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from the $^{28}\text{Si} + ^{16}\text{O}$ reaction**

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Statistical description of strongly damped binary yields from the $^{28}\text{Si}+^{16}\text{O}$ reaction

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Abstract

Experimental data on strongly energy-damped yields from the $^{28}\text{Si}+^{16}\text{O}$ reaction at $E_{\text{c.m.}} = 39.1$ MeV and 50.5 MeV are analyzed in the context of fission from the ^{44}Ti compound system. Several features of this system, including the presence of resonant-like structures in the elastic and inelastic-scattering excitation functions, the observation of large cross sections for strongly damped yields, and the recognition that there are relatively few channels open for reactions involving the near-grazing partial waves, have been taken to infer a deep-inelastic as opposed to fission origin of the strongly damped yields. We test this claim by comparing the predictions of the transition-state model for fission to the experimental results. The statistical model is found to adequately describe the experimental results at the higher energy. The fully

energy-damped *inelastic* yields at 39.1 MeV, however, are found to be far in excess of expectations based on the fission model. This result is in sharp contrast to what has been observed in the nearby $^{24}\text{Mg}+^{16}\text{O}$ system.

25.70.Lm, 24.10.Eq, 25.70.Hi, 25.70.Ij

In recent years, extensive efforts have been made in the study of fully energy-damped yields from light heavy-ion collisions ($20 \leq A_{C.N.} < 60$) [1–8]. Based on the substantial amount of data accumulated so far, it is now generally accepted that the observed yields arise primarily from a fusion-fission process [6–8]: a statistically equilibrated compound nucleus is formed that can decay to binary channels, with decay probabilities that are determined by the phase space available in these channels. The detailed analysis of mass distributions and the systematic investigation of different entrance channels populating a given compound nucleus support this picture. Several variants of the fission picture have been developed to describe the experimental results. These models share the assumption that an equilibrated compound nucleus is formed in the reaction and differ primarily in how they account for the available phase space for the fission channels [4,6,8,9].

For a few systems, principally those that display anomalous large-angle scattering (ALAS) in elastic yields or resonant behavior in the elastic, inelastic or α -transfer channels [10–12], an entrance-channel dependence is observed that may involve the strongly damped binary yields and is contrary to the expectations of the statistical models. These anomalous systems are always found to involve “ α -particle-like” nuclei such as ^{12}C , ^{16}O , ^{24}Mg , and ^{28}Si .

It has been shown that the number of open channels (NOC) that are available for the decay of a composite system is correlated to the reaction dynamics [13]. In particular, the normalized NOC values, N/F , have been compared for a large number of systems. By definition, N/F is obtained for a given system and impact parameter range b to $b+\Delta b$ by dividing the total number of open reaction channels for this range by the corresponding geometric cross section ($\Delta\sigma = 2\pi b\Delta b$). In systems where the N/F is large for the grazing partial waves, an entrance channel independent fusion-fission process appears to dominate the energy damped binary yields and no evidence is found for resonant or ALAS behavior. Examples of systems with large N/F include the $^{10,11}\text{B}+^{16,17,18}\text{O}$, $^{35}\text{Cl}+^{12}\text{C}$, $^{31}\text{P}+^{16}\text{O}$, $^{36}\text{Ar}+^{12}\text{C}$ and $^{28}\text{Si}+^{20}\text{Ne}$ reactions [4,5,8]. Alternatively, for systems where resonant behavior or ALAS is observed, such as the $^{12}\text{C}+^{12}\text{C}$, $^{16}\text{O}+^{12}\text{C}$, $^{24}\text{Mg}+^{12}\text{C}$, and $^{28}\text{Si}+^{12}\text{C}$ [10] reactions, N/F is found to be low [13]. In these systems the fully energy-damped binary

yields may involve both the fusion-fission process and a distinctly different, deep-inelastic mechanism [4,5,14].

The possibility of this coexistence was first proposed [4] for the $^{24}\text{Mg}+^{16}\text{O}$ system [16] and has more recently been suggested for the $^{24}\text{Mg}+^{24}\text{Mg}$ system [8]. In both of these cases, the main evidence for anomalous behavior is seen for less damped yields in either the elastic or inelastic channels or the α -particle transfer channels. The fully energy damped binary yields are still found to be largely consistent with the expectations of the fission models [4,8].

Recently, Oliveira *et al.* [15] observed strongly energy damped yields from the $^{28}\text{Si}+^{16}\text{O}$ reaction at center-of-mass energies of $E_{\text{c.m.}}=39.1$ MeV and 50.5 MeV. Fission-like cross sections of 29.6 ± 2.0 mb and 40.0 ± 2 mb, respectively, were deduced for the ^{16}O decay channel at the two energies. This reaction has previously been shown to exhibit a strong resonance component in the elastic and low-lying inelastic yields [10] and a contribution of orbiting-like, deep-inelastic components is expected based on a very low NOC. Fig. 1 compares N/F as a function of incident angular momentum for the $^{16}\text{O} + ^{28}\text{Si}$ system with similar calculations for nearby systems. The arrows indicate the grazing angular momenta at $E_{\text{c.m.}}=39.1$ MeV and 50.5 MeV, respectively. For both cases, the N/F values are relatively small suggesting the possibility of an orbiting like component to the reaction yield. The authors of the $^{28}\text{Si}+^{16}\text{O}$ study suggest, however, that a deep-inelastic mechanism is responsible for most or all of the observed fully energy damped yields.

To test the claim [15] that the observed cross sections are greater than can be obtained through a fission process, we have performed calculations within the framework of the transition-state model to compare with the data. We employ an extension of the standard transition-state picture that allows us to calculate the excitation-energy spectra for the fission channels. It is assumed that the available phase space at the saddle point determines the fission probability to a given mass partition. The decay to the final fragment states is then taken to occur with statistical weighting of the available mutual excitations. A complete description of the model calculations can be found in refs. [4], [7], and [8]. For the final excitation energy spectra we use the known levels in ^{12}C , ^{16}O , ^{20}Ne , ^{24}Mg , ^{28}Si ,

and ^{32}S to excitation energies of 32 MeV, 29 MeV, 28 MeV, 17 MeV, 14 MeV, and 12 MeV, respectively.

The calculated spectra for the $^{28}\text{Si}+^{16}\text{O}$ channels at the two energies studied in ref. [15] are shown in Fig. 2. To allow comparison with experimental results, a Gaussian line shape is assumed for the individual mutual excitations with a width of 1.5 MeV FWHM. Separate spectra are generated for the decay to all known levels in the fragments (dashed curves) and the decay to particle-bound states only (solid curves). Since there is expected to be some energy sharing between the fragments, the calculated excitation-energy below ≈ 16 MeV should not be significantly distorted because of the limited range of known energy levels in ^{28}Si . It is likely, however, that the calculated spectra at $E_{\text{c.m.}}=50.1$ MeV, which extends to higher excitation energy, are affected by incomplete information on the energy levels in ^{28}Si .

The arrows in Fig. 2 indicate the energies corresponding the observed maximum ^{16}O yields as reported in ref. [15] based on singles measurement, without detection of the ^{28}Si recoil. These energies are close to the corresponding peak energies for the calculated spectra where secondary evaporation is not considered. The agreement at $E_{\text{c.m.}}=50.1$ MeV might be somewhat fortuitous, however, since the effects of secondary light-fragment emission are not taken into account. At $E_{\text{c.m.}}=30.9$ MeV, secondary emission should not be as significant. Another cautionary note is that the experiment was performed with a SiO_2 target. In the singles measurement it is not possible to distinguish ^{16}O particles arising from reactions on ^{16}O and those from the fission of the ^{56}Ni system formed in the $^{28}\text{Si}+^{28}\text{Si}$ reaction. Based on the fission-model calculations, the cross section for this “background” reaction leading to ^{16}O fission fragments is expected to be 3.2 mb and 21 mb, respectively, at the two beam energies measured in ref. [15]. These are significant cross sections compared to what are quoted for the $^{28}\text{Si}+^{16}\text{O}$ measurement and suggest a possible danger in using the singles data.

In ref. [15], fission mass distributions are shown for events with $-10 \text{ MeV} < Q_{\text{reac}} < -7 \text{ MeV}$ taken at $\Theta_{\text{c.m.}} = 90^\circ$. The data for these distributions are obtained in a coincidence measurement of the reaction fragments. As such, the experiment should discriminate against

events where there is secondary light-particle evaporation from one or both of the fragments and should also be free of contaminant yields arising from the ^{28}Si in the target. In Fig. 3, we compare our calculated results to experiment by making a comparable selection on Q -value and only including events where both fragments are emitted in particle bound states. In performing the fusion-fission calculations, total fusion cross sections of 1035 mb and 1115 mb were assumed at the lower and higher energy, respectively, based on a critical distance model for fusion [4].

As seen in Fig. 3, the calculated mass distribution at the higher energy of 50.1 MeV is in good agreement with the experimental results. No evidence is seen for enhanced cross sections that could indicate the presence of a separate, deep-inelastic mechanism affecting the mass distribution. At $E_{c.m.}=39.1$ MeV, the calculated cross sections to mass transfer channels are also in reasonable agreement with the experimental results, but the calculated $^{16}\text{O}+^{28}\text{Si}$ channel cross section is much lower than observed experimentally. It should be noted that the total fusion cross section has not been measured for this system and, consequently, there is considerable uncertainty in this value. The shaded histograms in Fig. 3 correspond to an assumed fusion cross section of 1200 mb, at the upper limit as to what systematics in this mass region would suggest is a reasonable total fusion cross section. Still, the cross section to the $^{28}\text{Si}+^{16}\text{O}$ is far in excess to the predictions.

Studies of other systems where a resonance component is evident have also shown an enhanced yield for the elastic and less-damped *inelastic* yields as compared to the fission model predictions. This has been shown for the $^{24}\text{Mg}+^{16}\text{O}$ [16] and $^{24}\text{Mg}+^{24}\text{Mg}$ systems [8]. In both of these cases, however, the fully damped inelastic yields are found to be of a magnitude consistent with the fission calculations. A different situation emerges with the $^{28}\text{Si}+^{16}\text{O}$ results. Since the experimental mass distribution in the coincidence measurement corresponds to a Q -value range that excludes the low-lying elastic and inelastic states, it should only reflect the fully damped reaction component.

To achieve a greater cross section for the $^{28}\text{Si}+^{16}\text{O}$ channel in the transition-state calculation requires a lowering of the assumed fission barrier for this particular mass partition

by 2-3 MeV, while retaining the nominal barrier energies for the other fission mass partitions. Such a shell correction has been suggested [4] as a possible source for the large inelastic yields observed in the $^{28}\text{Si}+^{12}\text{C}$ reaction [1,2]. However, unlike what was found for the $^{28}\text{Si}+^{12}\text{C}$ reaction, it is necessary to assume that this shell correction is restricted to a limited spin range since the mass distribution at $E_{\text{c.m.}}=50.1$ MeV, where higher compound nucleus spins contribute to fission, would otherwise also be strongly affected. Alternatively, the results are consistent with the presence of a separate, energy-dependent, orbiting-like reaction mechanism.

We conclude that the statistical model provides a good overall agreement with all the available data (Q -value spectra and mass distributions) for the $^{28}\text{Si}+^{16}\text{O}$ reaction, with the exception of significantly underestimating the cross section in the inelastic channels at $E_{\text{c.m.}}=39.1$ MeV. This result could indicate an orbiting-like reaction mechanism. At $E_{\text{c.m.}}=50.1$ MeV, however, there is no evidence for a mechanism separate from fission.

The evidence of a strong, energy-dependent orbiting component in the $^{16}\text{O}+^{28}\text{Si}$ reaction suggests a complementary study of the $^{32}\text{S}+^{12}\text{C}$ reaction. This would allow a comparison of the energy-damped ^{12}C and ^{16}O cross sections for two reactions reaching a common ^{44}Ca compound system using a method that has been successfully adopted in refs. [5,6,12,16].

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REFERENCES

- [1] D. Shapira, R. Novotny, Y. D. Chang, K. A Erb, J.L.C. Ford Jr., J. C. Peng, and J. D. Moses, Phys. Lett. **114B**,111 (1982).
- [2] B. Shivakumar, S. Ayik, B.A. Harmon, and D. Shapira, Phys. Rev. C **35**, 1730 (1987).
- [3] B. Shivakumar, D. Shapira, P. H. Stelson, S. Ayik, B. A. Harmon, K. The, and D.A. Bromley, Phys. Rev. C **37**, 652 (1988).
- [4] S.J. Sanders, Phys. Rev. C **44**, 2676 (1991) and references therein.
- [5] C. Beck, B. Djerroud, F. Haas, R. M. Freeman, A. Hachem, B. Heusch, A. Morsad, and M. Vuillet-A-Cilles, Phys. Rev. C **47**, 2093 (1993) and references therein.
- [6] R. M. Anjos, N. Added, N. Carlin, L. Fante Jr., M. C. S. Figueira, R. Matheus, E. M. Szanto, C. Tenreiro, and A. Szanto de Toledo, Phys. Rev. C **49**, 2018 (1994) and references therein.
- [7] S.J. Sanders, A. Hasan, F.W. Prosser, B.B. Back, R.R. Betts, M.P. Carpenter, D.J. Henderson, R.V.F. Janssens, T.L. Khoo, E.F. Moore, P.R. Wilt, F.L.H. Wolfs, A.H. Wuosmaa, K.B. Beard, Ph. Benet, Phys. Rev. C **49**, 1016 (1994).
- [8] K. A. Farrar, S.J. Sanders, A.K. Dummer, A.T. Hasan, F.W. Prosser, B.B. Back, I.G. Bearden, R.R. Betts, M.P. Carpenter, B. Crowell, M. Freer, D.J. Henderson, R.V.F. Janssens, T.L. Khoo, T. Lauritsen, Y. Liang, D. Nisius, A.H. Wuosmaa, C. Beck, R.M. Freeman, Sl. Cavallaro, A. Szanto de Toledo, Phys. Rev. C **54**, 1249 (1996).
- [9] A. Szanto de Toledo, E. M. Szanto, M. Wolfe, B. V. Carlson, R. Donangelo, W. Bohne, K. Grabish, H. Morgenstern, and S. Proshitzki, Phys. Rev. Lett. **70**, 2070 (1993).
- [10] P. Braun-Munzinger and J. Barrette, Phys. Rep. **87**, 209 (1982).
- [11] F.Haas and Y. Abe , Phys. Rev. Lett. **46**, 1667 (1981).

- [12] A. Ray, D. Shapira, J. Gomez del Campo, H. J. Kim, C. Beck, B. Djerroud, B. Heusch, D. Blumenthal, and B. Shivakumar, Phys. Rev. C **44**, 514 (1991).
- [13] C. Beck, Y. Abe, N. Aissaoui, B. Djerroud, and F. Haas, Phys. Rev. C **49**, 2618 (1994).
- [14] W. Dünnweber, A. Glaesner, W. Hering, D. Konenerth, R. Ritzka, W. Trombik, J. Czakanski, and W. Zipper, Phys. Rev. Lett. **61**, 927 (1988).
- [15] J. M. Oliveira, A. Lépine-Szily, A.C.C. Villari, R. Lichtenthäler, L.C. Gomes, W. Sciani, P. Fachini, G.L. Lima, A.C.G. Martins, V. Chiste, J.M Casandjian, A.J. Pacheco, J.E. Testoni, D. Abriola, A.O. Macchiavelli, F. Hasenbalg, O.A. Capurro, D. Tomasi, J. Fernández Niello, and D. Brandizzi, Phys. Rev. C **53**, 2926 (1996).
- [16] A. Ray, S. Gil, M. Khandaker, D.D. Leach, D.K. Lock and R. Vandenbosch, Phys. Rev. C **31**, 1573(1985).

FIGURES

FIG. 1. Calculated values of the normalized number of open reaction channels as a function of the grazing angular momentum for the indicated systems. The arrows indicate the grazing angular momenta corresponding to the data of ref. [15].

FIG. 2. Calculated excitation-energy spectra for fission to the $^{16}\text{Si}+^{16}\text{O}$ channel at a) $E_{\text{c.m.}}=39.1$ MeV and b) $E_{\text{c.m.}}=50.1$ MeV. The dashed (solid) curves correspond to decay to all states (particle-bound states) in the fragments. The arrows indicate the locations of the peak cross sections observed in ref. [15].

FIG. 3. Charge distributions for the binary decay of the $^{28}\text{Si}+^{16}\text{O}$ reaction. Open bars represent the experimental cross sections from Oliveira *et al.* [15]. Cross sections are shown for events at $\Theta_{\text{c.m.}}=90^\circ$ and with $-10 \text{ MeV} < Q < -7 \text{ MeV}$. Crosshatched bars indicate the calculated cross sections using the same selection criteria as used for the experimental distribution. The shaded histograms assume a larger fusion cross section of $\sigma_{\text{fusion}}=1200 \text{ mb}$, as discussed in the text.

Fig. 1 - NOC

Fig. 2 - Ex spectra

Fig. 3- Exp/Theory