PHYSICAL REVIEW C VOLUME 11, NUMBER 2 FEBRUARY 1975

Production of Ca, Ga, and Br nuclei having angular momenta equal to or greater than the calculated liquid drop limit*

M. N. Namboodiri, E. T. Chulick, J. B. Natowitz, and R. A. Kenefick
Cyclotron Institute and the Departments of Physics and Chemistry, Texas A & M University, College Station, Texas 77843
(Received 16 September 1974)

A semiconductor detector telescope has been used to detect heavy recoil nuclei produced in the reactions of 157 and 262 MeV ^{14}N projectiles with ^{27}Al, Cr, and Ni target nuclei. Cross sections have been determined for the production of heavy recoiling compound nucleus residues. The limiting angular momenta which have been derived from these cross sections indicate the production of nonfissioning compound nuclei with angular momenta which equal or exceed the critical limit calculated using the liquid drop model. A comparison of the data with limits calculated using a reaction potential model recently proposed by Bass suggests that a picture based on dynamic restrictions to the fusion process provides a reasonable explanation of the results. However, the saturation limit predicted by the Bass model has not been observed.

[NUCLEAR REACTIONS $^{14}N+^{27}Al$, $^{14}N+Cr$, $^{14}N+Ni$, $E=157$ and 262 MeV, measured $\sigma(E)$ for compound nucleus residues. Deduced limiting J for production of nonfissioning compound nucleus.]

I. INTRODUCTION

Studies of the systematics of fusion reactions induced by heavy-ion projectiles provide a means of quantitatively testing theoretical calculations which predict limitations to the fusion process resulting either from dynamic restrictions in the entrance channel[1-5] or from intrinsic equilibrium limits[6] to the angular momentum of the compound nucleus. In general, the limitation to fusion observed in systems which have previously been studied can probably be attributed to dynamic limitations in the reaction entrance channel.

Thus, in order to employ heavy-ion reactions to make a definitive quantitative test of the predictions of intrinsic limits to the nuclear angular momentum, it is necessary to study systems in which the dynamic restrictions are expected to be less restrictive than such intrinsic limits. The results of our previous experiments,[7] performed with ^{12}C projectiles of energies as high as 180 MeV, suggested to us that dynamic limits might be less restrictive than the calculated liquid drop limits when projectiles of slightly higher energy and mass are incident on light targets. In the experiments reported here, the fusion of Al, Cr, and Ni nuclei with ^{14}N projectiles having kinetic energies of 157 and 262 MeV was studied. Cross sections were determined for the production of the residual heavy nuclei which result from the evaporative deexcitation following fusion of the projectile and target nuclei. Limiting angular momenta for the production of nonfissioning compound nuclei were extracted from those cross sections. These experimental limiting angular momenta are compared, in detail, with results of the liquid drop model (LDM) calculations[6] and of the nuclear reaction potential model suggested by Bass.[1]

II. EXPERIMENTS

A. Recoil cross section measurements

A semiconductor detector telescope consisting of three detectors with thicknesses 4.3, 100, and 1500 μm was employed to detect the recoiling heavy nuclei resulting from the irradiation of Al (107 $\mu g/cm^2$), Cr (530 $\mu g/cm^2$), and Ni (350 $\mu g/cm^2$) targets with 157 and 262 MeV ^{14}N ions extracted from the Texas A & M University (TAMU) variable energy cyclotron. Prior to its use in these experiments, the counter telescope was empirically calibrated by the use of accelerated ^{14}N, ^{16}O, ^{28}Si, ^{35}Cl, ^{40}A, ^{56}Fe, and ^{84}Kr ions to determine the response of the detectors as a function of energy and atomic number. As a result, recoiling reaction products penetrating the first detector could easily be separated from lighter species. The beam was monitored with a Faraday cup equipped with magnetic suppression for electrons. Measurements of the Rutherford scattering cross sections for ^{14}N on Au at 10° and at 15° were used to calibrate the monitor system. Data acquisition and processing techniques similar to those previously reported were used.[8]

B. Coincidence measurements

The purpose of our recoil measurements was to allow us to determine the cross sections for the production of compound nucleus residues. Recent experiments with high energy heavy ions have established that deep inelastic collisions involving large transfers of momentum from the projectile to the target can occur with significant probabilities.[9] Such collisions might produce energetic heavy recoils which could be mistaken for compound nucleus residues. In order to evaluate the

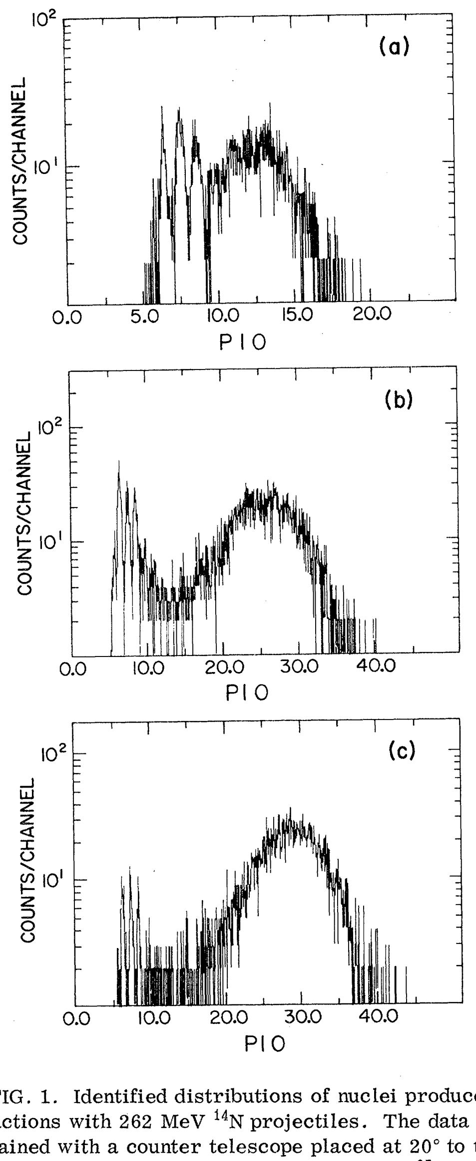

FIG. 1. Identified distributions of nuclei produced in reactions with 262 MeV ^{14}N projectiles. The data were obtained with a counter telescope placed at 20° to the beam direction. The target nuclei were (a) ^{27}Al, (b) Cr, and (c) Ni. The identification tag (PIO) is approximately equal to the atomic number of the detected nucleus.

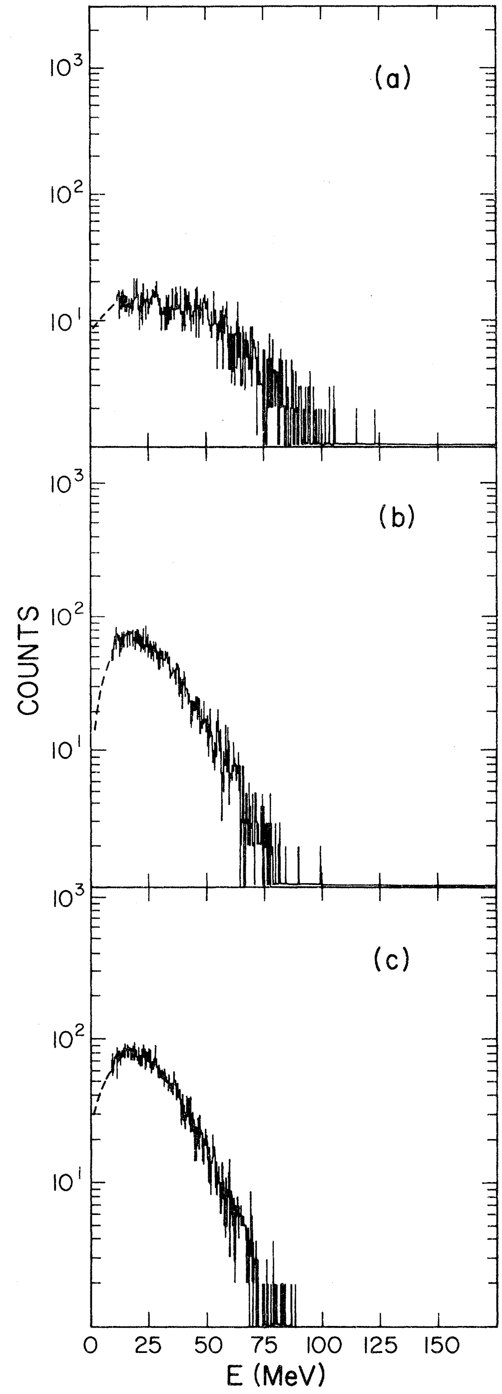

FIG. 2. Laboratory energy distributions of heavy recoils produced in reactions with 262 MeV ^{14}N projectiles. The data were obtained with a counter telescope placed at 20° to the beam direction. Targets were (a) ^{27}Al, (b) Cr, and (c) Ni. The energy spectrum of heavy recoils stopped in the first detector was added to the energy spectrum of identified heavy recoils. The dashed lines indicate the assumed extrapolations to lower energies.

possibility that our measurements for the ^{27}Al + ^{14}N system might be significantly affected by the occurrence of such deep inelastic reactions, we performed coincidence experiments in which an additional detector telescope, with an 8.4 μm ΔE detector, was used to measure the angular distribution of nuclei in coincidence with the recoil nuclei detected using the 4.3 μm ΔE detector. A number of angle pairs were studied using 157 MeV ^{14}N projectiles. Because only a low intensity beam of 262 MeV ^{14}N was available, only one measurement was made at this energy with the 4.3 μm detector at 16° and the 8.4 detector at 30°. Several different target to detector distances, ranging from 7 to 16 cm were used in these experiments.

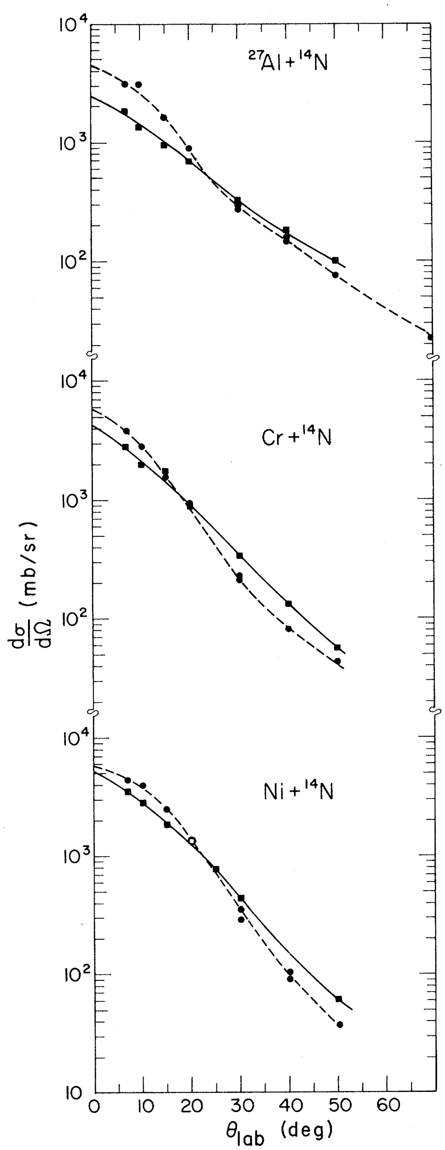

FIG. 3. Angular distributions of heavy recoil produced in reactions with 157 and 262 MeV ^{14}N projectiles. Targets were (a) ^{27}Al, (b) Cr, and (c) Ni. The solid symbols represent the experimental data: ●, 157 MeV: ■, 262 MeV.

III. RESULTS

In Fig. 1 we show some identified distributions of heavy nuclei which penetrated the first detector and stopped in the second detector. Shown in Fig. 2 are energy distributions obtained by combining the energy spectra of the heavy recoils with the corresponding energy spectra of nuclei which stopped in the first detector but had energies greater than 7 MeV, the maximum energy which ions of $Z \leq 8$ could deposit in the first detector. No corrections have been made for pulse height defect or energy losses in the target. As will be noted in the figure, corrections for the unobserved portion of the recoil energy spectra were estimated by extrapolation of the observed energy spectra.

In Fig. 3 we show the experimental angular distributions of the heavy recoiling nuclei. The extrapolation of the data to 0° is based upon a comparison with angular distributions obtained for similar systems using mica detectors which allowed the observation of recoils at very small angles. By integration over those angular distributions we obtained the total cross sections for production of recoils with $Z \geq 9$ from the ^{14}N + Al reaction, with $Z \geq 16$ from the ^{14}N + Cr reaction and with $Z \geq 17$ from the ^{14}N + Ni reaction.

In each of the reactions studied, the observed distributions in atomic number, energy, and angle of the heavy recoils are consistent with the distributions to be expected for fusion of the target and projectile nuclei followed by evaporative deexcitation of the resultant compound nucleus. As an additional check on the ^{27}Al + ^{14}N reaction mechanism, we used the results of the coincidence experiments described in Sec. II B to estimate the cross section for events in which a detected heavy recoil was in coincidence with a nucleus of $Z \geq 5$. We have assumed that such nuclei will most likely result from transfer reactions rather than from evaporative deexcitation of the compound nuclei. In the experiments with 157 MeV ^{14}N projectiles we estimate that less than 1% of the detected heavy recoils result from such transfer reactions. Although an extensive study was not possible with the 262 MeV projectiles, the one experiment which we were able to perform indicated that there is no significant increase in this correction factor at 262 MeV. Therefore, we have taken the measured cross sections for the production of heavy recoils to be the cross sections for the production of compound nucleus evaporation residues.

In Table I, the experimental cross sections σ_{HR} for the production of the compound nucleus residues are presented. Also listed in the table are values of σ_R, the total reaction cross section, which have been calculated using radius parameters derived from experimental measurements of total reaction cross sections.[10] In the sharp cut-off approximation, the maximum angular momentum $L\hbar$ corresponding to a cross section σ may be derived from the expression

$$L^2\hbar^2 = 2\mu E_{c.m.}\pi^{-1}\sigma, \quad (1)$$

where μ is the reduced mass and $E_{c.m.}$ is the projectile energy in the center of mass. This expression has been used to determine the limiting angular momenta for the production of compound nucleus residues. These limiting angular momenta are also listed in Table I.

IV. DISCUSSION

In this section we compare the experimental limiting angular momenta presented in Table I with calculated limiting angular momenta obtained from two quite different models, the liquid drop model and the dynamic model recently proposed by Bass. In making this comparison, we emphasize again that the experimental limiting angular momenta are for the production of nuclei taken to be the heavy residues of nonfissioning compound nuclei. As such, they represent lower limits to the fusion process since fission is not included.

A. Comparison of the experimental limiting angular momenta with liquid drop model predictions of an equilibrium angular momentum limit

Cohen, Plasil, and Swiatecki[6] have calculated the equilibrium configurations and potential energies of uniformly charged drops undergoing rotation and have computed fission barriers as a function of the angular momentum, charge, and mass of the drop. A specific prediction of this calculation is the angular momentum at which the fission barrier disappears. Such angular momentum limits may be taken as the LDM predictions for the highest angular momenta that nuclei can sustain. The predicted limits are indicated in Fig. 4 and listed in column 6 of Table I for the compound nuclei ^{41}Ca, ^{66}Ga, and ^{72}Br.

Since the LDM calculation predicts that nuclei with angular momenta close to the calculated limits have fission barriers approaching zero, the limiting angular momenta for the production of nonfissioning compound nuclei are expected to be even lower than the values listed in column 6. Plasil and Blann[11] have incorporated the angular momentum dependent fission barriers into an evaporation code ALICE. Using this code we have calculated the limiting angular momenta for the production of compound nucleus residues in the ^{14}N induced reactions which we have studied. These limiting angular momenta are listed in column 7 of Table I and have also been included in Fig. 4.

Ignoring the intrinsic spins of the target nuclei and equating L to J, we note that in the irradiations with 157 MeV ^{14}N projectiles the experimental limiting angular momenta for the production of the nonfissioning compound nuclei of Ga and Br agree within experimental errors with the values predicted by the evaporation calculation. In the experiments with 262 MeV ^{14}N projectiles, however, the experimental limiting angular momenta are higher than the values calculated using the evaporation code and, in fact, in the case of the reaction of ^{14}N with ^{27}Al, higher than the critical limit of $43\hbar$ predicted by the liquid drop model. Thus, the magnitudes of the cross sections indicate the

TABLE I. A comparison of predicted limiting angular momenta with the limiting angular momenta extracted from the cross sections for production of heavy recoils in the reaction with ^{14}N projectiles.

Energy (MeV)	Compound nucleus [a]	Experimental cross section σ_{HR} (mb)	Total reaction cross section [b] σ_R (mb)	Sharp cutoff limiting angular momenta ($\hbar$)	Liquid drop model limit ($\hbar$)	Evaporation calculation limit ($\hbar$)	Bass model limit ($\hbar$)	f	Bass model saturation limit ($\hbar$)
157	^{41}Ca	1360 ± 200	1600	44 ± 4	43	35	38	0.675	39
	^{66}Ga	1220 ± 180	1920	51 ± 4	67	54	48	0.563	63
	^{72}Br	1650 ± 250	1930	60 ± 5	77	55	51	0.539	68
262	^{41}Ca	945 ± 140	1750	48 ± 4	43	39	39	0.675	39
	^{66}Ga	1220 ± 180	2140	65 ± 5	67	60	63	0.563	63
	^{72}Br	1560 ± 230	2190	75 ± 6	77	60	66	0.539	68

[a] Compound nucleus resulting from the most abundant target isotope.

[b] Based upon radius parameters obtained from analysis of total reaction cross sections for heavy-ion induced reactions.

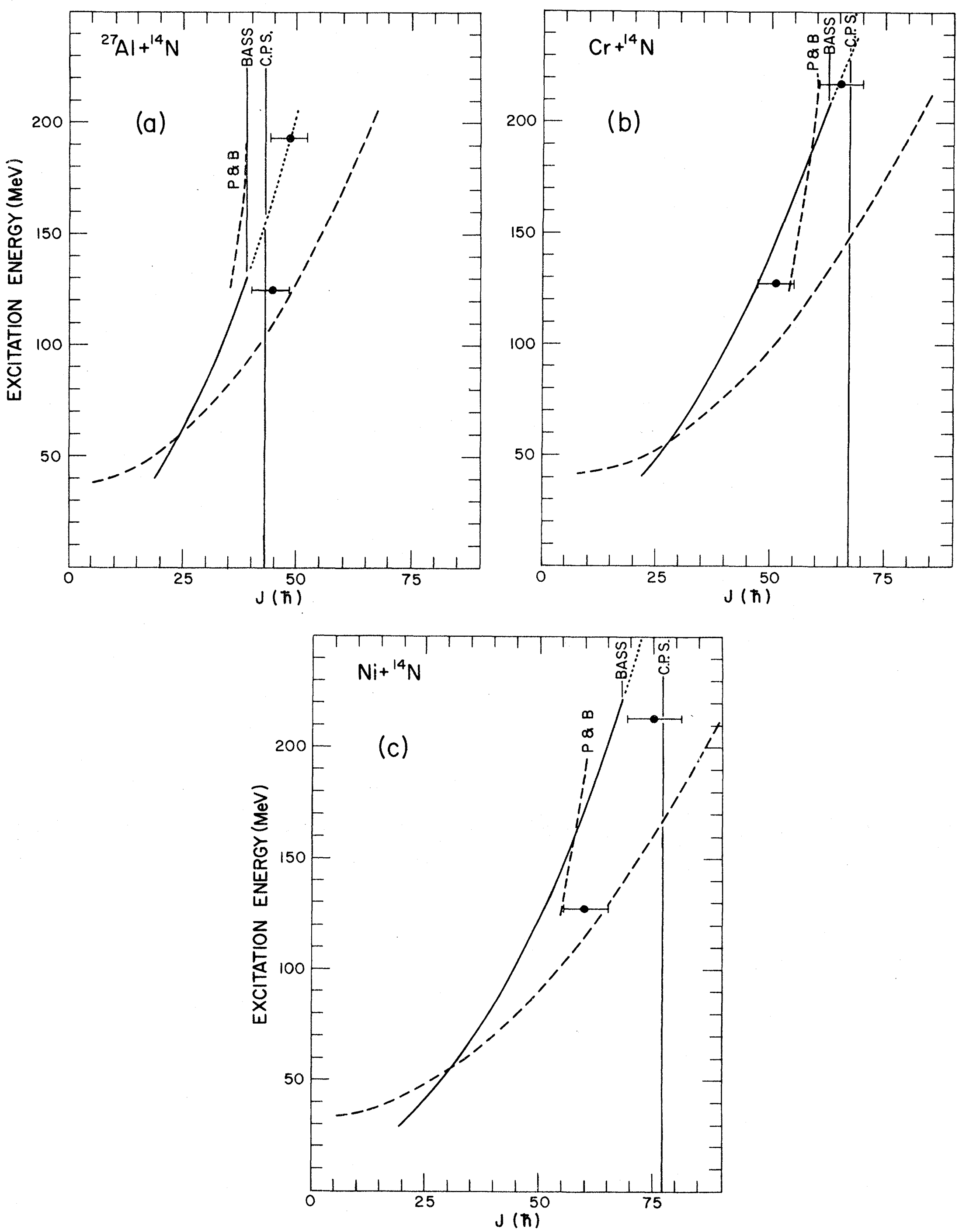

FIG. 4. Angular momentum limits for reactions induced by ^{14}N projectiles. Targets were (a) ^{27}Al, (b) Cr, and (c) Ni. The solid symbols with error bars are the sharp cutoff limiting angular momenta derived from the cross sections for production of nonfissioning compound nuclei (see text). The long-dashed line indicates the maximum possible angular momentum corresponding to grazing collisions. Various theoretical limits to the angular momentum are also represented. The line labeled C.P.S. is the liquid drop limit calculated by Cohen, Plasil, and Swiatecki. The line labeled BASS indicates the limits calculated using the model proposed by Bass. The dotted extension above the predicted saturation limit is calculated using Eq. (4). The dashed line labeled P & B shows the results of the Plasil and Blann evaporation calculation.

formation of compound nuclei having angular momenta equal to or exceeding the LDM limit but not decaying predominantly by a symmetric fission mode.

To obtain further information on the probability of fission in these systems, we have constructed the angle integrated yield distribution histograms presented in Fig. 5. Since the 4.3 μm ΔE detector did not allow experimental resolution of the individual atomic numbers, we constructed Fig. 5 by binning the continuous portions of the identified distributions into atomic number bins of a width determined by reference to the calibration data and to previous experiments,[7,8] on similar systems, using an 8.4 μm ΔE detector which allowed resolution of elements with $Z \leq 18$. By integrating over the resultant angular distributions for each atomic number we were able to determine the cross sections represented by the solid line histograms in Fig. 5. These histograms represent only the nuclei of higher atomic number which were transmitted through the first detector. We do not expect that better experimental resolution or the addition of the yields for recoils stopped in the first detector would appreciably alter the shapes of the distributions presented in Fig. 5. The absence of large cross sections for fission in the reactions with Cr and Ni is evidenced by the low yields of products near the atomic number corresponding to symmetric breakup.

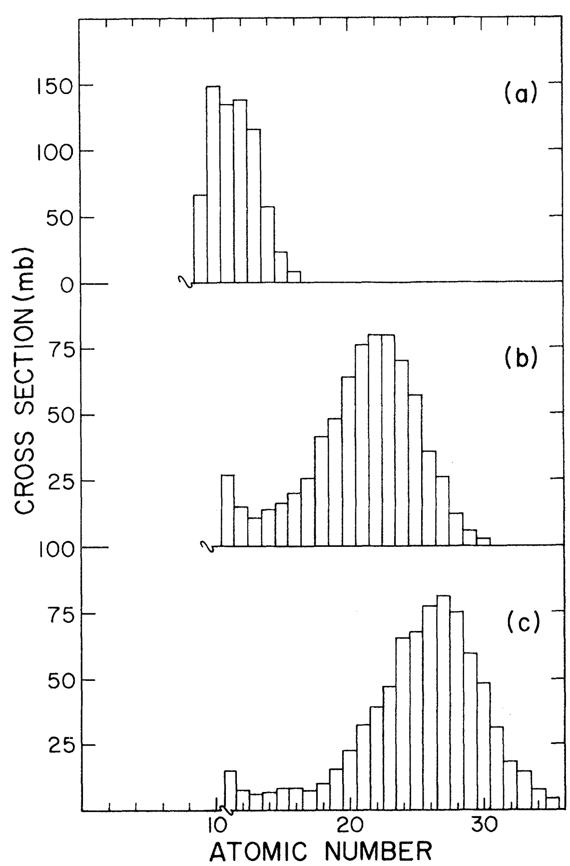

FIG. 5. Angle integrated elemental yield distributions of the identified higher atomic number elements produced in the reactions with 262 MeV ^{14}N projectiles. The targets were (a) ^{27}Al, (b) Cr, and (c) Ni.

For the N+Al reactions, products of symmetric fission would be difficult to distinguish from deep inelastic transfer processes. However, in experiments on a very similar system, ^{12}C + ^{27}Al at energies of 100 and 180 MeV, fission cross sections were found to be small.[7]

It might be argued that for the light compound nuclei produced in these reactions fission could be a very asymmetric process indistinguishable from small fragment evaporation. A significant probability for such fission events would be in disagreement with the LDM calculations which predict that nuclei with angular momenta close to the LDM limit are stable against asymmetric distortions. Specifically, Cohen, Plasil, and Swiatecki predict that for the nuclei ^{41}Ca, ^{66}Ga, and ^{72}Br, the symmetric saddle points are stable with respect to asymmetric distortions for J values greater than about $32\hbar$, $40\hbar$, and $33\hbar$, respectively (from Fig. 2(b) of Ref. 6).

Since those angular momenta are well below the experimental fusion limits and since the higher angular momentum states of the compound nucleus are those for which fission should be most probable, it would be expected that fission should be essentially symmetric in the reactions under study. This conclusion is of course based on the predictions of purely static calculations of the saddle point properties without the inclusion of dynamics. However, at least in the case of zero angular momentum, dynamic calculations[12] predict that the descent from the symmetric saddle point to scission of light nuclei results in symmetric fission.

B. Comparison of the experimental limiting angular momenta with predictions of the Bass model

In the model proposed by Bass,[1] the potential energy as a function of r, the separation distance between the two interacting heavy nuclei, is given as

$$V_l(r) = \frac{Z_1 Z_2 e^2}{r} + \frac{\hbar^2 l(l+1)}{2\mu r^2} - \frac{d}{R_{\text{fus}}} a_s A_1^{1/3} A_2^{1/3} \exp\left[-\frac{r - R_{\text{fus}}}{d}\right], \quad (2)$$

where the subscripts 1 and 2 refer to the two interacting nuclei, Z is the atomic number, A the atomic mass, μ the reduced mass, l the angular momentum quantum number, d the range of the nuclear interaction, a_s the surface energy parameter of the liquid drop model mass formula, and $R_{\rm fus}$ the characteristic distance for fusion at which the nuclei lose their individual identities. For the parameters d and a_s, Bass uses the values 1.35 fm and 17.9 MeV, respectively. The distance $R_{\rm fus}$ is taken as $r_0(A_1^{1/3}+A_2^{1/3})$ with r_0 set equal to 1.07 fm which makes $R_{\rm fus}$ essentially equal to the sum of the half-density radii of the two nuclei. Recently, Galin *et al.*[13] using a microscopic nuclear potential have analyzed experimental data on the limits to heavy-ion fusion and have found that the data are consistent with a fusion distance characterized by a radius parameter of 1.0 ± 0.07 fm. In our calculations with the Bass model we have taken $R_{\rm fus}$ to be the sum of the half-density radii of the two nuclei and have evaluated this quantity by interpolating between experimental values obtained for nuclear charge distributions.[14]

Figure 6 shows potentials for the system ^{14}N $+^{27}$Al calculated for L values equal to $0\hbar$, $26\hbar$, and $39\hbar$. For low values of L the potential is attractive at the fusion distance $R_{\rm fus}$. As L increases, the maximum in the potential shifts to smaller values of r. For ^{14}N$+^{27}$Al, $L=26\hbar$ is the highest L value for which the potential is attractive at $r=R_{\rm fus}$. Bass assumes that the potential of Eq. (2) is valid until the collision partners approach to $r=R_{\rm fus}$, at which point fusion is assumed to take place if the potential is attractive. However, as the nuclei merge together a partial conversion of orbital angular momentum into internal angular momentum of the individual nuclei takes place through surface interactions. Therefore, the model stipulates that the test for attractiveness of the potential at $R_{\rm fus}$ must be made with the centrifugal term computed using only a fraction f of the original angular momentum. The dependence of f upon the mass ratio of the two colliding nuclei may be estimated using a classical model in which it is assumed that complete equalization of surface velocities occurs for rigidly rotating nuclei.[1] In such a case,

$$f=\left[1+\frac{2}{5}\left(\frac{A_1R_1^2}{\mu R_{\rm fus}^2}+\frac{A_2R_2^2}{\mu R_{\rm fus}^2}\right)\right]^{-1}, \qquad (3)$$

where R_1 and R_2 are the half-density radii of the two interacting nuclei. The dependence of f upon the mass ratio A_1/A_2 is shown in Fig. 7. For ^{14}N$+^{27}$Al, $f=0.675$. Using this value in the Bass model leads to the prediction that fusion will occur up to a maximum $L=39\hbar$.

Consider the potential for $L=39\hbar$ in Fig. 6. Although the conversion of orbital angular momentum into internal angular momentum could begin as soon as the nuclei begin to overlap at $r=R_{\rm int}$, Bass assumes that the conversion is not significant until $r=R_{\rm fus}$ at which point the appropriate angular

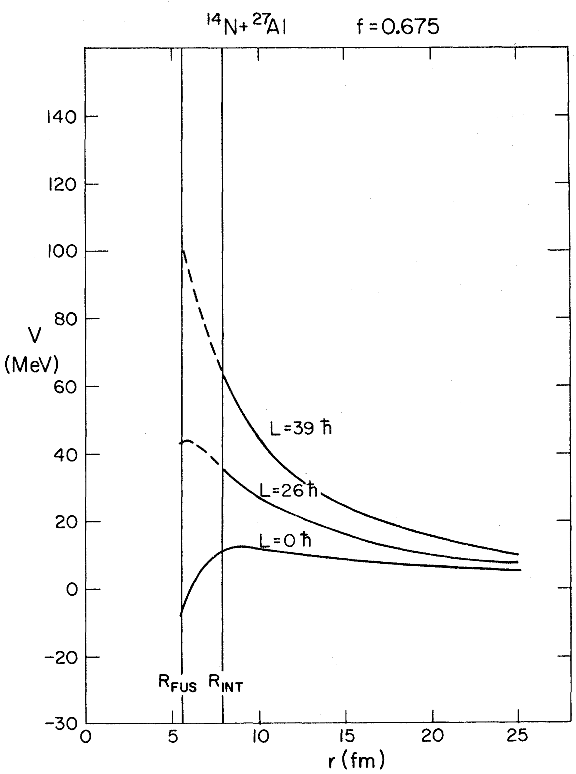

FIG. 6. Potential energy curves calculated for the reaction of ^{14}N with ^{27}Al. The calculations show results for $L=0\hbar$, $26\hbar$, and $39\hbar$ and were calculated using Eq. (2) in the text.

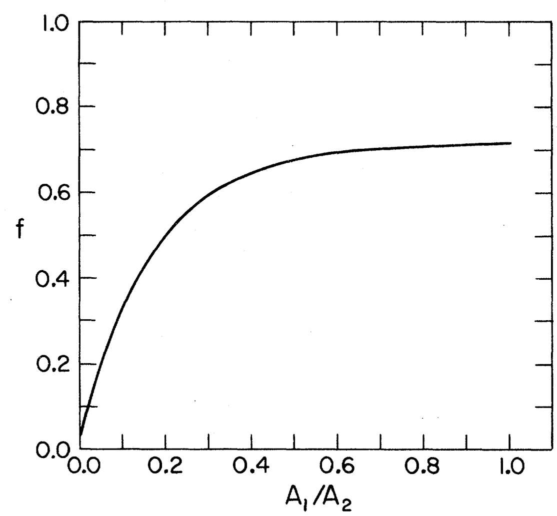

FIG. 7. The dependence of f on the mass ratio of the colliding nuclei. The value of f is obtained using Eq. (3) in the text.

momentum for evaluating the potential is instantly reduced to the fraction f of the orbital angular momentum. Thus the $L=39\hbar$ potential would correspond to the uppermost curve of Fig. 6 all the way to $r=R_{fus}$. At R_{fus} the effective potential for this trajectory would change to a new value with a centrifugal term, $L_{eff}=0.675\times 39\hbar = 26\hbar$.

In a given reaction, trajectories with asymptotic orbital angular momenta greater than a saturation value L_{sat} will not lead to fusion. Those trajectories with $L<L_{sat}$ will result in fusion if the energy is sufficient for the nuclei to approach to $r=R_{fus}$. Bass gives equations for calculating L_{sat} and the $E_{c.m.}$ at which saturation occurs. Up to L_{sat}, the limiting angular momentum at each energy is given by the asymptotic L value for which the potential at R_{fus} equals $E_{c.m.}$. From Bass's potential we can write the following simple equation valid below $L=L_{sat}$

$$L_{lim}\hbar = \left[2\mu R_{fus}{}^2\left(E_{c.m.} - \frac{Z_1 Z_2 e^2}{R_{fus}} + \frac{d a_s A_1{}^{1/3} A_2{}^{1/3}}{R_{fus}}\right)\right]^{1/2}. \qquad (4)$$

Note that Eq. (4) is independent of f, the magnitude of f being important only in determining the saturation L value.

In Table I the Bass model limiting angular momenta are listed for the reactions studied in this work. Also listed for each reaction is the value of f calculated with Eq. (3) and the corresponding saturation values of L.

In Fig. 4 we show the energy dependence of the limiting angular momenta predicted by the Bass model. The solid curves up to the saturation values are given by Eq. (4). The dotted extensions are also calculated using Eq. (4). These dotted extensions would be applicable if no saturation actually occurred or if smaller f values are appropriate.

For the reaction of ^{14}N with ^{27}Al, the experimental limiting angular momentum of $48\hbar$ is nine units above the predicted value of L_{sat} although it is in excellent agreement with the value of L calculated by assuming that Eq. (4) continues to be valid. In the reactions with Cr the measured values are in good agreement with the calculated values. The experimental values are somewhat higher than the calculated limits in the reactions with Ni nuclei. While it is clearly desirable to have further data at higher excitation energies, the present data may be an indication that the potential model of Bass is reasonably successful in describing the approach of two heavy nuclei but may not be appropriate to describe the final coalescence of the two into a compound nucleus.

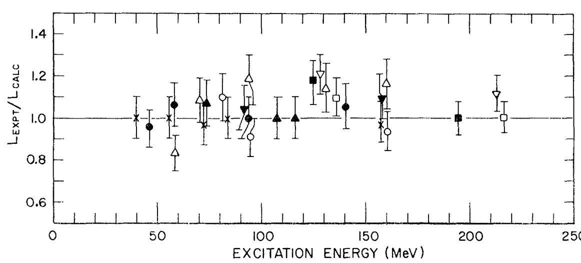

FIG. 8. Comparison of recent data for the energy dependence of the limiting angular momenta with values calculated using Eq. (4) (see text). The ratio of the experimental value to the calculated value is plotted as a function of excitation energy of the compound nucleus. Reactions included are: $^{12}C+^{27}Al$, ●; $^{12}C+Ti$, ○; $^{12}C+Ni$, ×; $^{40}A+^{121}Sb$, △; $^{14}N+^{27}Al$, ■; $^{14}N+Cr$, □; $^{14}N+Ni$, ▽; $^{40}A+^{77}Se$, ▲; $^{40}A+^{107}Ag$, ▼.

In order to test the usefulness of Eq. (4) in predicting limiting angular momenta we have compared L_{lim} values calculated using this equation with the recent experimental data.[7,13,15] This comparison is shown in Fig. 8 as a plot of the ratio of experimental to calculated L_{lim} versus the excitation energy in the compound nuclei. Except for the reactions of 262 MeV ^{14}N with Al, Cr, and Ni, the experimental limits are all below the predicted saturation limits. It is clear from this figure that the Bass model as represented by Eq. (4) is in good agreement with experimental data over a range of approximately 200 MeV in excitation energy. A more detailed approach to the question of fusion might provide more insight into the nature of the fusion process and details of dynamical effects such as friction. The reasonable success of Eq. (4) in the calculation of the energy dependence of the limiting angular momentum should make it a useful relation for the description of a wide variety of systems. This success suggests that, up to the time of fusion, there may not be a large conversion of orbital angular momentum into internal rotation of the two colliding nuclei. This rather extreme assumption bears further study.

It should be pointed out that for heavier systems for which the Bass potential is not attractive even when $L=0$, the fusion barrier may also be calculated from Eq. (4) as the center of mass energy corresponding to fusion at $L=0$. Bass presents a similar expression for calculating fusion barriers.

V. CONCLUSIONS

Both the evaporation calculation of Plasil and Blann which is based on the angular momentum dependent fission barriers of the liquid drop model and the reaction potential model of Bass, which includes a consideration of the dynamic effect of nuclear friction, lead to similar predictions of the limiting angular momentum for the production of nonfissioning compound nuclei in the reactions of ^{14}N with ^{27}Al, Cr, and Ni. However, the evaporation calculation predicts large cross sections for symmetric fission which are not observed. Therefore even though the angular momentum limits of the evaporation calculation are sometimes in fair agreement with those measured, the calculation does not appear to provide an appropriate description of the mechanism which limits the formation of nonfissioning compound nuclei in the systems studied.

It is possible, within experimental error, that the intrinsic limit of the type predicted by the LDM has been observed in the reaction of ^{14}N with ^{27}Al. However, since the intrinsic angular momentum limit calculated using the liquid drop model has been exceeded in the reaction of 262 MeV ^{14}N with ^{27}Al and has been equaled in the reactions with Cr and Ni, it may be that any actual intrinsic limit to the nuclear angular momentum, of the type indicated by the LDM calculations, occurs at higher angular momenta than those calculated. Assuming the evaporation calculation to be qualitatively correct, a crude estimate of the magnitude of the possible discrepancy between the calculated limits and actual nuclear limits may be obtained by using the results of the Plasil and Blann evaporation calculation. For Ca compound nuclei produced in the irradiations with 262 MeV ^{14}N, the calculated limit for residue production is about $9\hbar$ lower than the angular momentum at which the fission barrier disappears. For Br compound nuclei the calculated limit for residue production is about $15\hbar$ lower than the angular momentum at which the fission barrier disappears. Under the assumption that the evaporation calculations are valid and that the nuclei with the highest angular momenta are those which fission, actual angular momentum limits of the type predicted by the LDM would be expected to be approximately $9\hbar$ to $15\hbar$ higher than the experimental limits reported in this paper.

The calculation of Bass is in generally good agreement with previously reported fusion cross section data. However, the saturation limit predicted by the Bass model has been exceeded in the reaction of ^{14}N with ^{27}Al which suggests that the model may not be adequate to describe the final coalescence of the two reacting nuclei.

Note added. Recently, Nix[16] has suggested that if the diffuseness of the nuclear surface is taken into account, the value of f, particularly for light nuclei would decrease signficantly. A preliminary estimate for the $^{14}N + ^{27}Al$ system indicates that the Bass model saturation limit would be raised to $47.5\hbar$.

ACKNOWLEDGMENTS

We wish to thank R. Bass, F. Plasil, and R. Nix for helpful communications and suggestions, and K. Das and L. Webb for assisting with the data processing. We wish also to particularly acknowledge the contribution of cyclotron operator Robert J. Reynolds to this research. His untimely death saddens each of us.

---

*Research supported in part by the U.S. Atomic Energy Commission and the Robert A. Welch Foundation.

[1]R. Bass, Phys. Lett. 47B, 139 (1973); Nucl. Phys. A231, 45 (1974).
[2]D. H. E. Gross and H. Kalinowski, Phys. Lett. 48B, 302 (1974).
[3]R. H. Davis, Phys. Rev. C 9, 2411 (1974).
[4]J. P. Bondorf, M. I. Sobel, and D. Sperber, unpublished.
[5]A. M. Zebelman and J. M. Miller, Phys. Rev. Lett. 30, 27 (1973).
[6]S. Cohen, F. Plasil, and W. J. Swiatecki, Ann. Phys. (N.Y.) 82, 557 (1974).
[7]J. B. Natowitz, E. T. Chulick, and M. N. Namboodiri, Phys. Rev. Lett. 31, 643 (1973).
[8]E. T. Chulick, J. B. Natowitz, and C. Schnatterly, Nucl. Instrum. Methods 109, 171 (1973); E. T. Chulick, M. N. Namboodiri, and J. B. Natowitz, in Proceedings of the International Conference on the Physics and Chemistry of Fission, Rochester, New York, 1973 (to be published) [IAEA-SM-174/104].
[9]L. G. Moretto, Bull. Am. Phys. Soc. 19, 465 (1974).
[10]B. Wilkins and G. Igo, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei, Pacific Grove, California* (Univ. of California Press, Berkeley, 1963), p. 241.
[11]F. Plasil and M. Blann, ORNL (unpublished); M. Blann and F. Plasil, Phys. Rev. Lett. 29, 303 (1972).
[12]J. R. Nix, Nucl. Phys. A130, 241 (1969).
[13]J. Galin, D. Guerreau, M. Lefort, and X. Tarrago, Phys. Rev. C 9, 1018 (1974).
[14]R. Hofstadter, Rev. Mod. Phys. 28, 214 (1956).
[15]J. B. Natowitz, E. T. Chulick, and M. N. Namboodiri, Phys. Rev. C 6, 2133 (1972).
[16]J. R. Nix, private communication.