff accelerator [6] at the Nuclear Structure Facility, SERC Daresbury Laboratory. The ($^{6}\vec{\text{Li}}$,^{7}Li) data analyzed in the present work were obtained simultaneously with the scattering and charge-exchange data published by Ward *et al.* [7,8], who gave a detailed description of the data acquisition [8].

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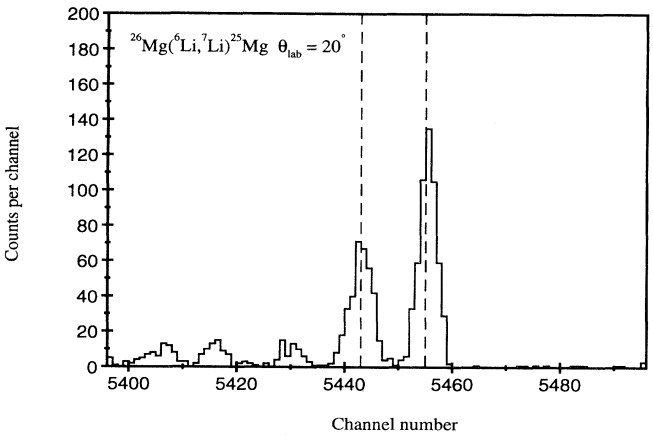

FIG. 1. Sample ^{7}Li spectrum. The right-hand peak corresponds to the formation of ^{25}Mg and ^{7}Li in their ground states, while the left-hand peak is the sum of two peaks each corresponding to the formation of one residual in the ground state and the other residual in the first excited state.

A sample ^{7}Li spectrum is shown in Fig. 1. The ^{7}Li spectra were complicated by the fact that ^{7}Li has a first excited state at only 0.478 MeV of excitation. This state was strongly excited, causing each state in ^{25}Mg to be associated with two peaks in the ^{7}Li spectra, corresponding to the formation of ^{7}Li in the ground and first excited states. Owing to this phenomenon, it was not possible to resolve the peak corresponding to the first excited state of ^{25}Mg at 0.585 MeV. Thus, this work presents angular distributions of differential cross section and vector analyzing power for the ^{26}Mg($^{6}\vec{\text{Li}}$,^{7}Li)^{25}Mg populating the ground state of ^{25}Mg only. The analyzing power data are presented using the Madison Convention [9]. The closure of the Nuclear Structure Facility prevented the measurement of the analyzing powers T_{20}, T_{22}, and T_{21}.

III. ANALYSIS

A. Optical potential

The interaction between the projectile and target nuclei was described by the optical potential $U(r)$ given by

$$U(r) = V_c(r) - V_0 f(x_0) - i\left(W_s f(x_s) - 4a_d W_d \frac{d}{dr} f(x_d)\right), \quad (1)$$

where the potential form factors $f(x_n)$ have the Woods-Saxon shape given by

$$f(x_n) = (e^{x_n} + 1)^{-1} \quad (2)$$

and

$$x_n = \frac{r - r_n A^{1/3}}{a_n}, \quad (3)$$

where r_n and a_n are the reduced radius and diffuseness of the potential respectively. V_c is the Coulomb potential due to a sphere of 1.25 fm reduced radius.

B. Spectroscopic amplitudes

Spectroscopic amplitudes for the $1p_{3/2}$ and $1p_{1/2}$ transfers in $^{6}\text{Li}_{\text{g.s.}} \rightarrow ^{7}\text{Li}_{\text{g.s.}}$ and $^{6}\text{Li}_{\text{g.s.}} \rightarrow ^{7}\text{Li}^{*}$ were taken from the tabulation of Cohen and Kurath [10]. The spectroscopic amplitude for the $1p_{3/2}$ transfer between the 3^{+} (2.18 MeV) state of ^{6}Li and the ground state of ^{7}Li, that is $^{6}\text{Li}^{*} \rightarrow ^{7}\text{Li}_{\text{g.s.}}$, is equal the amplitude for the $1p_{3/2}$ transfer $^{7}\text{Li}_{\text{g.s.}} \rightarrow ^{6}\text{Li}^{*}$. Shell-model spectroscopic amplitudes for transitions between the ground state of ^{26}Mg and states in ^{25}Mg were taken from the work of Ward *et al.* [8]. The bound state orbitals were calculated from separation energies in a Woods-Saxon potential with $r_0 = 1.25$ fm and $a_0 = 0.65$ fm.

C. Calculations

1. *DWBA calculations*

FRDWBA calculations were performed using the King's College London version [11] of the code FRUCK2 [12,13]. Initial calculations were performed with the entrance channel parameters of set 1 and the exit channel parameters of set 2 in Table I. Set 1 was derived by Ward *et al.* [7] from an optical model analysis of $^{6}\vec{\text{Li}} + ^{26}$Mg elastic scattering data obtained simultaneously with the ($^{6}\vec{\text{Li}}$,^{7}Li) data presented here. Set 2 was derived by Cook *et al.* from an optical model analysis of data for ^{7}Li scattering by ^{25}Mg at 89 MeV [14]. The results of the calculation are shown as solid lines in Fig. 2. The magnitude and slope of the differential cross section data are well reproduced. However, the differential cross section data exhibits maxima near $\theta_{\text{c.m.}} = 17°$, 25°, and 33°, whereas the FRDWBA predicts maxima near 19°, 27°, and 36°. Similarly, the analyzing power data have maxima near 14° and 20° and a minimum at 17°, whereas the FRDWBA predicts corresponding structures near 16°, 23°, and 20°. Thus, although much of the structure present in the differential cross section and analyzing power data was reproduced, the FRDWBA predictions were approximately 3° out of phase with the data.

To test whether this difference in phase arose from

TABLE I. Parameters for the FRDWBA and CCBA analysis of data for the reaction ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg. The Coulomb radius r_c was assumed to be 1.25 fm in all cases. Potential depths are in MeV and geometric parameters are in fm.

Set	V_0	r_0	a_0	W_s	r_s	a_s	Reference
1	166.430	1.150	0.847	15.663	2.010	0.727	[7]
2	142.740	1.300	0.800	36.880	1.300	0.800	[14]
3	208.600	1.210	0.750	19.800	1.790	0.890	[15]

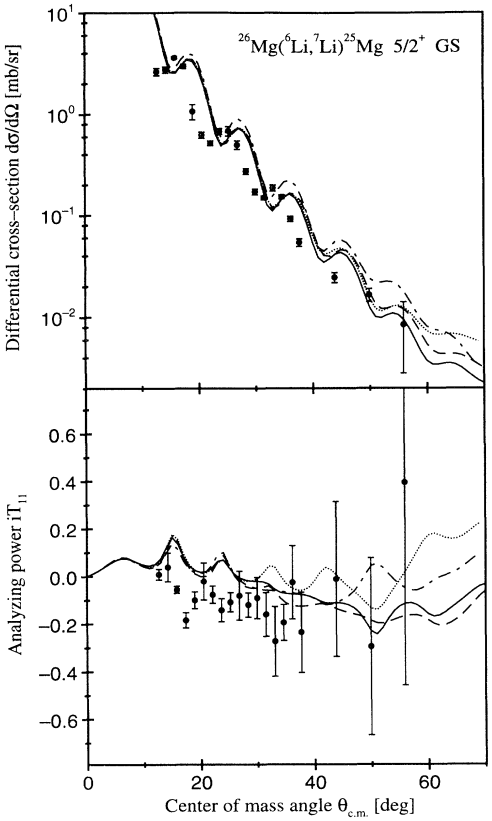

FIG. 2. FRDWBA predictions for the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction using different optical model parameter sets.

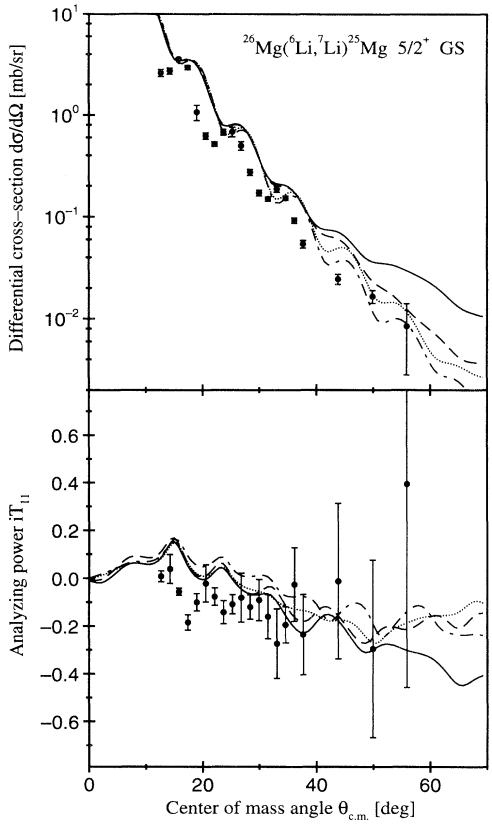

FIG. 3. FRESCO predictions for the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction. The dotted lines are FRDWBA predictions, the dot-dashed lines are the results of CCBA calculations using the coupling scheme shown in Fig. 4(a), the dashed lines include ground state reorientation of ^{7}Li only, and the solid lines correspond to the coupling scheme shown in Fig. 4(b).

poor parametrization of the exit channel, calculations were performed with other potential sets describing the ^{7}Li + ^{25}Mg system. Parameter set 3 of Table I, which Schumacher *et al.* [15] used in their FRDWBA analysis of the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction at 36 MeV, was tested. The corresponding prediction is shown as a dashed line in Fig. 2. Employing parameter set 1 of Table I in both the entrance and exit channels was also tried, with the results shown as a dotted line in Fig. 2. Calculations were also performed with deformed optical potentials derived from a coupled-channels analysis [7] of differential cross section data, for elastic and inelastic scattering, in both the entrance and exit channels, yielding the dot-dashed line in Fig. 2. The FRDWBA predictions obtained with these four different combinations of parameter sets are similar and all exhibit a $\sim 3^{\circ}$ phase discrepancy with the data.

2. *CCBA calculations*

Since the choice of optical model parameters had little effect on the predictions, it was inferred that the discrepancy between the data and the predictions stemmed from something other than poor parametrization of the exit channel. Consequently, a CCBA analysis of the ($^{6}\vec{\text{Li}}$,^{7}Li) data was performed using version FRV of the finite-range coupled-channels code FRESCO [16]. First, the FRDWBA analysis performed with FRUCK2 was repeated using FRESCO. The results obtained were very similar to those described earlier, indicating agreement between the two codes. The dotted lines in Fig. 3 are the results of a FRESCO FRDWBA calculation using potential sets 1 and 2 in the entrance and exit channels, respectively.

Couplings between the ground state of ^{6}Li and the $T = 0$ triplet of excited states at 2.18, 4.31, and 5.65 MeV were introduced using the techniques described by Ward *et al.* [7] and the scheme shown in Fig. 4(a). The results of the calculation are shown as dot-dashed lines in Fig. 3. The introduction of couplings in ^{6}Li affected the magnitude of the predicted analyzing power and generated more oscillatory structure. However, the phases of the data and the predictions still differ by approximately 3°. This calculation was performed using parameter sets 1 and 2 in the entrance and exit channels, respectively. Ward *et al.* [8] demonstrated that the inclusion of projectile excitations degraded the description of the elastic scattering differential cross section data. They also showed that acceptable reproduction of the elastic scat-

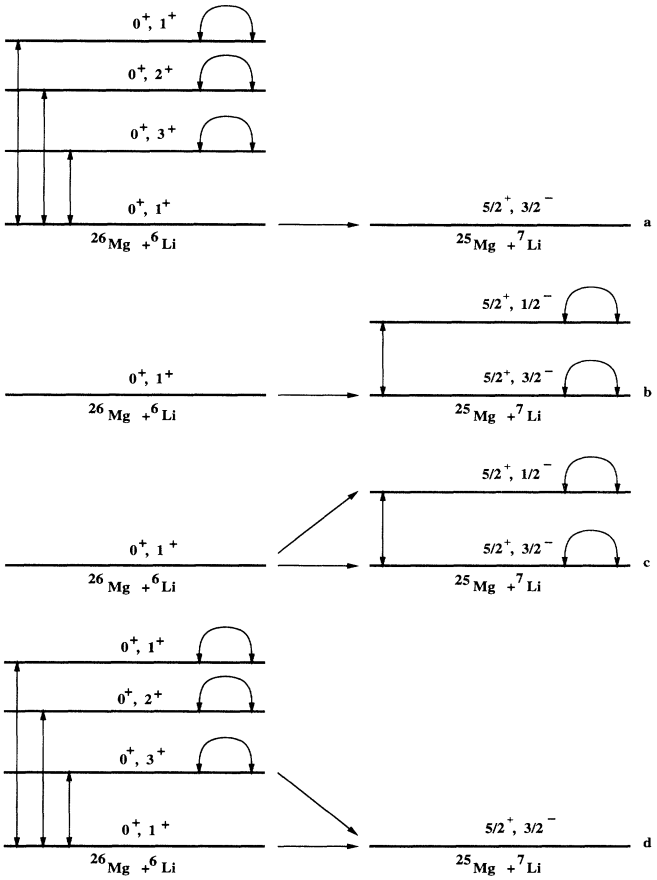

FIG. 4. CCBA coupling schemes for the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction. The first spin parity refers to the target-residual nucleus, while the second refers to the projectile-ejectile.

tering differential cross section data was restored when the optical potential was modified. The CCBA calculation described earlier was repeated using the modified parameter set in the entrance channel, but the results for the (^{6}Li,^{7}Li) reaction were found to be almost identical to the results obtained using the unmodified parameter set.

Reorientation of the ground state of ^{7}Li was then included in the calculations. Coulomb reorientation was included with $M(E2) = 5.22e$ fm^2, while the deformation length for nuclear reorientation was assumed to be $\delta_2 =$ 2.37 fm for both the real and imaginary potentials. These values were used by Kuburas *et al.* in their study of the elastic and inelastic scattering of polarized ^{7}Li by ^{54}Fe at 70 MeV [17] and by Karban *et al.* in their study of the ^{54}Fe($^{7}\vec{\text{Li}}$,^{6}Li)^{55}Fe reaction [3]. To keep processing time to a minimum, the ^{6}Li inelastic excitations described in the preceding paragraph were omitted from this calculation. The results of this calculation are shown as dashed lines in Fig. 3. The calculation was then extended to include coupling between the ground state of ^{7}Li and the $\frac{1}{2}^-$ first excited state at 0.478 MeV, using the scheme shown in Fig. 4(b). The Coulomb coupling strength was calculated from the $B(E2)$ value for the transition between these states, yielding $M(E2) = 5.76\,e$ fm^2. Again, nuclear coupling was included with $\delta_2 = 2.37$ fm for both the real and imaginary potentials. These values were also used by Kuburas *et al.* [17] and Karban *et al.* [3]. The results of these calculations are shown as solid lines in Fig. 3. The introduction of inelastic excitation of ^{7}Li has generated more oscillatory structure, but the 3° phase difference between prediction and data is still present.

The preceding analysis demonstrated that the discrepancy between the data and the FRDWBA predictions was not caused by inelastic excitations in ^{6}Li and ^{7}Li. It remained possible that nucleon transfers to and from excited states of the projectile or ejectile might have an effect. The solid lines in Fig. 5 are the results of calculations using the coupling scheme shown in Fig. 4(c). These predictions differ only slightly from those calculated with ^{7}Li inelastic excitations alone. The dotted lines in Fig. 5 are the results of FRDWBA calculations (as in Fig. 3).

Calculations including nucleon transfer to excited states in ^{6}Li are not so straightforward, as the excited states of ^{6}Li are unbound and known to have strong $\alpha+d$ cluster structure. The dashed lines in Fig. 5 include rotational excitation of ^{6}Li to the first excited state followed by the addition of a neutron, using the coupling scheme

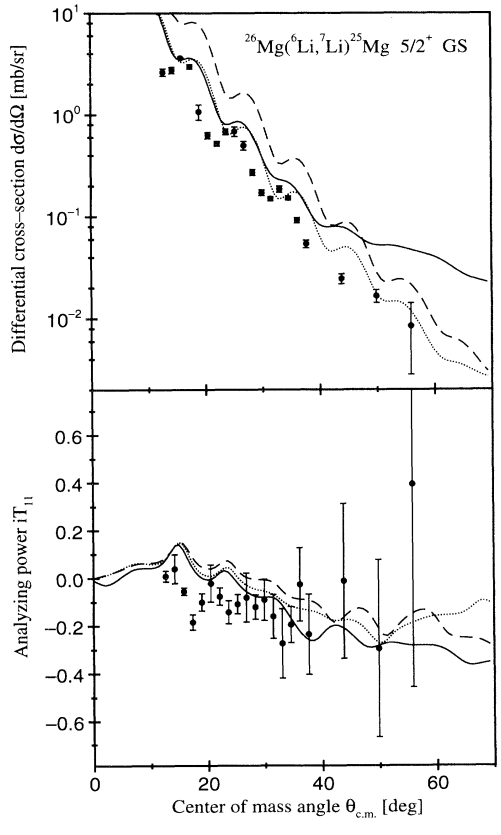

FIG. 5. FRESCO predictions for the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction. The dotted lines are FRDWBA predictions, while the solid and dashed lines are the results of CCBA calculations using the coupling schemes shown in Figs. 4(c) and 4(d), respectively.

depicted in Fig. 4(d). The differential cross section data are overpredicted by this calculation, while the predicted vector analyzing power is very similar to that predicted by the FRDWBA. The overprediction of the differential cross section may be interpreted as resulting from the approximation of an unbound state with a bound state. A CCBA calculation using a modified parameter set in the entrance channel, which reproduced the elastic scattering differential cross section data rather better than that using set 1, gave almost identical results for the (^{6}Li,^{7}Li) reaction observables. It should be noted that these calculations do not take account of either the unbound nature of ^{6}Li* or the $\alpha+d$ cluster structure of the state. A more realistic treatment of this particular reaction mechanism is not available to the authors of the present work.

IV. CONCLUSIONS

In summary, differential cross section and vector analyzing power data have been obtained for the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction at 60 MeV bombarding energy. FRDWBA calculations were found to reproduce much of the structure of the cross section and analyzing power data, but a $\sim 3°$ phase difference was seen to exist between prediction and data. This phase discrepancy was not attributable to parameter ambiguities and was not removed by the inclusion of inelastic excitations in either ^{6}Li or ^{7}Li. Schumacher *et al.* observed a similar phase difference between FRDWBA prediction and data in their analysis of differential cross section data for the ^{26}Mg(^{6}Li,^{7}Li)^{25}Mg reaction at 36 MeV [15]. Also, DeVries *et al.* [18], in their analysis of the ^{12}C(^{14}N,^{13}N)^{13}C reaction at 100 MeV, reported that differential cross section data for the $\frac{1}{2}^+$ (3.09 MeV) state in ^{13}C had a $\sim 3°$ phase discrepancy with FRDWBA calculations. Data for the $\frac{1}{2}^-$ ground and $\frac{5}{2}^+$ (3.85 MeV) states in ^{13}C, populated by $1p_{1/2}$ and $1d_{5/2}$ transfers in the target-residual system respectively, were well described. However, it is worthwhile to note that the $\frac{5}{2}^+$ differential cross section data of DeVries *et al.* were relatively structureless.

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[1] D. Fick, G. Grawert, and Irena M. Turkiewicz, Phys. Rep. **214**, 1 (1992).
[2] Irena M. Turkiewicz, Z. Moroz, K. Rusek, I.J. Thompson, R. Butsch, D. Kramer, W. Ott, E. Steffens, G. Tungate, K. Becker, K. Blatt, H.J. Jänsch, H. Leucker, and D. Fick, Nucl. Phys. **A486**, 152 (1988).
[3] O. Karban, G. Kuburas, C.O. Blyth, H.D. Choi, S.J. Hall, S. Roman, G. Tungate, I.M. Turkiewicz, and N.J. Davis, Nucl. Phys. **A535**, 377 (1991).
[4] O. Karban, G. Kuburas, C.O. Blyth, H.D. Choi, S.J. Hall, S. Roman, G. Tungate, I.M. Turkiewicz, and N.J. Davis, J. Phys. G **18**, L197 (1992).
[5] O. Karban, W.C. Hardy, K.A. Connell, S.E. Darden, C.O. Blyth, H.D. Choi, S.J. Hall, S. Roman, and G. Tungate, Nucl. Instrum. Methods A **274**, 4 (1989).
[6] J.S. Lilley, Phys. Scr. **25**, 435 (1982).
[7] R.P. Ward, N.M. Clarke, K.I. Pearce, C.N. Pinder, C.O. Blyth, H.D. Choi, P.R. Dee, S. Roman, G. Tungate, and N.J. Davis, Phys. Rev. C **50**, 918 (1994).
[8] R.P. Ward, N.M. Clarke, C.N. Pinder, K.I. Pearce, C.O. Blyth, H.D. Choi, P.R. Dee, S. Roman, G. Tungate, and N.J. Davis, Phys. Rev. C **48**, 2366 (1993).
[9] S.E. Darden, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions*, Madison, 1970, edited by H.H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, 1971), p. 39.
[10] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).
[11] N.M. Clarke, King's College London version of the FRDWBA computer code FRUCK2, 1986 (unpublished).
[12] P.D. Kunz, FRDWBA computer code FRUCK2, 1980 (unpublished).
[13] J.R. Comfort, extended version of the FRDWBA computer code FRUCK2, 1983 (unpublished).
[14] J. Cook, N.M. Clarke, and R.J. Griffiths, Nucl. Phys. **A357**, 246 (1981).
[15] P. Schumacher, N. Ueta, H.H. Duhm, K.-I. Kubo, and W.J. Klages, Nucl. Phys. **A212**, 573 (1973).
[16] I.J. Thompson, Comput. Phys. Rep. **7**, 167 (1988).
[17] G. Kuburas, O. Karban, C.O. Blyth, H.D. Choi, S.J. Hall, S. Roman, G. Tungate, I.M. Turkiewicz, and N.J. Davis, Nucl. Phys. **A542**, 479 (1992).
[18] R.M. DeVries, M.S. Zisman, J.G. Cramer, K.-L. Liu, F.D. Becchetti, B.G. Harvey, H. Homeyer, D.G. Kovar, J. Mahoney, and W. von Oertzen, Phys. Rev. Lett. **32**, 680 (1974).