PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

α-clustering probabilities extracted from the ^{12}C(α,2α)^{8}Be reaction at 200 MeV

G. F. Steyn,[1] S. V. Förtsch,[1] A. A. Cowley,[2] J. J. Lawrie,[1] G. J. Arendse,[2] G. C. Hillhouse,[2] J. V. Pilcher,[1] F. D. Smit,[1]
and R. Neveling[2]
[1]*National Accelerator Centre, Faure, 7131, South Africa*
[2]*Department of Physics, University of Stellenbosch, Stellenbosch, 7600, South Africa*

(Received 9 December 1998)

The energy-sharing distribution at a coplanar symmetric quasifree angle pair has been measured for the ^{12}C(α,2α)^{8}Be(g.s.) reaction at an incident energy of 200 MeV. The measured knockout cross sections are compared with distorted wave impulse approximation calculations. Extracted spectroscopic factors are found to be in reasonable agreement with a theoretical prediction and results from (p,$p\alpha$) studies. The present results indicate a transition in the dynamics of this reaction in the incident energy region 140–200 MeV.
[S0556-2813(99)00604-4]

PACS number(s): 24.50.+g, 25.55.−e

I. INTRODUCTION

An anomaly in the α-cluster spectroscopic factors extracted from energy-sharing distributions measured in (α,2α) knockout reactions has already been observed quite some time ago. For example, Chant and Roos [1] reported an absolute spectroscopic factor of almost two orders of magnitude larger than the value expected from shell-model predictions [2] in their analysis of the ^{16}O(α,2α)^{12}C(g.s.) data of Ref. [3], which were measured at an incident energy of 90 MeV. This result is unexpected since studies of the (p,$p\alpha$) reaction on various nuclei yield values in good quantitative agreement with theoretical predictions.

A subsequent study of the (α,2α) reaction on targets of ^{9}Be, ^{12}C, ^{16}O, and ^{20}Ne at an incident energy of 139 MeV [4] has yielded spectroscopic factors of between 9 and 30 times in excess of theoretical predictions and values obtained from (p,$p\alpha$) reactions. The discrepancy increases with increasing target mass. In spite of this, the qualitative features of the measured energy-sharing distributions are reasonably well reproduced with the distorted wave impulse approximation (DWIA) theory, in those regions of the measured spectra where the knockout process dominates. In addition, cross sections for free α-α scattering are found to be in good qualitative agreement with half-off-shell two-body cross sections extracted from the (α,2α) data, over several orders of magnitude. Since the spectroscopic factor extracted in these studies is given by the ratio of a measured knockout cross section and a calculated DWIA cross section, these values are unquestionably model dependent. However, a consistent underprediction of the DWIA cross section is obtained for various sets of optical potentials if either theoretical or experimental (p,$p\alpha$) spectroscopic factors are adopted.

A sensitivity to the parameters for the bound-state wave function was established in the study at 139 MeV [4], but extremely physically unrealistic values need to be adopted in order to reproduce the expected spectroscopic factors. It was shown that ''realistic'' spectroscopic values can be obtained by artificially increasing the bound-state radius parameter to a value of 2.52 fm. This excessive value is twice the value expected from electron-scattering experiments. Nevertheless, this result is interesting because it reveals a possible correlation between the value of the extracted α-cluster spectroscopic factor and the radial localization at the maximum of the knockout cross section. The nuclear interior was more deeply probed in corresponding (p,$p\alpha$) reaction studies, therefore investigations of the (α,2α) reaction at higher incident energies were clearly needed to determine if such a correlation can be observed experimentally. Whereas artificially increasing the bound-state radius parameter extends the localization of the radial bound-state wave function towards larger radii, higher incident energies move the localization of the knockout cross section at its peak value toward smaller radii.

Progress in extending these studies to higher incident energies is, however, severely hampered by experimental limitations. First, the maximum value of the knockout cross section decreases rapidly with increasing incident energy, just as it behaves with increasing target mass. In addition, previous investigations at incident energies below 200 MeV all seem to have suffered to some extent from interference due to sequential decay processes. This problem becomes increasingly worse with larger asymmetry of the scattering geometry, thereby limiting the extraction of good spectroscopic information. A measurement at or near the coplanar symmetric quasifree angle pair (i.e., equal angles on opposite sides of the incident beam direction for which zero recoil momentum of the heavy residual reaction product is kinematically allowed) largely escapes the interference problem, but the two body α-α knockout collision then invariably occurs near a local minimum in the angular distribution, which gives a low (α,2α) cross section. Nevertheless, a study of the ^{9}Be(α,2α)^{5}He reaction at an incident energy of 197 MeV [5] confirmed the above-mentioned correlation and also produced extracted spectroscopic factors in good agreement with both a theoretical prediction [2] and the values obtained in ^{9}Be(p,$p\alpha$)^{5}He reaction studies [1,6–8]. Very limited data at 850 MeV [9] also seem to be in agreement with results from (p,$p\alpha$) reaction studies. In a very recent study of the (α,2α) reaction on ^{9}Be and ^{12}C, the incident energy of 580

MeV [10] was high enough to achieve a clear separation between knockout and sequential decay contributions, for various sets of asymmetric quasifree angle pairs. These authors also report a reasonable agreement with the theoretical prediction and with the results of proton-induced knockout studies. Therefore it seems that the problem of anomalously high spectroscopic factors extracted with the $(\alpha,2\alpha)$ reaction is limited to incident energies below 200 MeV.

There are several reasons why it is desirable to extend the previous study at 200 MeV [5] towards heavier target nuclei. First, a comparison of previous results of the $(\alpha,2\alpha)$ reaction on ^{9}Be [4,5] suggests that a dramatic change in the reaction dynamics occurs in the incident energy region 139–200 MeV. It is therefore important to establish whether this transition can also be observed in other light nuclear systems. As has already been mentioned, the apparent discrepancy in extracted spectroscopic factors increases rapidly with increasing mass. The extent of the mass dependence is evident by noticing that the discrepancy was not observed in a study of the $^6\mathrm{Li}(\alpha,2\alpha)^2\mathrm{H}$ reaction at energies ranging from 77 MeV to 119 MeV [11], while a notable discrepancy was found for the $^7\mathrm{Li}(\alpha,2\alpha)^3\mathrm{H}$ reaction [12] in the same incident energy region. Furthermore, a relatively large discrepancy was observed on ^{9}Be at 139 MeV [4]. It is therefore possible that the $(\alpha,2\alpha)$ reaction on ^{12}C would reveal the apparent incident-energy dependence of the α-cluster spectroscopic factor to an even more substantial degree than on the lighter target nuclei. But, by increasing the target mass from $A=9$ to $A=12$, a reduction of about an order of magnitude in the quasifree knockout cross section is expected at an incident energy of 200 MeV. The need to keep the accidental-to-true coincidence ratio at an acceptable level further limits the intensity of the incident α-particle beam. Consequently, a very low count rate is encountered in measurements at or near the coplanar symmetric quasifree angle pair.

Due to the above-mentioned difficulties, the present study investigates the $^{12}\mathrm{C}(\alpha,2\alpha)^8\mathrm{Be}$ reaction at an incident energy of 200 MeV for one angle pair only, namely the coplanar symmetric quasifree set. Short experimental runs at a few asymmetric quasifree angle pairs confirmed that the knockout peak would indeed be superimposed on a substantial background due to sequential decay processes at this energy. Testing the factorization approximation of the DWIA is therefore precluded for the present conditions. However, it was shown that factorization holds at 139 MeV for target masses ranging from $A=9$ to $A=20$ [4] and at 197 MeV on ^{9}Be [5]. Also, at an incident energy of 580 MeV, cross section data of the $(\alpha,2\alpha)$ reaction on ^{9}Be and ^{12}C generally follow the angular dependence of α-α elastic scattering data [10]. One can therefore confidently assume that the factorized DWIA should also be a fair approximation in the present case.

The experimental procedure is described in Sec. II. Details of the DWIA theory and calculations are presented in Sec. III. The results are presented and discussed in Sec. IV. A summary and conclusion are presented in Sec. V.

II. EXPERIMENTAL PROCEDURE

An α-particle beam of 200 ± 1 MeV energy was delivered by the separated-sector cyclotron facility of the National Accelerator Center to irradiate a self supporting carbon foil of 1.25 mg cm^{-2} thickness inside a 1.5 m diameter scattering chamber. The two scattered α-particles were detected in coincidence with two identical ΔE-E detector telescopes, mounted coplanar on opposite sides of the beam. The ΔE detectors were 150 μm thick Si surface-barrier detectors, followed by stopping NaI E detectors. Each telescope subtended a solid angle of 3 msr. Coincidence α-particle energy spectra were measured at the coplanar symmetric quasifree angles of $43.5°/-43.5°$. The accidental-to-true ratio of coincident α-particle events was maintained at a level of 25%. The gains of the NaI detectors were monitored by means of pre-scaled pulsers triggering light-emitting diodes (LEDs) imbedded in the crystals, the light output of which enabled correction for gain drift. In this way an energy resolution of less than 1% of the beam energy could be maintained over extensive periods of time. The typical count rate was 8 events per hour for knockout events leaving the residual ^{8}Be nucleus in its ground state. Data were collected until a statistical accuracy of marginally better than 10% was achieved at the maximum of the energy-sharing distribution. Other experimental details, such as beam offset determination, beam halo monitoring, dead time correction, determination of the accidental-to-true coincidence ratio, detector calibration, etc., are as discussed in Ref. [5].

III. CALCULATIONS

The theoretical analysis was performed in terms of the DWIA formalism [13] using the computer code THREEDEE of Chant and Roos [14] . As the details are summarized elsewhere [5], only a few aspects are discussed here.

The differential cross section for the knockout reaction $A(\alpha,2\alpha)B$, where the bound α-cluster has a total angular momentum J and orbital angular momentum L, is given by

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_2}=F_K S_{LJ}\left.\frac{d\sigma}{d\Omega}\right|_{\alpha-\alpha}\sum_{\Lambda}|T_{BA}^{\alpha L\Lambda}|^2, \tag{1}$$

where F_K is a kinematic factor, $d\sigma/d\Omega|_{\alpha-\alpha}$ is a half-off-shell two-body α-α cross section, and S_{LJ} is the cluster spectroscopic factor for specific L (projection Λ) and J, hereafter referred to as S_α, since $L=J$. The expression $\Sigma_\Lambda|T_{BA}^{\alpha L\Lambda}|^2$ is referred to as the distorted momentum distribution (see Ref. [5]).

This formulation of the DWIA employs the factorization approximation, which leads to the half-off-shell two-body cross section being treated as a multiplicative factor. An additional approximation is made by replacing this cross section with the experimental free α-α cross section, which is fully on-shell. Two prescriptions may be used for the latter approximation. In the initial energy prescription (IEP) the scattering is assumed to occur with the relative energy of the projectile and the bound cluster, while in the final energy prescription (FEP) the relative energy of the emitted α-particles is assumed for this purpose. Interpolated values of the two-body cross section were obtained by means of a polynomial fit to the α-α elastic scattering cross sections of Refs. [15,16].

Bound-state potential parameters of an α-particle in the $3S$-state in ^{12}C (as listed in Table I) are taken from Ref. [1].

TABLE I. Optical potential parameters for both the $\alpha+{}^{12}$C and $\alpha+{}^{8}$Be systems. The well depths for the $\alpha+{}^{12}$C system were subsequently multiplied by B/A (see text). The optical potential is defined as follows: $V_{opt}=-Vf(r,r_R,a_R)-iWf(r,r_I,a_I)+V_C$, where $f(r,r_i,a_i)=[1+\exp((r-r_iA^{1/3})/a_i)]^{-1}$; A is the appropriate nuclear mass; V_C is the Coulomb potential of a uniformly charged sphere of radius $r_cA^{1/3}$; and E_α is the laboratory kinetic energy.

Set	V (MeV)	r_R (fm)	a_R (fm)	r_c (fm)	W (MeV)	r_I (fm)	a_I (fm)	Ref.
I	V_1	1.245	a_{RN}	1.2	W_1	1.57	a_{IN}	[17]
II	V_2	0.991	0.807	1.2	W_2	3.006	0.577	[5]
III	88.86	0.991	0.807	1.2	4.94	3.006	0.577	[18]
IV	65.87	1.483	0.655	1.2	34.94	1.057	1.054	[18]

	V_{BS} (MeV)	r_{BS} (fm)	a_{BS} (fm)	r_c (fm)	Ref.
Bound state	89.9	1.23	0.75	1.23	[1]

$V_1=101.1+6.051ZA^{-1/3}-0.248E_\alpha$.
$W_1=26.82-1.706A^{1/3}+0.006E_\alpha$.
$a_{RN}=0.817-0.0085A^{1/3}$.
$a_{IN}=0.692-0.02A^{1/3}$.
$V_2=-0.223E_\alpha+120.2$.
$W_2=0.0109E_\alpha+4.17$.

The distorted waves for the incident and the two scattered α particles were generated from the optical potentials listed in Table I. Set I is the global α-nucleus potentials of Nolte *et al.* [17]. Set II represents an energy-dependent potential set obtained from elastic $\alpha+{}^{6}$Li data [5]. Sets III and IV were extracted from $\alpha+{}^{6}$Li and $\alpha+{}^{9}$Be elastic scattering data, respectively, measured at 104 MeV [18]. As discussed in Refs. [1,5,13], the potential well depths in the entrance channel were scaled by the mass ratio of the residual nucleus to the target nucleus, B/A. This procedure modifies the optical potentials to apply to scattering from the ^{8}Be core, averaged over the ^{12}C target nucleus.

IV. RESULTS AND DISCUSSION

The binding-energy spectrum measured for the ^{12}C(α,2α)^{8}Be reaction at 200 MeV is shown in Fig. 1. The ground and first excited states in ^{8}Be are clearly resolved, and a clean separation between them was obtained in the two-dimensional energy-sharing distribution.

The projected energy-sharing distribution, leaving the residual ^{8}Be nucleus in its ground state, is shown in Fig. 2. The maximum cross section is 380 nb sr^{-2} MeV^{-1} at the quasifree energy with a statistical uncertainty of about 9%. The measured data are compared with several DWIA calculations, utilizing different sets of optical potentials for the projectile and ejectile distortions (see Table I). This is done because optical potentials for α-nucleus interactions are not as well established as, for example, for proton-nucleus interactions. Since there are uncertainties associated with specific choices of optical potentials, we opted to employ several sets and we also compare the results of the analysis of the present

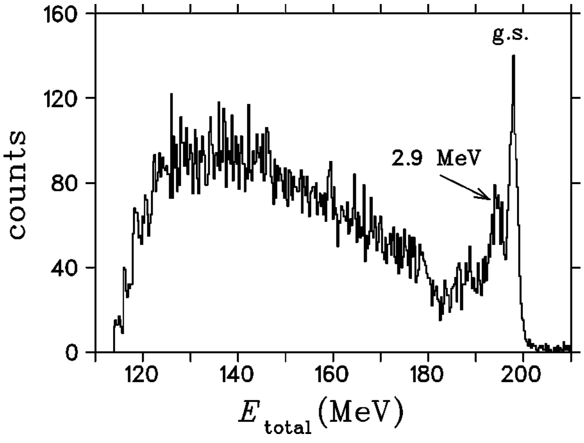

FIG. 1. Experimental binding-energy spectrum for the ^{12}C(α,2α)^{8}Be reaction at an incident energy of 200 MeV, showing the ground state (g.s.) and first excited state (at 2.9 MeV) in ^{8}Be.

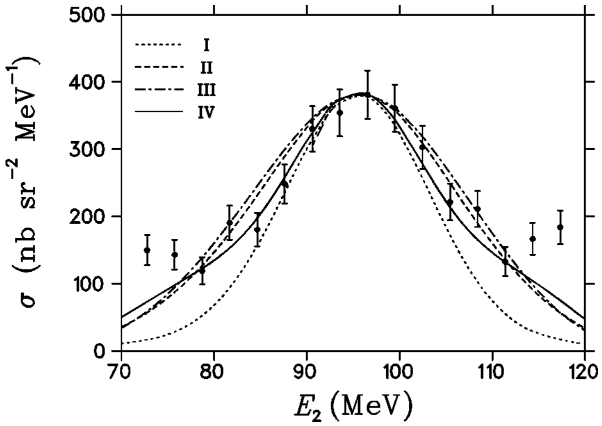

FIG. 2. Energy-sharing spectrum at 200 MeV of the ^{12}C(α,2α)^{8}Be(g.s.) reaction at the coplanar symmetric quasifree angle pair. The curves are DWIA predictions according to the final energy prescription (FEP) as obtained with the optical potentials listed in Table I, as indicated.

TABLE II. Spectroscopic factors S_α extracted by normalizing the DWIA calculations performed with the different optical potential parameter sets listed in Table I to experimental cross sections at the quasifree symmetric angles for the $^{12}C(\alpha,2\alpha)^{8}Be$ reaction at 139 and 200 MeV.

	S_α					
	FEP			IEP		
Set	139 MeV	200 MeV	Ratio	139 MeV	200 MeV	Ratio
I	17	0.48	35	29	0.78	37
II	8.0	0.31	26	13	0.50	26
III	5.0	0.25	20	8.4	0.4	21
IV	40	1.4	29	67	2.2	30
Theory [a]	0.55	0.55	1.0	0.55	0.55	1.0

[a] Shell model calculation of Ref. [2]. The indicated ratios are for purposes of comparison only.

data with corresponding results of a re-analysis of the 139 MeV data of Ref. [4]. Alpha-cluster spectroscopic factors (S_α) were extracted by fitting the calculated DWIA cross sections to the maxima of the observed quasifree knockout peaks in the measured energy-sharing distributions. These values are presented in Table II.

The calculated energy-sharing distribution obtained with the global potentials of Nolte *et al.* (set I) is somewhat narrower than predicted by the other optical potentials, and perhaps marginally narrower than the measured distribution. Potential sets II, III and IV yield distributions that seem to be marginally wider than the measured distribution. Since the data below 80 MeV and above 110 MeV are affected by contributions due to sequential decay processes, one should only compare results in the region of the knockout peak. Generally, the agreement is satisfactory.

We also performed calculations using the potentials extracted by Smith *et al.* [19] from $\alpha+{}^{12}C$ elastic scattering data. In this case, however, the measured energy-sharing distribution could only be reproduced qualitatively if the entrance channel scaling is omitted. With scaling we find a significant deterioration in the shape of the predicted energy-sharing distribution at both 139 and 200 MeV, which is not observed for any of the other potentials used. In this case, the DWIA calculations yield three narrow nodes in the region of the knockout peak. At present we are unable to explain this unexpected phenomenon. We therefore omitted these potentials in our present analysis.

In spite of differences between results obtained with different optical potentials, Table II shows that the spectroscopic factors extracted at 200 MeV are all of the same order of magnitude as the theoretical prediction of Ref. [2]. In sharp contrast, the values extracted at 139 MeV are consistently larger, by more than an order of magnitude, than the theoretical value. Ratios of the spectroscopic factors extracted at 139 and 200 MeV have values between 20 and 37. Compared to the large disagreement found at 139 MeV, spectroscopic factors extracted at 200 MeV are found to be in reasonable agreement with the theoretical prediction.

The radial localization of the DWIA cross section for the $^{12}C(\alpha,2\alpha)^{8}Be$ reaction at 139 MeV was determined for various values of the bound-state radius parameter and compared to a similar calculation at 200 MeV with a realistic bound-state radius parameter (see Table I). In order for the comparison to be inherently consistent, we adopted the final energy prescription and the same optical parameters (set I—see Table I) throughout. Figure 3 shows histograms of the differential contributions to the DWIA cross section as a function of the radial distance. These values were obtained by taking differences between calculated cross sections obtained with different radial cutoff values, as described in Refs. [4,5]. In each case the relevant α-cluster radial bound-state wave function is also shown. The figure shows that for an incident α-particle energy of 139 MeV, the reaction is localized in the asymptotic tail part of the bound-state wave function towards smaller values of the bound-state radius. As the bound-state radius is increased, the maximum of the bound-

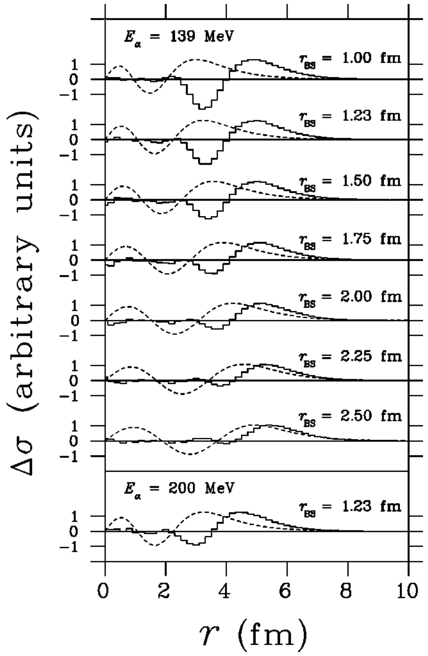

FIG. 3. Histograms of $\Delta\sigma$, depicting calculated radial distributions of differential contributions to the DWIA cross sections for the $^{12}C(\alpha,2\alpha)^{8}Be$(g.s.) reaction at zero recoil momentum. Various choices of the bound-state radius parameter, r_{BS}, are considered at an incident energy of 139 MeV, and compared to the result at 200 MeV with a realistic value for this parameter (see text). For convenient radial reference, the 3S bound-state radial wave function is shown as a dashed curve in each case.

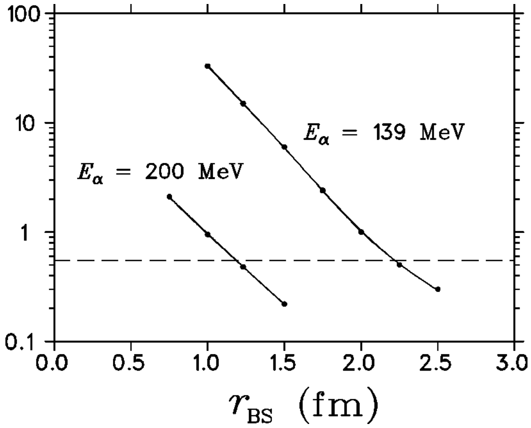

FIG. 4. Dependence to the bound-state radius parameter of the spectroscopic factors extracted in the ^{12}C(α,2α)^{8}Be(g.s.) reaction at incident energies of 139 and 200 MeV. The theoretical spectroscopic factor of Ref. [2] is indicated by the broken line.

state wave function moves closer to the peak of the radial cross-section distribution. Even though the peak of the radial distribution is located at a smaller radius at 200 MeV, the relative localization as compared to the wave function seems to be similar to the case at 139 MeV for a bound-state radius parameter of 1.75 fm. In Fig. 4 we show the corresponding extracted spectroscopic factors as a function of the bound-state radius parameter. The spectroscopic factor clearly has a strong exponential dependence on the value of the bound-state radius parameter, at both incident energies. At 200 MeV the extracted spectroscopic factor equals the theoretical prediction for a bound-state radius parameter very close to the realistic value of 1.23 fm (see Table I). At 139 MeV a value somewhat larger than 2 fm is required. Thus, in order to reproduce the theoretical spectroscopic factor, the extent to which the radial bound-state wave function needs to be probed by the (α,2α) reaction on ^{12}C at 139 MeV seems to be somewhat different than at 200 MeV. By and large, however, the result of the present study is similar to that of Ref. [5] for the ^{9}Be(α,2α)^{5}He reaction. Certainly, the observed phenomenon is rather dramatic, as is perhaps best displayed by the ratios given in Table II.

V. SUMMARY AND CONCLUSION

The energy-sharing distribution at a coplanar symmetric quasifree angle pair was measured for the ^{12}C(α,2α)^{8}Be(g.s.) reaction at a nominal incident energy of 200 MeV. The agreement in shape with results of the DWIA theory is found to be reasonable. Extracted spectroscopic factors are in reasonable agreement with a theoretical estimate and with results from knockout studies with the (p,$p\alpha$) reaction. In addition, the present results are also in agreement with a recent study of the (α,2α) reaction at 580 MeV. Similar to a previous study on the target nucleus ^{9}Be at this energy, the present results are in strong contrast to the anomalous spectroscopic factors obtained in (α,2α) studies at lower incident energies.

It is evident that a transition in the reaction dynamics of the (α,2α) reaction occurs in the incident energy region 139–200 MeV, which is presently not well understood. The extracted spectroscopic factor does seem to be related to the radial localization of the reaction, or to the extent to which the radial bound-state wave function is probed. However, the radial localization (relative to the maximum of the bound-state wave function) at which the theoretical spectroscopic factor is reproduced (by adjusting the bound-state radius) seems to differ somewhat for different incident energies (i.e., 139 and 200 MeV). It is clear, though, that the large discrepancy in the extracted spectroscopic factors at 139 MeV when a realistic value for the bound-state radius is employed, is not observed at 200 MeV.

This study provides further proof that the (α,2α) reaction becomes a reliable spectroscopic tool at incident energies of 200 MeV and above. Although the failure to extract reasonable values from experiments at incident energies of only 60 MeV lower than this value is an established fact, the explanation remains elusive. Clearly, additional theoretical and experimental investigations are required either to determine the reason for the breakdown of the DWIA at the lower incident energies, or to discover whether the excessively high spectroscopic values under those conditions have any physical significance.

---

[1] P. G. Roos, N. S. Chant, A. A. Cowley, D. A. Goldberg, H. D. Holmgren, and R. Woody III, Phys. Rev. C **15**, 69 (1977).
[2] D. Kurath, Phys. Rev. C **7**, 1390 (1973).
[3] Joseph D. Sherman, D. L. Hendrie, and M. S. Zisman, Phys. Rev. C **13**, 20 (1976).
[4] C. W. Wang, N. S. Chant, P. G. Roos, A. Nadasen, and T. A. Carey, Phys. Rev. C **21**, 1705 (1980).
[5] A. A. Cowley, G. F. Steyn, S. V. Förtsch, J. V. Pilcher, F. D. Smit, and D. M. Whittal, Phys. Rev. C **50**, 2449 (1994).
[6] C. W. Wang, P. G. Roos, N. S. Chant, G. Ciangaru, F. Khazaie, D. J. Mack, A. Nadasen, S. J. Mills, R. E. Warner, E. Norbeck, F. D. Becchetti, J. W. Janecke, and P. M. Lister, Phys. Rev. C **31**, 1662 (1985).
[7] A. Nadasen, P. G. Roos, N. S. Chant, C. C. Chang, G. Ciangaru, H. F. Breuer, J. Wesick, and E. Norbeck, Phys. Rev. C **40**, 1130 (1989).
[8] T. Yoshimura, A. Okihana, R. E. Warner, N. S. Chant, P. G. Roos, C. Samanta, S. Kakigi, N. Koori, M. Fujiwara, N. Matsuoka, K. Tamura, E. Kubo, and K. Ushiro, Nucl. Phys. **A641**, 3 (1998).
[9] N. Chirapatpimol, J. C. Fong, M. M. Gazzaly, G. Igo, A. D. Liberman, R. J. Ridge, S. L. Verbeck, C. A. Whitten, Jr., D. G. Kovar, V. Perez-Mendez, N. S. Chant, and P. G. Roos, Nucl. Phys. **A264**, 379 (1976).
[10] A. Nadasen, J. Brusoe, J. Farhat, K. A. G. Rao, D. Sisan, J. Williams, P. G. Roos, F. Adimi, T. Gu, M. Khayat, and R. E. Warner, Phys. Rev. C **59**, 760 (1999).
[11] A. Okihana, T. Konishi, R. E. Warner, D. Francis, M. Fuji-

wara, N. Matsuoka, K. Fukunaga, S. Kakigi, T. Hayashi, J. Kasagi, N. Koori, M. Tosaki, and M. Greenfield, Nucl. Phys. **A549**, 1 (1992).

[12] R. E. Warner, A. Okihana, M. Fujiwara, N. Matsuoka, S. Kakigi, S. Hayashi, K. Fukunaga, J. Kasagi, and M. Tosaki, Phys. Rev. C **45**, 2328 (1992).

[13] N. S. Chant and P. G. Roos, Phys. Rev. C **15**, 57 (1977).

[14] N. S. Chant, code THREEDEE, University of Maryland (unpublished).

[15] P. Darriulat, G. Igo, and H. G. Pugh, Phys. Rev. **137**, B315 (1965).

[16] G. F. Steyn, S. V. Förtsch, J. J. Lawrie, F. D. Smit, R. T. Newman, A. A. Cowley, and R. Lindsay, Phys. Rev. C **54**, 2485 (1996).

[17] M. Nolte, H. Machner, and J. Bojowald, Phys. Rev. C **36**, 1312 (1987).

[18] R. M. DeVries, J.-L. Perrenoud, I. Slaus, and J. W. Sunier, Nucl. Phys. **A178**, 424 (1972).

[19] S. M. Smith, G. Tibell, A. A. Cowley, D. A. Goldberg, H. G. Pugh, W. Reichart, and N. S. Wall, Nucl. Phys. **A207**, 273 (1973).