ACO2-76ERO374.

[a]Current address: Bell Laboratories, Holmdel, N. J. 07733.

[b]Permanent address: Physikalisches Institut der Universität Erlangen-Nürnberg, Erlangen, West Germany.

[1]D. A. Bromley, J. A. Kuehner, and E. Almqvist, Phys. Rev. Lett. 4, 365 (1960).

[2]M. Gai, Bull. Amer. Phys. Soc. 24, 843 (1979), and 25, 592 (1980), and in Proceedings of the International Conference on Nuclear Physics, Berkeley, California, 24–30 August 1980, LBL Report No. LBL-11118 (unpublished), pp. 424, 425; M. Gai and D. A. Bromley, to be published.

[3]A. Gobbi, R. Wieland, L. Chua, D. Shapira, and D. A. Bromley, Phys. Rev. C 7, 30 (1973).

[4]P. Braun-Munzinger and J. Barrette, Phys. Rev. Lett. 44, 719 (1980).

[5]D. Shapira, R. G. Stokstad, and D. A. Bromley, Phys. Rev. C 10, 1063 (1974).

[6]R. E. Shaw, Jr., J. C. Norman, R. Vandenbosch, and J. C. Bishop, Phys. Rev. 185, 1040 (1969).

[7]F. Iachello, Phys. Rev. C 23, 2778 (1981).

[8]K. Erb and D. A. Bromley, Phys. Rev. C 23, 2781 (1981).

[9]N. Bohr, Nature 137, 344 (1936); N. Bohr and F. Kalckar, Mat.-Fys. Medd. Danske Vid. Selsk 14, No. 10 (1937).

[10]A. S. Rinat and J. Arvieux, Phys. Lett. 104B, 182 (1981); A. S. Rinat, private communication.

Limiting Angular Momenta for Light Heavy-Ion Fusion at High Energy

A. Szanto de Toledo

Laboratorio Pelletron, Instituto de Física da Universidade de São Paulo, São Paulo, Brazil, and Department of Physics, University of Rochester, Rochester, New York 14623

and

T. M. Cormier, M. Herman, B. Lin, and P. M. Stwertka

Department of Physics, University of Rochester, Rochester, New York 14623

and

M. M. Coimbra and N. Carlin Filho

Laboratorio Pelletron, Instituto de Física da Universidade de São Paulo, São Paulo, Brazil

(Received 12 August 1981)

The shapes of angular distributions in reactions $^{12}C(^{16}O, \alpha)$ to the $J^\pi = 0^+$ ^{24}Mg ground state are studied from $E(^{16}O) = 28.5$ to 100 MeV. The position of the first minimum (and maximum) of these oscillatory angular distributions is expected to be sensitive to the presence of a low–angular-momentum cutoff in the compound-nucleus formation cross section. No evidence for a low-L cutoff is found even at energies well beyond the predicted threshold.

PACS numbers: 25.70.Fg, 25.70.Bc

Time-dependent Hartree-Fock (TDHF) theory predicts the inhibition of low–impact-parameter fusion in nucleus-nucleus collisions at high energy.[1] This fact has provoked a number of experimental investigations attempting to isolate the effect.[2,3] An unambiguous result, however, has not been forthcoming chiefly because the low partial waves make an extremely small contribution to the fusion cross section. Recently, it has been shown by Szanto de Toledo and Hussein[4] that the presence of the low-L cutoff predicted by TDHF theory will strongly influence the shapes of zero-channel-spin angular distributions in statistical compound-nucleus decay. In the present Letter we report the results of applying this method to the fusion of $^{16}O + ^{12}C$ to search for the predicted inhibition of low-L fusion.

We have studied the ground-state transition (α_0) of the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$ from $E(^{16}O) = 28.5$ to 100 MeV. The shapes of the α_0 angular distributions have been analyzed within the statistical-model framework. Our results show no significant deviation from compound-nucleus predictions using *no* low-L cutoff. Upper limits for the minimum angular momentum contributing to $^{16}O + ^{12}C$ fusion are established up to $E(^{16}O) = 100$

MeV.

Angular momentum matching conditions in statistical compound-nucleus decay to a discrete state force a localization of the contributing partial cross sections, σ_J, in angular momentum space. The distribution of σ_J is strongly peaked with a center of gravity $\langle J \rangle$, the mean compound-nucleus spin contributing to the excitation of the final state.[5,6] If a low-angular-momentum cutoff occurs in the entrance channel, the average compound-nucleus spin distribution is shifted to a *higher* value with a corresponding increase in $\langle J \rangle$. In the case of zero-channel-spin reactions, the angular distributions display an oscillatory behavior with a period related to $\langle J \rangle$ and a damping factor related to the width of the σ_J distribution. Consequently the truncation of the low-L components of σ_J modify the shape and period of the angular distribution.[4,5] This effect can be investigated by following the energy dependence of the angles of the first minimum (φ) and first maximum (Φ) of the α_0 angular distribution.

The statistical model gives approximately[5] $\varphi \simeq 3\pi/4\langle J \rangle$ and $\Phi = 5\pi/4\langle J \rangle$, and for zero channel spin, $\langle J \rangle$ is approximately the grazing angular momentum L_g^{α} of the outgoing particle. Thus in the absence of a low-L cutoff one expects that φL_g^{α} and ΦL_g^{α} are constant and independent of bombarding energy:

$$\varphi L_g^{\alpha} = \varphi\left[\frac{2\mu R^2}{\hbar^2}\left(E + Q - \frac{ZZ'e^2}{R}\right)\right]^{1/2} \simeq \tfrac{3}{4}\pi; \qquad (1)$$

$$\Phi L_g^{\alpha} \simeq \tfrac{5}{4}\pi.$$

Measurements were made on the University of Rochester MP tandem accelerator and the University of São Paulo 8UD Pelletron. Silicon position-sensitive detectors were used for $E(^{16}O) < 55$ MeV and the University of Rochester split-pole spectrograph for >55 MeV. An accurate angle calibration was achieved in both cases based on measurements at both positive and negative angles to determine true zero degrees.

Bombarding-energy-averaged α spectra [Fig. 1(a)] were obtained either by using a thick self-supporting C foil [$\Delta E(^{16}O) = 1.2-1.8$ MeV] or by explicitly averaging the angular distributions measured in fine steps [$\Delta E(^{16}O) = 300$ keV]. This procedure should virtually eliminate statistical compound-nucleus fluctuations.

The excitation function for the α_0 differential cross section at the angle Φ of the first maximum is shown in Fig. 1(b). The dashed lines represent a Hauser-Feshbach calculation performed using the code STATIS.[6] Averaged level-density parameters were adjusted in order to reproduce the experimental cross section at $E_{lab} = 51$ MeV ($a \sim A/6$). An uncertainty of 25% is attributed to the absolute experimental cross section, due mainly to uncertainties in target thickness determination. In this calculation, no low-L cutoff has been applied, and a critical angular momentum value for compound-nucleus formation has been used $L_c = (\sigma_{fus}/\pi\lambda^2)^{1/2} - 1$, where the experimental fusion cross section σ_{fus} has been taken from Ref. 7.

Some typical angular distributions are shown in Fig. 2. The small points are least-square fits by sums of Legendre polynomials [$d\sigma/d\Omega = \sum_k a_k \times P_k(\cos\theta)$] used to extract the values of φ and Φ from the experimental data. The full lines represent statistical-model calculations. An absolute renormalization smaller than 25% has been allowed [see Fig. 1(b)]. No low-L cutoff has been applied in these calculations.

The energy dependence of φ and Φ plotted times L_g^{α} from Eq. (1) is shown in Fig. 3. The vertical

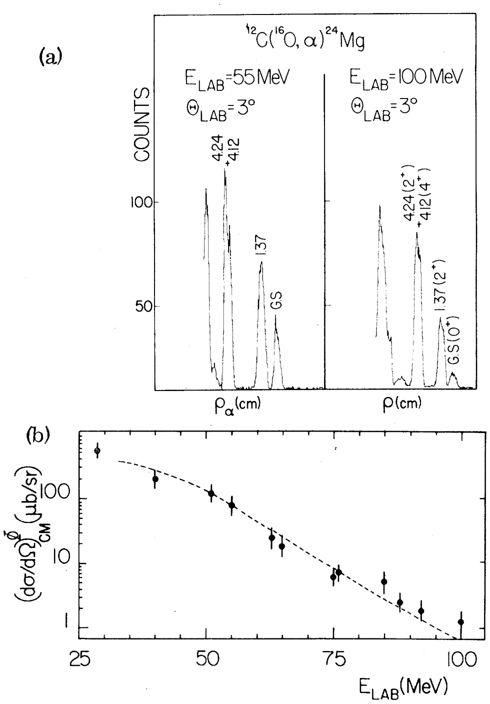

FIG. 1. (a) Typical α spectra observed at $E_{lab} = 55$ and 100 MeV. (b) Excitation function of the ground-state transition: $d\sigma/d\Omega$ at the first-maximum angle Φ. The dashed line shows the theoretical (Hauser-Feshbach) prediction assuming $J_{min} = 0$.

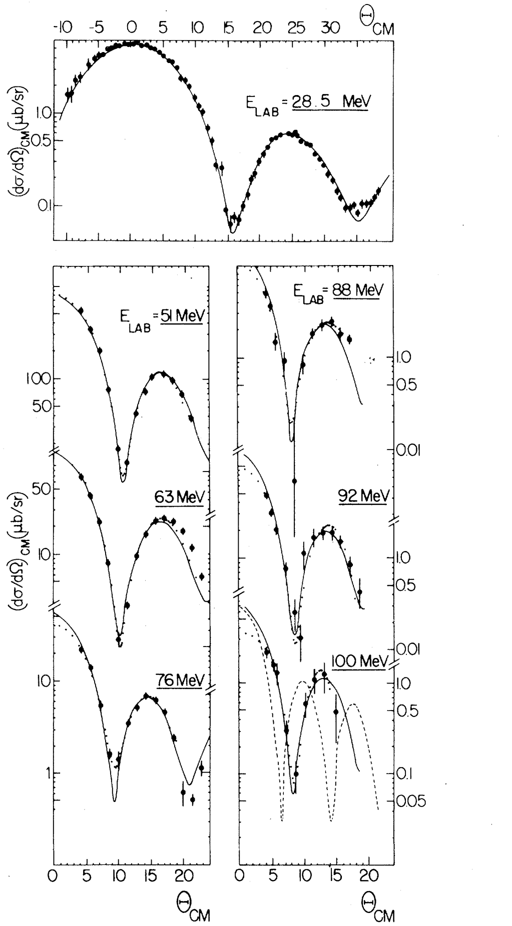

FIG. 2. Typical angular distributions. The small points correspond to least-square fits by sums of Legendre polynomials. The full lines show the result of statistical-model calculations assuming $J_{min} = 0$. The dashed line at $E_{lab} = 100$ MeV is the result of the same calculation, in which a cutoff at $J_{min} = 14\hbar$ is applied.

error bars give the angle uncertainty resulting from counting statistics and fitting, and the horizontal error bars give the energy-averaging interval. The solid line shows the prediction of a full Hauser-Feshbach statistical-model calculation (STATIS[6]) assuming no low-L cutoff, while the dashed line shows the effect of including a low-L cutoff given by

$$L_{min}^2 = \frac{2\mu R^2}{\hbar^2}\left\{E_{c.m.} - \frac{ZZ'e^2}{R} - \frac{A_2(A_1+A_2)}{A_1} \times\left[\left(1+\frac{B}{\epsilon_F}\right)^{1/2} - 1\right]\epsilon_F\right\}, \quad (2)$$

where $\epsilon_F = 35$ MeV, $B = 8$ MeV, $A_2 > A_1$, and $R = 1.4(A_1^{1/3} + A_2^{1/3})$. This equation has been shown[1]

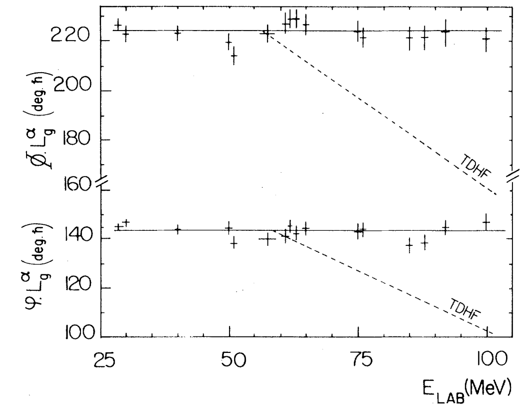

FIG. 3. Experimental values obtained for $\varphi L_g^\alpha(E_{lab})$ and $\Phi L_g^\alpha(E_{lab})$. The full line describes the Hauser-Feshbach theoretical trajectory if $J_{min} = 0$ is assumed. If the TDHF-predicted J_{min} values are considered in the calculations, the dashed trajectory is obtained.

to contain the essential ingredients of the time-dependent Hartree-Fock theory and, in particular, is in accord with full TDHF calculations for $^{16}O + {}^{16}O$,[1] $^{12}C + {}^{12}C$,[1] and $^{16}O + {}^{27}Al$.[8]

Since a sharp-cutoff approximation is used in the calculations and only integer L values are used, the theoretical trajectory in the φL_g^α-E_L plane (dashed lines) has been smoothed.

Figure 3 shows clearly that no significant deviation from the $L_{min} = 0$ statistical-model calculation is observed. To illustrate the effect of the inclusion of a low-L cutoff on the shape of the angular distribution, the 100-MeV plot in Fig. 2 shows also the theoretical prediction (dashed line) when the TDHF-predicted value of L_{min} is considered. A drastic change in the oscillatory behavior is then observed.[9]

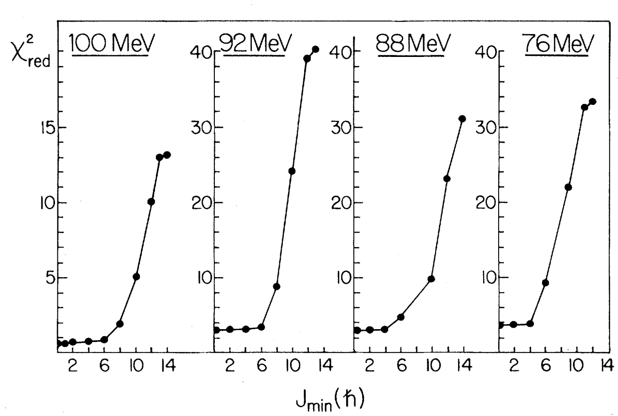

FIG. 4. χ^2 fits of the shape of the experimental angular distributions by the theoretical angular distribution as a function of the low-angular-momentum cutoff.

To eliminate the influence of the parameters of the statistical-model calculations on the results, the energy dependence of the transmission coefficients has been investigated in order to fit the low-energy data ($E_{lab} < 55$ MeV) below the L_{min} threshold. All the parameters used in the statistical-model calculations, with the exception of the limiting angular momenta values, have been kept fixed.

To estimate limits for L_{min} values, as a function of the bombarding energy, χ^2 fits by the shape of the predicted angular distributions (as a function of L_{min}) have been performed (Fig. 4). The decrease of χ^2, even at low-L_{min} values, indicates that these low–angular-momentum partial waves still contribute to the compound-nucleus formation, even at energies well beyond the predicted threshold. For very low L values, our method becomes insensitive as a result of the localization, in angular momentum space, of the contributing compound-nucleus partial cross sections (σ_J) to the ground-state transition.

In conclusion, the experimental angular distributions of the $^{12}C(^{16}O,\alpha_0)$ transition were measured in a wide energy interval, $28.5 \leq E_{lab} \leq 100$ MeV, and are reproduced by statistical-model calculations without the need of a low-L cutoff in the σ_J distributions of the compound-nucleus angular momenta. Results of the present work suggest upper limits for L_{min} that are much lower than the values predicted by the time-dependent Hartree-Fock theory.

One of us (A.S.T.) acknowledges the kind hospitality at the Nuclear Structure Research Laboratory, Rochester. This work was supported in part by the National Science Foundation under Grant No. PHY-79-23307A01 and by the Conselho Nacional de Desenvolvimento Científico e Tecnológico Brazil. One of us (T.M.C.) was supported in part by the Alfred P. Sloan Foundation.

[1]P. Bonche, S. E. Koonin, and J. W. Negele, Phys. Rev. C 13, 1226 (1976); S. E. Koonin, K. T. R. Davies, V. Maruhn-Rezwani, H. Feldmeir, S. J. Krieger, and J. W. Negele, Phys. Rev. C 15, 1359 (1977); Cheuk-Yin Wong, in *Proceedings of the Workshop on Time-Dependent-Hartree-Fock Methods, Orsay/Saclay, 1979*, edited by P. Bonche, B. Giraud, and Ph. Quentin (Editions de Physique, Paris, 1979).

[2]S. Kox, A. J. Cole, and R. Ost, Phys. Rev. Lett. 44, 1204 (1980).

[3]J. B. Natowitz, G. Doukellis, B. Kolb, G. Rosner, and Th. Walcher, Nucleonika 24, 443 (1979); A. Lazzarini, H. Doubre, K. T. Lesko, V. Metag, A. Seamster, R. Vandenbosh, and W. Merryfield, Phys. Rev. C 24, 309 (1981).

[4]A. Szanto de Toledo and M. S. Hussein, Phys. Rev. Lett. 46, 985 (1981).

[5]M. S. Hussein and A. Szanto de Toledo, Instituto de Física da Universidade de São Paulo Report No. IFUSP/P-265 (to be published).

[6]R. G. Stokstad, Wright Nuclear Structure Laboratory, Yale University, Internal Report No. 52, 1972 (unpublished).

[7]D. Kovar *et al.*, Phys. Rev. C 20, 2147 (1979), and references therein.

[8]K. R. S. Devi, A. K. Dhar, and M. R. Strayer, Phys. Rev. C 23, 2062 (1981).

[9]When $L_{min} \neq 0$ values are considered in the calculations, the maximum angular momentum L_{max} allowed for the compound nucleus is recalculated such that the experimental fusion cross section is reproduced, i.e., $(L_{max}+1)^2 - (L_{min}+1)^2 = \sigma_{fus}/\pi\lambda^2$.