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Determination of Limiting Angular Momenta for Fusion from Statistical-Model Fits to Mass Distributions of Evaporation Residues

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(Received 28 November 1979)

Improved statistical-model calculations allow a search for the lower and upper limiting angular momenta of compound-nucleus formation that give best fits to evaporation-residue mass distributions. For the $^{16}O+^{16}O$ reaction in the energy range $E_{lab}=35-80$ MeV, optimal fits are obtained for low-l cutoff 0, and maximum l equal to l_{cr}, obtained from total fusion cross sections.

PACS numbers: 25.70.Bc, 25.70.Hi

The decay of the compound nucleus is well understood in terms of a statistical evaporation model. The fusion reaction leading to compound-nucleus formation, on the other hand, is a highly complex process whose theoretical description always requires simplifying assumptions. A basic question is which impact parameters (partial waves l) lead to fusion. The maximum l value (l_{cr}) determines the maximum possible so-called critical angular momentum J_{cr} of the compound nucleus. l_{cr} can be calculated[1] from the total fusion cross section [$\sigma_{fusion}=\pi\lambda\!\!\!^{-2}(l_{cr}+1)^2$] if we assume that the probability of compound-nucleus formation is unity for all incoming partial waves between 0 and l_{cr}. A cutoff for low l values is predicted, however, by recent time-dependent Hartree-Fock calculations[2] and discussed in experimental publications.[1,3]

One way to gain information on limiting l values is to perform statistical-model calculations for J distributions and to choose the correct distribution by the best fit to the data. Unfortunately, useful calculations are time consuming and require large amounts of computer storage. Most calculations that are found in the literature are therefore one-shot calculations that use a distribution between $J=0$ and $J=l_{cr}$ with l_{cr} as determined from total fusion cross sections. The interpretation of differences between experiment and theory remains rather speculative. We report here on a method that permits the choice of the best statistical-model fit from a large number of calculations with different initial angular momentum distributions of the compound nucleus.

In this Letter we concentrate our investigation on the compound system $^{16}O+^{16}O$, where extensive data are reported[3] for energies $E_{lab}=35-80$ MeV. Less intensive studies on other compound systems with $A\leqslant 32$ where there are experimental data available[1,4,5] seem to confirm the results reported here.

The statistical-model calculations were carried out using the Monte Carlo computer code LANCELOT.[5,6] Relative probabilities for competing decay modes from a parent nucleus with excitation energy E_x and angular momentum J_I are calculated using the Hauser-Feshbach formula[7] which, for emission of a particle b of spin j removing orbital angular momentum l and kinetic energy ϵ, may be written

$$P^{J_I,E_x}(b,l,\epsilon)=T_l(\epsilon)\sum_{S=|J_I-l|}^{J_I+l}\;\sum_{J_f=|S-j|}^{S+j}\rho(E_f,J_f). \tag{1}$$

Here $T_l(\epsilon)$ is a transmission coefficient obtained, with the parabolic barrier approximation,[8] from optical-model potentials and $\rho(E_f,J_f)$ is the density of states in the daughter nucleus which at low energies is obtained from experimentally observed levels, and at higher energies is the Lang[9] Fermi-gas density with parameters obtained from Gilbert and Cameron.[10] Emission of neutrons, protons, deuterons, α particles, and γ rays is included in the calculations. Yrast lines are calculated using the rigid-body moment of inertia including a rotational stretching correction (Puhlohfer[11]). The corresponding parameters and the choice of optical-model potential parameters were optimized by comparing model predictions with data on compound systems with $A < 32$ at low energies where no low-l cutoff would be expected to exist. A good description of all systems investigated was obtained with a unique parameter set which was therefore used in the present study. It should be stated that our yrast lines agree well with recent shell-corrected liquid-drop–model calculations.[12]

In a first step we tested the sensitivity of evaporation-residue mass yields to the critical angular momentum l_{cr} over the range $l_{\mathrm{cr}}^0 \pm 3$ where l_{cr}^0 is the value determined from the total fusion cross section. For each value of l_{cr} a value of

$$\chi^2 = \sum_n [(\sigma_{\mathrm{exp}}{}^n - \sigma_{\mathrm{th}}{}^n)/\Delta\sigma_{\mathrm{exp}}{}^n]^2$$

was calculated as a measure of the quality of the fit to the evaporation-residue mass distribution. In all cases a single minimum for χ^2 was determined which agreed well with values of l_{cr}^0 obtained from the experimental fusion cross sections.

A more economic procedure was used to search on both l_{cr} and low-l cutoff (l_c) for the $^{16}\mathrm{O} + {}^{16}\mathrm{O}$ data from Ref. 3. For each energy several thousand evaporation events were created using LANCELOT for an l distribution with $0 \leq l \leq l_{\mathrm{cr}}^0 + 3$. The program lists for each event the initial J value of the compound nucleus and the complete evaporation cascade. Different initial distributions corresponding to different values of l_{cr} and l_c are then selected out of the initial file and the residue spectrum for each pair l_{cr}, l_c is compared with the experimental data. Thus values of χ^2 over the plane l_{cr}, l_c can rapidly be generated and may be displayed on a contour plot. Figure 1 shows this plot at three energies for the $^{16}\mathrm{O} + {}^{16}\mathrm{O}$ system. At all energies we observe one deep minimum located on the axis, $l_c = 0$, with l_{cr} equal to values known from total fusion cross sections. The same holds also for energies 35, 45, and 52 MeV not shown in the plot.

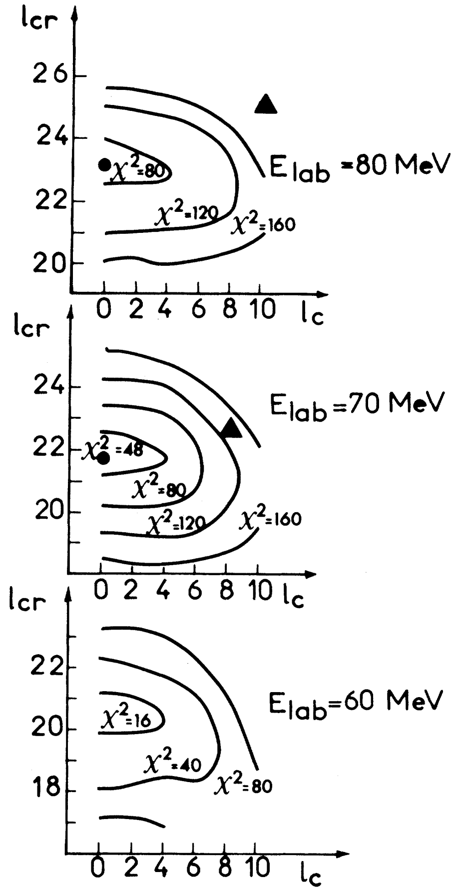

FIG. 1. Lines of equal χ^2 in the plane formed by the critical angular momentum for fusion (l_{cr}) and low angular momentum cutoff (l_c; events with $l < l_c$ are rejected). χ^2 measures the quality of the statistical-model fit with an initial J distribution of the compound nucleus that is determined by l_{cr} and l_c. The dots correspond to the χ^2 minimum. The triangles correspond to a χ^2 value where l_c has been determined from Ref. 2 and l_{cr} adjusted to get the experimental fusion cross section.

It can be seen from Fig. 1 that the fits (values of χ^2) get a slightly incorrect estimate of the $^{23}\mathrm{Na}$-to-$^{20}\mathrm{Ne}$ mass ratio, their sum being correctly predicted, however. As shown in Fig. 2, exclusion of low l values changes this ratio in the wrong sense as well as seriously deteriorating the prediction for other isotopes such as $^{28}\mathrm{Si}$ which, as detailed investigation revealed, is almost entirely produced by four-nucleon evaporation from the low-l region.

It should be stressed that no signifivance can be attributed to the absolute values[13] of χ^2 since the data set is, strictly speaking, incomplete (absence of Z identification, nonmeasurement of small or zero contributions from masses < 20 or > 29) and may also contain undetected systematic errors. Thus in considering relative values of χ^2 we are assuming, as in Ref. 3, that the statistical model is applicable.

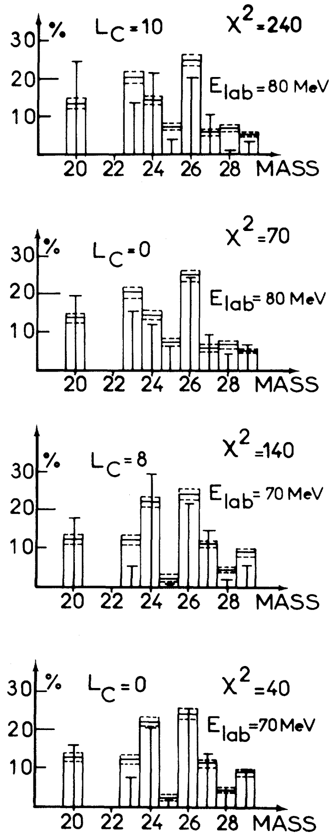

FIG. 2. Experimental evaporation-residue yields from Ref. 3 (histograms with dotted lines indicating error bars) compared with LANCELOT predictions (capped vertical lines) at two energies for points in the l_c-l_{cr} plane indicated in Fig. 1.

With this assumption, we summarize the importance of our results as follows:

Statistical-model calculations are indeed sensitive to limiting antular momenta. Comparison with the data strongly selects one unique pair of values l_{cr}, l_c.

The fact that values of l_{cr} independently obtained from statistical-model fits and total fusion cross sections agree gives increased confidence in the application of the statistical model.

The energy dependence of l_{cr} can be obtained by measuring an excitation function of relative mass distributions only, l_{cr} being determined from statistical-model fits. It is even sufficient to do this at only one angle as angular distributions are well described by the statistical model.[5]

Finally, our results are in strong disagreement with a low-l cutoff proposed for $^{16}O + ^{16}O$ in Ref. 2. Exclusion of low l values always worsens the quality of the statistical-model fit.

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