MASTER

FUSION MEASUREMENTS IN LIGHT AND MEDIUM
MASS HEAVY-ION REACTIONS

Progress Report
for Period June 1, 1980 - May 31, 1981

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Progress Report

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Abstract

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Abstract

The data obtained for fusion residues from the $^{16,18}\text{O} + ^{24,26}\text{Mg}$ systems have been analyzed and are being compared to each other and to predictions from the fusion-evaporation code CASCADE. Analysis of data obtained for a small step excitation curve for the $^{16}\text{O} + ^{24}\text{Mg}$ system has been started to determine the possible presence of structure in the fusion cross section. Additional data for the fusion cross sections of these systems have been obtained at energies from 100 to 140 MeV at the ATLAS facility and are being analyzed. Initial measurements of the fusion-fission cross sections for ^{58}Ni beams, at energies up to 320 MeV on targets from ^{116}Sn to ^{170}Yb , have been made. Analysis is in progress and additional experiments are planned. A collaboration is planned at Notre Dame for experiments to determine the "entry line" for fusion in the $^{12}\text{C} + ^{16}\text{O}$ system, both for the interest in this system and for preparation for additional experiments at higher energies at Michigan State when the new facility there becomes available. These experiments should lead to information about the importance of incomplete fusion in this system. Experiments to test the limitation on fusion cross sections predicted by the rotating liquid drop model are planned as higher energies become available at ATLAS and MSU.

I. Fusion Residues from $^{16,18}\text{O} + ^{24,26}\text{Mg}$.

Our main effort at the University of Kansas this past year has been to analyze data obtained at Argonne National Laboratory in August, 1979, and April, 1980. There were two separate purposes for these experiments. The first experiment involved investigations of the three systems $^{16}\text{O} + ^{26}\text{Mg}$, $^{18}\text{O} + ^{24}\text{Mg}$, and $^{16}\text{O} + ^{24}\text{Mg}$. A systematic entrance channel effect had been noticed by us¹ and independently by others² for the fusion cross sections in the systems where ^{16}O was the projectile as opposed to those for which the neighboring nuclides ^{15}N and ^{18}O were the projectiles. We wished to see if this difference was reflected in the relative production of specific fusion residues for these systems. For, this, we obtained gamma-ray spectra for beam energies of 25 to 70 MeV in large (about 5 MeV) steps. From these spectra, the relative cross sections for production of specific residues have been extracted and are being compared to each other and to the predictions of the fusion-evaporation code CASCADE³. A preliminary report of this work was given at the fall, 1980, meeting of the APS.⁴ An expanded and updated version of this talk is included in this report as an appendix.

The second experiment was undertaken to obtain gamma-ray spectra for the system $^{16}\text{O} + ^{24}\text{Mg}$ at bombarding energies of 40 to 51 MeV in 350-keV steps. Investigations of the fusion yields in lighter systems of "alpha-particle" nuclei, from $^{12}\text{C} + ^{12}\text{C}$ to $^{12}\text{C} + ^{24}\text{Mg}$, have shown systematic oscillations or resonances, deviating from the usual smooth rise and leveling off of the fusion cross section with increasing beam energy seen in other light heavy-ion systems.⁵ (Similar structure has been reported in the somewhat heavier, but self-conjugate, systems $^{24}\text{Mg} + ^{24}\text{Mg}$ ⁶ and $^{28}\text{Si} + ^{28}\text{Si}$ ⁷.)

Because better statistical accuracy can be obtained more easily with gamma-ray data and because this structure has been most apparent for the production of those specific residues which result from alpha-particle boilloff, we have used this technique to attempt to establish the presence of similar structure for this next heavier system. Analysis of these data has only recently been started.

¹F. W. Prosser, Jr. et al., Phys. Rev. C 21, 1819 (1980).

²R. Rascher, W. F. J. Muller, and K. P. Lieb, Phys. Rev. C 20, 1028 (1979).

³F. Puhlhofer, Nucl. Phys. A280, 267 (1977).

⁴R. A. Racca et al, Bull. Am. Phys. Soc. 25, 733 (1980).

⁵D. G. Kovar et al, Phys. Rev. C 20, 1305 (1979). P. Deyoung et al., Bull. Am. Phys. Soc. 24, 851 (1979). J. Kolata et al., Bull. Am. Phys. Soc. 24, 835 (1979).

⁶C. M. Jachinski et al., Bull. Am. Phys. Soc. 25, 592 (1980).

⁷R. R. Betts, S. B. DiCenzo, and J. K. Peterson, Phys. Rev. Lett. 43, 253 (1979).

II. Collaboration in Experiments on the Argonne Tandem-Linac System.

A. $^{16}\text{O} + ^{24,26}\text{Mg}$.

In February, 1980, we assisted in fusion measurements for these systems at beam energies up to 140 MeV. We wished to confirm the constancy of the fusion cross section for $^{16}\text{O} + ^{24}\text{Mg}$ for energies between 70 and 100 MeV and its decrease between 100 and 140 MeV that had been noted earlier.¹ It was also of interest to see if the same effect occurs with $^{18}\text{O} + ^{24}\text{Mg}$, and to determine the reaction mechanisms that begin to compete strongly with fusion.

B. $^{16,18}\text{O} + ^{24}\text{Mg}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$.

The first of these systems was included to complete the information from the February run. When machine difficulties prevented use of a Mg beam, we decided to use the time to extend our previous measurements of the third system, $^{18}\text{O} + ^{24}\text{Mg}$, into the higher energy region now available. Analysis of the data from the July run, as well as the previous O + Mg runs, is being supervised by D. G. Kovar.

C. Heavy-Ion Reaction with Beams of Ni Isotopes.

In November, 1980, we participated in experiments with the first use of ^{58}Ni beams at ATLAS. Beams at energies up to 318 MeV were used to bombard targets of $^{116,124}\text{Sn}$, $^{144,154}\text{Sm}$, and ^{170}Yb . At these energies for these systems, fusion-symmetric fission becomes a major component of the total reaction cross section. Solid state detectors in coincidence were used to measure the excitation curves for this process at the folding angle for the fission products. This was the first in a series of experiments planned for these systems to study this process, its competition with the fusion-boiloff process, and the importance of other competing reaction processes. Repetition of these experiments with a ^{64}Ni beam is

also planned to study the rôle of neutron excess in the results. W. Henning is in charge of the analysis of these experiments.

¹D. G. Kovar et al., Bull. Am. Phys. Soc. 25, 524 (1980).

III. Future Plans

We plan to complete the analysis of the gamma-ray data for the $O + Mg$ systems this spring and to have papers prepared for publication by early summer. Hopefully, the time scale will be the same for the analysis of the higher energy fusion of these systems which is being done by other members of the collaboration. A second ^{58}Ni run is being scheduled for this spring and we will continue to participate in these experiments. Two other general areas I plan to explore, which may prove to be related, are the questions of the role of pre-equilibrium light-ion emission in the fusion process (incomplete fusion) and of the possible limitation on fusion predicted by the rotating liquid drop model.

A. Pre-equilibrium processes.

We have a series of experiments planned at the University of Notre Dame with physicists from there and from Michigan State University. The basic topic is the investigation of the fusion of $^{12}C + ^{16}O$ at energies below and above the "turnover" in the fusion cross section. Our immediate interest is in the determination of the "entry lines" in the residual nuclei as a function of bombarding energy, and the techniques developed for this system will be of future use for heavier nuclei when the facility at MSU becomes available. We have experiments planned to measure the average gamma-ray energy for the production of specific residues, the average gamma-ray multiplicity and its spread, the average gamma-ray multipolarity, and the spectra of the neutrons, protons and alpha particles emitted in the production of these residues. In addition to establishing the position of the entry line for each residue, the data may provide information on the role of pre-equilibrium emission at the higher bombarding energies.

B. Rotating liquid drop limitation to fusion.

A variety of apparently conflicting results have been reported on the presence of such a limitation to the fusion cross section. Stokstad et al.¹ have reported a sudden falloff of the fusion cross section for the $^{12}\text{C} + ^{14}\text{N}$ system at high energy. The limiting angular momentum was found to be in excellent agreement with the prediction of rotating liquid drop model for that which could be sustained by an $A = 26$ compound system. Some other systems, $^{16}\text{O} + ^{40}\text{Ca}$ for example,² have been studied at energies where this limitation is predicted and have not observed it. A falloff in the fusion cross section which has a superficial similarity has been observed for the systems $^{16}\text{O} + ^{24,26}\text{Mg}$.³ However, the angular momenta involved for the bombarding energies from 100 to 138 MeV where this was seen are well below those for which the RLDM limitation should occur. A possible explanation may lie in the pre-equilibrium emission of light particles which may carry off enough angular momentum to reduce that of the subsequent fused system to below the RLDM limit,² but this is in need of further investigation.

¹R. G. Stokstad et al., Phys. Lett. 70B, 289 (1977).

²S. E. Vigdor et al., Phys. Rev. C 20, 2147 (1979).

³D. G. Kovar et al., Bull. Am. Phys. Soc. 25, 254 (1980).

IV. Personnel.

Francis W. Prosser, Principal investigator

Robert A. Racca, Research assistant

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V. Publications and Contributions.

F. W. Prosser, Jr., R. A. Racca, K. Daneshvar, W. Henning, D. G. Kovar, K. E. Rehm, and S. L. Tabor, Phys. Rev. C 21, 1819 (1980). (copy attached)
R. A. Racca, F. W. Prosser, Jr., K. Daneshvar, C. N. Davids, and D. G. Kovar, Bull. Am. Phys. Soc. 25, 733 (1980).

Yields of Specific Residue Nuclei from the Fusion of $^{16,18}_0 + ^{24,26}_{\text{Mg}}$.

R. A. RACCA, and F. W. PROSSER, JR., University of Kansas*, and K. DANESHVAR, C. N. DAVIDS, and D. G. KOVAR, Argonne National Laboratory⁺--Gamma-ray yields from the interaction of $^{16}_0 + ^{24}_{\text{Mg}}$, $^{16}_0 + ^{26}_{\text{Mg}}$, and $^{18}_0 + ^{24}_{\text{Mg}}$ were measured over the energy range $30 \text{ MeV} \leq E_{\text{lab}} \leq 70 \text{ MeV}$. Total fusion cross sections for these interactions have been obtained previously.¹ The objective was to see if the entrance channel effects observed with the use of $^{16}_0$ as a projectile as opposed to the use of other nearby nuclei such as $^{15}_\text{N}$ and $^{18}_0$,² would be reflected in the pattern of residual nuclei. Preliminary results indicate that a correlated entrance channel effect exists. The experimental results for the three systems will be compared with each other and with the theoretical predictions from the code CASCADE³.

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+Work done under the auspices of the Department of Energy.

¹S. L. Tabor et al., Phys. Rev. C 17, 2136, (1978).

²F. W. Prosser, Jr. et al., Phys. Rev. C 21, 1819 (1980).

³F. Pühlhofer, Nucl. Phys. A280, 267 (1977).

FUSION RESIDUES FROM $^{16,18}\text{O} + ^{24,26}\text{Mg}$

- I. Introduction
- II. Experimental Procedure
- III. Analysis
- IV. Results
- V. Comparison With Theory
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I. Introduction

Recent measurements^{1,2} of the fusion cross-section for several mass 42 systems indicate the presence of an overall entrance channel effect in the so called barrier-dominated energy region. The systems of interest were $^{16}\text{O} + ^{26}\text{Mg}$, $^{18}\text{O} + ^{24}\text{Mg}$ and $^{15}\text{N} + ^{27}\text{Al}$. It is apparent from the data that the behavior of σ_{fus} for the $^{16}\text{O} + ^{26}\text{Mg}$ system is different from that of the other two systems. This effect is parametrized by the expression

$$\sigma_{\text{fus}} = \pi R_B^2 (1 - V_B/E),$$

where the barrier parameters, V_B and R_B , for the system involving the ^{16}O projectile differ from those for the systems involving ^{18}O or ^{15}N . Rascher et al.³ have also noted similar differences for fusion reactions involving ^{16}O and ^{18}O projectiles.

In this work, individual fusion-boiloff residues for the $^{16}\text{O} + ^{26}\text{Mg}$ and $^{18}\text{O} + ^{24}\text{Mg}$ systems are identified by measuring the intensities of the characteristic gamma rays for each of the nuclei produced in the evaporation process. It is hoped that the overall entrance channel effect seen previously can be observed in the relative production of specific residues. Fusion residues were also identified for the $^{16}\text{O} + ^{24}\text{Mg}$ system and the results compared with those for the mass 42 systems above. This comparison will isolate any changes in the fusion cross section due to isotopic differences in the target or projectile.

Data were obtained for the mass 42 systems at a number of laboratory energies from 25 to 70 MeV. Comparisons were made for those bombarding energies corresponding to the same excitation energy of the compound systems. Data were also obtained for the $^{16}\text{O} + ^{24}\text{Mg}$ system at energies of 30 to 67 MeV. Results for each of the three systems were then compared with the predictions of an evaporation model calculation.

II. Experimental Procedure

Gamma-ray intensities were measured and recorded using a Ge(Li) detector positioned at 90° relative to the incident beam. The detector face was covered

by a graded absorber to screen out unwanted X-rays. Targets used were 50 mg/cm² ²⁴Mg and ²⁶Mg evaporated onto a 2 mil gold backing, which was sufficiently thick to stop the beam at all bombarding energies. Using conventional electronics, the data were digitized and stored as a one-dimensional 4096 channel array on the PDP 11/45 on-line computer at Argonne. The fusion residues resulting from the evaporation process are uniquely determined by their characteristic gamma-ray transitions between low-lying states. All nuclei with $Z > 12$ were counted as evaporation residues. The absence of Ne lines in the spectrum implies that the fusion-fission mode of decay is not significant for the range of bombarding energies used.

III. Analysis

A portion of a typical gamma-ray spectrum is shown in Figure 1. For the most part, the spectrum is relatively clean, that is, the energy resolution of the detection system was sufficiently good to produce sharply defined peaks rising above the general background. By identifying each gamma-ray line with its parent nucleus, the production of various fusion residues due to the fusion-evaporation process can be verified. This identification, using only singles spectra, is possible if the various levels for each residue are well known. An extensive compilation of energy levels for the residues in question has been done by Meijer et al.^{4,5}

All spectra were analyzed using the Mod Comp II computer facility at the University of Kansas. Data analysis was greatly facilitated by the Tektronix 4027 interactive color graphics terminal which permitted a close-up inspection of any portion of the spectra in question. The details of this system have been discussed in a previous report.⁶ Background subtraction was accomplished by two different methods. The method yielding the most consistent results was performed in the following way. The background behavior on the high and low energy sides of each peak were fitted to a straight line using a least squares

fit routine that was part of the data analysis code ANLPHS.⁷ In many cases, the absence of adjacent gamma-ray lines in the vicinity of the line in question allowed the use of as many as 50-100 points for the fit. The presence of other lines in close proximity with the line in question frequently limited this number, especially in the low energy portion of the spectra where the density of peaks is much greater than in the high energy portion. A minimum of about 10 points was used for any fit and in all cases the background appeared to be well represented by the straight line. The uncertainties arising from different reasonable choices of the background were, in almost all cases, less than or approximately equal to the statistical error. Hence, it was not necessary to assign a subjective error to the final gamma-ray yields.

In several cases it was necessary to unfold two gamma-ray lines due to partial overlap. The method for accomplishing this was simple and straightforward. A "clean" gamma-ray line in the same energy region of the spectrum was chosen as a standard. The width at various fractions of the maximum was noted and this standard shape was then applied to unfold the overlap peaks. Since the number of overlap peaks as well as the degree of overlap were small, it was feasible to perform this calculation without the aid of a sophisticated computer code. All the results obtained from this method were quite reasonable and the unfolded shapes conformed rather well with the standard shape. It should be noted that the success of this method depends upon the correct choice of a standard shape. Since the heavy residues must maintain most of the beam momentum, their recoil direction will be strongly forward peaked. Nevertheless, there will be some transverse momentum resulting in a trajectory in the shape of a cone. This leads to doppler broadening for very fast transitions from low lying states which may be strongly populated by direct feeding in the boiloff process. As mentioned previously, a thick Au backing was used on the target support which stops the residues locally and minimizes this effect.

IV. Results

A. Mass 42 Systems

The reactions $^{16}\text{O} + ^{26}\text{Mg}$ and $^{18}\text{O} + ^{24}\text{Mg}$ both lead to the same fused system, ^{42}Ca , where the compound nucleus is formed at excitation energies of 33 to 60 MeV and angular momenta as high as $30\hbar$. The de-excitation process is accomplished by the emission of protons, neutrons, alpha particles, and gamma rays. As mentioned in section II, all observed nuclei with $Z > 12$ are assumed to result from the fusion-evaporation process. It appears, however, from the results that there is no significant amount of fusion boiloff products lighter than ^{30}Si .⁸

The analysis was conducted in two stages, the first being to firmly establish the existence of a particular fusion residue by searching the spectra for a strong characteristic transition belonging to that nucleus. Second, once the presence of a particular residue is confirmed, all the gamma rays in the cascading sequence are then identified in an attempt to find the total yield which feeds the ground state. Note that any direct feeding to the ground state of each residue during the reaction is not seen and consequently is not included in the total yield. The results show that there is no evidence of any transitions belonging to ^{42}Ca , which indicates that for the excitation energies used, the probability for particle boiloff completely dominates over gamma decay. There is also no evidence for the existence of fusion residues resulting from single nucleon or single alpha-particle boiloff. It appears that, for the heavier residues, those levels which lie far above the gamma-ray cascade band⁹ are the ones most likely to be populated. Gamma-ray lines associated with two- and three-nucleon boiloff are clearly observed in the spectra. The various evaporation modes for the $^{16}\text{O} + ^{26}\text{Mg}$ and $^{18}\text{O} + ^{24}\text{Mg}$ systems are shown in Figures 2 and 3 respectively. Since only singles spectra are recorded in this work, the relative energy behavior becomes an important tool in residue identification. As expected, the two-nucleon decay mode peaks rather early and falls off rapidly with energy. During this fall-off the

three-nucleon decay mode gains strength and peaks at a somewhat higher energy. In addition, because of coulomb effects, the (2p,n) decay will reach its maximum at a slightly higher energy than the (p,2n) mode.¹⁰

Other two- and three-particle decay modes that are present include (α ,p), (α ,n) and (α ,p,n). Again note that for both systems studied, all of the residues resulting from these decay modes exhibit shapes which are mutually consistent. In Figures 2 and 3 each residue is represented by the strongest transition found for that nucleus. In general, there are several transitions which feed the ground state; however, one line will usually dominate over the rest. Hence, the intensities are representative of the relative strengths with which specific residues are produced.

Also seen in the spectra are several residues which are produced via four- or five-particle decay. Except for ^{38}Ar , these yields are relatively small compared with those mentioned above. It can be seen from Figures 2 and 3 that the shape of the excitation curve for the ^{38}Ar residue indicates a (2p,2n) boiloff mode rather than alpha-particle decay. Apparently, in agreement with theory, the states in ^{38}Ar populated by alpha-particle emission from the ^{42}Ca fused system decay by further particle emission over the entire energy range covered. Furthermore, it appears from the data that more strength is distributed among the lighter fusion residues as the bombarding energy increases. This effect has been noted previously in other systems.¹¹

At this stage of the analysis, there is evidence for the existence of $^{40}\text{Ar}(2p)$, $^{33}\text{P}(2\alpha,p)$, $^{33}\text{S}(2\alpha,n)$ and $^{30}\text{Si}(3\alpha)$. However, due to poor statistics and in some cases severe overlap with lines from other residues, the yields for these nuclei will be more difficult to determine.

B. $^{16}\text{O} + ^{24}\text{Mg}$

The fusion residues for the $^{16}\text{O} + ^{24}\text{Mg}$ system display a similar energy behavior with those discussed for the mass 42 systems above. The results are shown in

Figure 4. Again, as before, note that there is no evidence for any single nucleon boiloff. Residues resulting from two- and three-nucleon boiloffs are present in the spectrum; however, since the fused system does not have a neutron excess, a preference for proton emission over neutron emission is to be expected. No evidence is seen for the existence of any isotopes of Ca but, as Figure 4 shows, the presence of $^{38}\text{Ar}(2p)$ and $^{37}\text{Cl}(3p)$ is firmly established. Furthermore, the $(p,2n)$ and (α,n) decay modes are completely suppressed in favor of the $(2p,n)$ and (α,p) decay modes, respectively. As is the case with the mass 42 fused system, the intensities for each of the boiloff residues produced behave with energy as expected.

Overlap problems for this system were somewhat more serious than for the mass 42 system. Higher level transitions have been identified for several important residues. Unfortunately, those levels which feed the ground state are in some cases badly overlapping and impossible to resolve. The fusion residues $^{38}\text{K}(p,n)$ and $^{35}\text{Cl}(\alpha,p)$ have been omitted from the present discussion in spite of the fact that several characteristic lines for each have been identified in the spectrum. The same problem arises for the pairs $^{36}\text{Ar}(2p,2n)$ and $^{33}\text{S}(\alpha,2p,n)$ and $^{32}\text{S}(2\alpha)$ and $^{31}\text{P}(2\alpha,p)$. For each pair, the $2^+ \rightarrow 0^+$ transition in the even-even nucleus is unresolved from an important ground state transition in the odd-A nucleus. The problem is compounded in ^{32}S , where the $4^+ \rightarrow 2^+$ transition is unresolved from the $2^+ \rightarrow 0^+$ transition, as well. A very similar energy behavior for each pair of residues causes even more difficulty. At this point, only partial strengths for the production of these yields can be obtained.

V. Comparison With Theory

The reactions in the work are assumed to be complete fusion reactions where the initial projectile + target forms a highly excited compound system which subsequently decays by particle and gamma-ray emission. Quantitative predictions of the above process have been performed using the nuclear evaporation code

CASCADE.¹² The code is based on the following model. The assumption is made that a highly excited compound system is formed in statistical equilibrium, which can boil off neutrons, protons, alpha particles, and gamma rays. The Hauser-Feshbach formula together with the statistical nuclear decay model is applied and the cross-sections for the various decay modes are calculated. In the version of the code used here, nuclear de-excitation due to the emission of other light particles, such as d , ^3He , ^6Li , etc., is assumed to be small and consequently is neglected. De-excitation by fission is also not included in the calculation. No evidence for fission is present in the data at any of the excitation energies used.

For the purposes of calculation, the range of excitation energies in each residue has been divided into three separate regions. The first or lowest excitation energy region, which extends typically to 4 MeV, is that for which the experimentally known spins, energies and parities for the nuclear levels of each fusion residue are used. The next region of medium excitation extends from the top of the first region up to a selectable energy chosen in our calculation to be 15 MeV. An analytical level density formula is used to describe the nuclear levels and empirically^{14,15} determined parameters are used for each boiloff nucleus. The third and highest excitation energy region is assumed to begin at an energy ELDM, the point where the nucleus behaves as predicted by the liquid drop model. Level densities are again represented by the Fermi gas level density formula as in the intermediate region. However, since rotations and centrifugal stretching are causing core deformations, it is necessary to use a different set of level density parameters.

A reasonable set of input parameters was chosen and the predictions of the code were compared with the data. The results for both the $^{18}\text{O} + ^{24}\text{Mg}$ and $^{16}\text{O} + ^{26}\text{Mg}$ systems are shown in Figures 5-9. In each of these figures, the total strength which feeds the ground state has been calculated and compared with the prediction of CASCADE. To facilitate the comparison, an average multiplicative scale factor was used to change the gamma-ray intensities to a cross-section

scale. This scale factor is in reasonable agreement with one calculated on the basis of the nominal target thickness and the experimental geometry.

Because the overall entrance channel effect for the mass 42 systems discussed previously² is a relatively weak one, it may be expected that any entrance channel effects which are reflected in the individual residue behavior should also be weak. It can be seen in Figure 5 that the fit for the $^{180} + ^{24}\text{Mg}$ system agrees somewhat better with the code predictions than the fit for the $^{160} + ^{26}\text{Mg}$ system. In the latter system, if the cascade curve is scaled to fit the low energy data, the high energy side is grossly underpredicted. Conversely, if the curve is scaled to fit the high energy data, the low energy side will be overpredicted. In Figure 6, it is again seen that the agreement in shape for the $^{180} + ^{24}\text{Mg}$ system is somewhat better than for the $^{160} + ^{26}\text{Mg}$ system, while the agreement in total intensity is much better for the $^{160} + ^{26}\text{Mg}$ system. Figures 7, 8, and 9 show fits which are comparable for both systems. It appears at this stage of the analysis that the better shape agreement of the $^{180} + ^{24}\text{Mg}$ system with the code may be weak evidence for an entrance channel effect. It is necessary to compare more residues with the code to test conclusively this point.

In some cases the total residue strengths are in very poor agreement with the evaporation code predictions. It is of interest to investigate whether or not this is due to the particular choice of input parameters that one uses. Variations of two critical input parameters in the liquid drop region¹² for several different excitation energies have been tried and the results compared. The first parameter, the deformability δ , is expected to change the results drastically since it determines the shape of the yrast line in this highest energy region. According to the discussion in reference 12, an appreciable fraction of the de-excitation cascade is expected to take place in the vicinity of the yrast line and consequently will be sensitive to the shape and spin dependence of the levels in this region. The second parameter, the transition energy ELDM, from the intermediate to the highest energy region is also expected to be crucial to the final results

since it essentially determines at what excitation energy the deformation discussed above becomes important.

Preliminary results indicate that the predictions of the code are insensitive to changes in these parameters for both the $^{18}\text{O} + ^{24}\text{Mg}$ and $^{16}\text{O} + ^{26}\text{Mg}$ systems. This is rather surprising in view of the previous discussion. One possible explanation may be that since the compound system is being formed at energies and angular momenta significantly higher than the gamma-ray cascade band (and hence the yrast line), the decays which occur in this highest energy region will be relatively insensitive to moderate changes in the position of the yrast line. Consequently, the population of those states which govern the yrast line in the lowest energy region will not be affected. It is apparent that further experimentation is needed to identify the position of the gamma-ray cascade band in terms of energy and angular momentum for each fusion residue.

As mentioned in section I, a study of the $^{16}\text{O} + ^{24}\text{Mg}$ system was undertaken in order to distinguish the real entrance channel effects in the mass 42 system from changes in the cross-section resulting from the use of dissimilar targets or projectiles. It is, therefore, interesting to compare the predictions of CASCADE for the residues resulting from the fusion-evaporation of the $^{16}\text{O} + ^{24}\text{Mg}$ system with those for the mass 42 systems discussed above. The experimental points and CASCADE predictions for the $^{36}\text{Cl}(3p,n)$ mass 40 fusion residue is shown in Figure 10. As expected the yield increases with increasing excitation energy. However, the data does not extend sufficiently high enough to determine at what energy saturation occurs. Note from the figure that the evaporation code slightly underpredicts the data at the lowest energies. A remarkably similar behavior can be seen in Figure 7 for the ^{38}Ar fusion residue which results from 4-nucleon boiloff of the mass 42 compound system. The ^{38}Ar residue resulting from the (2p) boiloff mode in the mass 40 system is shown in Figure 11. This can be compared with the ^{40}K residue in the mass 42 system shown in Figure 8. The evaporation code correctly predicts the rapid increase in yields in the lower energy region; however, the high

energy tail is underpredicted in all three systems. The (α ,2N) boiloff modes for the mass 40 and 42 systems are shown in Figures 12 and 5, respectively. Again, similar behavior is seen for these systems in that the experimental maximum occurs at several MeV higher than that predicted by the evaporation code. Finally, the (2p,n) boiloff mode for each of the fused systems is shown in Figures 9 and 13. The energy behavior is predicted equally well by CASCADE for all three systems. The above comparisons seem to indicate that there is no strong evidence for any systematic differences in the fusion cross-sections resulting from the use of the different targets and projectiles. Additional comparisons between fusion residues resulting from boiloff modes other than those discussed above are needed in order to test this point conclusively. In particular, the problems with the analysis of six important residues from the mass 40 system must be resolved before definite conclusions can be reached.

VI. Summary

The analysis of the two mass 42 systems is nearly complete and there appears to be some differences in the ability of CASCADE to reproduce the experimented yields. Whether these effects are related to the structure of the nuclei or to the slight difference in maximum angular momentum in the entrance channels at a given excitation energy has not been determined. Analysis of the $^{16}\text{O} + ^{24}\text{Mg}$ system may be crucial in determining this question, but this has been hindered by the presence of unresolved lines in the spectra.

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FIGURE CAPTIONS

- Figure 1 Portion of a typical gamma-ray spectrum for the $^{160} + ^{26}\text{Mg}$ system at $E(^{160}) = 40.0$ MeV. The first two strong lines in the lowest portion of the spectrum represent coulomb excitations in the Au backing. A few of the other lines in the spectrum represent gamma-rays from those residues which result from the boiloff of the ^{32}S fused system (see text).
- Figure 2 Relative partial strengths of the dominant fusion boiloff modes for the $^{160} + ^{26}\text{Mg}$ system. In each case, the data points are replaced by a smooth curve to avoid confusion. Note the increase in strength of the lighter fusion residues with increasing energy.
- Figure 3 Same as Figure 2 except for the $^{180} + ^{24}\text{Mg}$ system.
- Figure 4 Same as Figure 2 except for the $^{160} + ^{24}\text{Mg}$ system.
- Figure 5 Total intensity which feeds the ground state for the (α, p, n) decay mode resulting from fusion-evaporation of the mass 42 system for each entrance channel studied. The smooth curve represents the predictions of CASCADE. The dashed lines, which represent the code predictions changed by the scale factor indicated, are shown to facilitate comparison with the data. The upper half shows the comparison for the $^{180} + ^{24}\text{Mg}$ system while the lower half shows that for the $^{160} + ^{26}\text{Mg}$ system.
- Figure 6 Same as Figure 5 except for the (2α) decay mode.
- Figure 7 Same as Figure 5 except for the $(2p, 2n)$ decay mode.
- Figure 8 Same as Figure 5 except for the (p, n) decay mode.
- Figure 9 Same as Figure 5 except for the $(2p, n)$ decay mode.
- Figure 10 Total intensity which feeds the ground state for the $(3p, n)$ decay mode resulting from fusion-evaporation of the $^{160} + ^{24}\text{Mg}$ fused system. The smooth curve represents the predictions of CASCADE.
- Figure 11 Same as Figure 10 except for the $(2p)$ decay mode.
- Figure 12 Same as Figure 10 except for the $(\alpha, 2p)$ decay mode.
- Figure 13 Same as Figure 10 except for the $(2p, n)$ decay mode.

Figure 1

Figure 2

RELATIVE INTENSITY (ARB. UNITS)

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 11

Figure 10

Figure 13

Figure 12