Unified multifragmentation-evaporation nuclear reaction models

Paul J. Karol and Kathryn L. Kolsky*
Department of Chemistry, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
(Received 18 June 1990)

A simple and exactly solvable unified model for fragmentation was recently proposed. It involved a single parameter which served to tune relative contributions of evaporation and multifragmentation to the mass-yield distribution for nuclear reactions. We have measured mass-yield curves for intermediate-mass products from medium-mass nuclei by radioactivation techniques. They are compared to the model's predictions. No choice of the single parameter is able to reproduce the observed trend. It is argued that by disregarding initial intranuclear cascading, the model is incomplete. Its advantage might lie in combining it with intranuclear cascade/evaporation calculations.

Considerable interest exists in the study of nuclear spallation, particularly fragmentation induced by simple and complex nuclear projectiles at intermediate through high energies. Continued attention to fragment study is partially motivated by hypotheses that statistical effects of the critical point in the nuclear liquid-gas phase diagram might be in evidence. Both experiment and theory were reviewed by Hüfner[1] in 1985 and by Lynch[2] in 1987. Among their conclusions was the recognition that experiment and theory were not well reconciled.

Very recently, Mekjian presented an elegant, exactly soluble, unified model for a fragmentation process that contains a single free parameter.[3,4] The magnitude of this parameter tunes the complete mass-yield distribution smoothly between two extremes. One extreme is complete fragmentation of a composite of A nucleons into its A nucleons. The other extreme is fusion with no fragments emitted. Intermediate values produce the familiar composite U-shaped curves that include contributions from both light-fragment production and evaporation, and also mass-yield curves that reflect a power-law dependence on cluster mass. The model differs from many of its phase-space counterparts mentioned in Refs. 1 and 2 in two ways: First, by its reliance on just a single phenomenological parameter, one which Mekjian argues is determined by fundamental thermodynamic considerations such as density, temperature, and binding energy. Second, by its subsequent generation of verifiable complex features; that is, the unified model predicts not only inclusive observables (mass yields), but detailed exclusive behavior such as multiplicities and correlations.

The fragment mass distribution function from an original total of A particles yielding a cluster of size k is given by Mekjian as

$$Y_A(k,x)=\frac{A!}{k(A-k)!}\frac{x\Gamma(x+A-k)}{\Gamma(x+A)} ,$$

where x is the tuning parameter that governs the evolution of the partitioning and $k=A_p$ is the product mass number. $\Gamma(z)$ is the gamma function. High values for x are expected, if at all, for very-high-energy interactions, and low values for the sub-GeV region. For $x=1$, the above function reduces to an A-independent power law

$$Y_A(k,1)=\frac{1}{k} .$$

Evidence usually invoked in favor of such unified models is the agreement with one of the simplest inclusive measurements, that of the experimental product mass-yield curve $\sigma(A_p)$vs A_p. In fact, it was such a conformity that ignited the flurry of critical phase-transition efforts.[5] For high-energy proton-nucleus reactions, calculated and experimental mass-yield distributions are illustrated from Au in Fig. 1(a) and from Ag in 1(b). The histograms are the calculated phase-space model results of Gross *et al.*[6] The smooth curves show the trends predicted by Mekjian's unified model. We have explored how these trends vary with choice of x and display two representative extremes. The heavy dashed curves are for $x=1$ and indicate how the yield continuously drops off through the intermediate fragment masses. In contrast, for $x=0.01$ (and other low values), the yield of fragments is nearly constant over a very broad range of intermediate masses centered about $A_p \approx A/2$. For $x \ll 1$ it is easy to show that this midpoint yield varies as $\approx 4x/A$.

In Fig. 1(a) the Au data are obtained from radiochemical yields determined by Kaufman *et al.* at 11.5 GeV.[7] The Ag data at 300 GeV in Fig. 1(b) are from Bujak *et al.*[8] The former authors measured production cross sections from Au over a wide energy domain, ranging from 0.2 to 300 GeV. The determination of mass yields by their technique requires summing isobaric yields over all contributing atomic numbers, $\sigma(A_p)=\sum_Z \sigma(A_p,Z)$. Sufficient data to perform such sums precisely are rarely obtained because of half-life considerations, the usual case being measurement of just a single isobar. Consequently, the imprecision of each mass-yield extraction us-

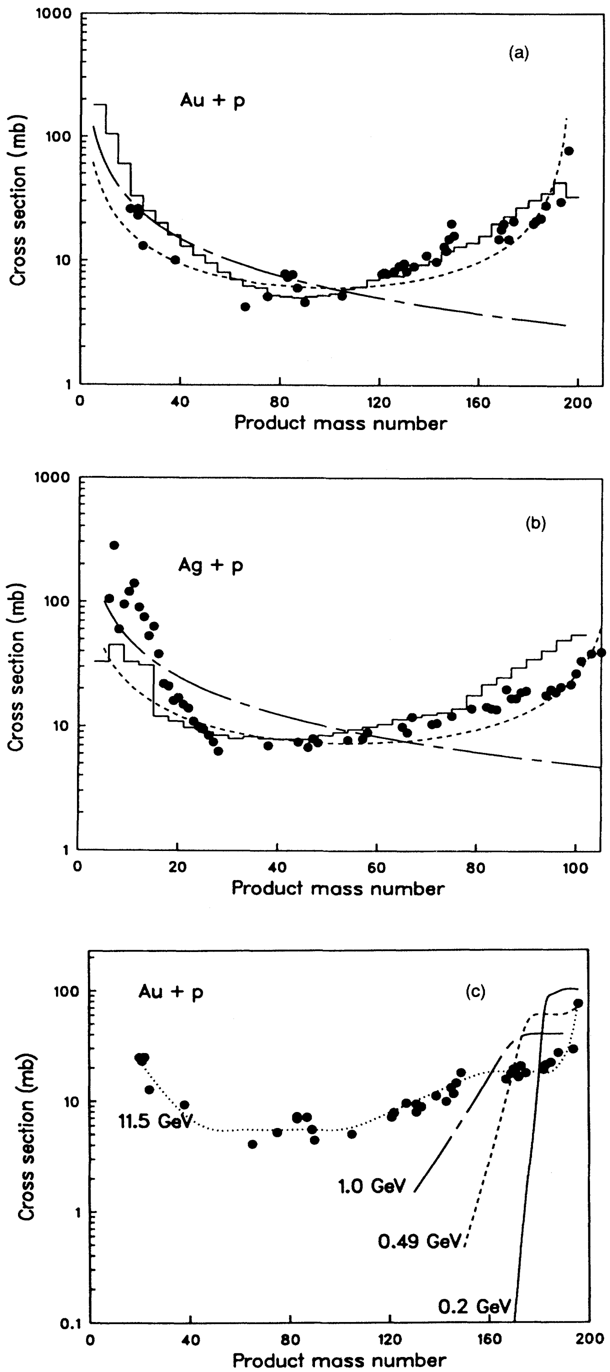

FIG. 1. Mass-yield distribution for high-energy proton-nucleus interactions. Data for Au (a) at 11.5 GeV and (c) curves for other energies are obtained from Refs. 7 and 9, respectively. The curve in (c) for 11.5 GeV has been redrawn by us. The curves in (c) for gold spallation mass yields illustrate the shallow-spallation "shoulder," but the fission peaks have been omitted for clarity. In (b) data for Ag at 300 GeV are from Bujak *et al.* (Ref. 8). The histograms in (a) and (b) are due to the phase-space model of Gross *et al.* (Ref. 6). Heavy- and light-dashed curves in (a) and (b) are for Mekjian's unified model for $A=197$ and 108 using $x=1$ and 0.01, respectively, arbitrarily normalized to illustrate the dependence on product mass.

ing cross-section systematics is not negligible. However, the general trends are extremely clear as seen in Fig. 1(c), which also includes the results of Kaufman and Steinberg over a range of projectile energies.[9] For removal of somewhat more than a few mass numbers, the isobaric yields remain relatively constant, forming a "shoulder" extending over several masses. In Fig. 1(c) we have reconstructed the authors' 11.5-GeV curve to reflect the shoulder shown at lower energies and consistent with the data. Following the shoulder is an extensive exponential falloff and eventually a sharp rise into the light-fragment mass range.

We have been conducting systematic determinations of mass yields from a variety of medium-mass targets bombarded with 0.8-GeV protons[10,11] and 0.72-GeV alphas.[12] Precise radiochemical measurements have shown that the shapes of the isobaric charge distributions $\sigma(A_p,Z)$ vs Z at $A_p=\text{const}$ are independent of energy and projectile. Radiochemical yields for a number of nuclides at $A_p \approx 72$ and most recently ≈ 46 from ^{89}Y, ^{92,96,100}Mo and ^{130}Te isotopic targets have been used to improve the precision of mass-yield distribution curves, which we report here for these "spallation" systems. Our mass-yield results are seen in Fig. 2 to vary exponentially over several orders of magnitude with ΔA as large as 85 and extending down to product mass numbers as low as ≈ 40. Also shown in Fig. 2 are (arbitrarily normalized) predictions from Mekjian's unified model for a range of tuning parameter choices. It is clear that no choice comes close to the observed generic pattern.

The disparity between experimental and theoretical mass-yield distributions also indicates at least one explanation of the model's apparent shortcoming. In not

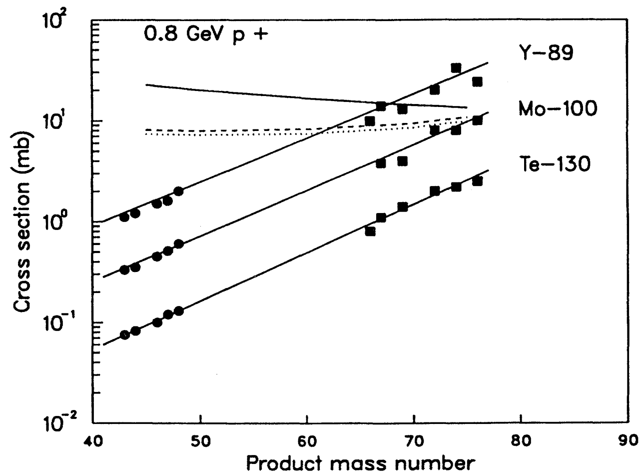

FIG. 2. Present work mass-yield distributions for spallation from intermediate-mass targets using 0.8-GeV protons. Square data points are from Ref. 10. Circular data points are from current work (Ref. 11). Uncertainties in data are $\approx 15\%$. Solid, dashed, and dotted curves are for Mekjian's unified model for $A=100$ using $x=1$, 0.01, and 0.0001, respectively, and are arbitrarily normalized to the ^{100}Mo curve at $A_p=80$.

reproducing the shallow-spallation "shoulder," the unified model disavows the role of the initial intranuclear cascade that establishes a spectrum of dynamically equilibrated but thermodynamically heated residues. It is the latter that presumably cool by statistical multifragmentation. We have tried various combinations of cascade residue distributions and are still not able to reproduce both the shallow-spallation shoulder and exponential tail down to $A_p \approx 40$ with a single choice of the tuning parameter. In contrast to this qualitative defect, the single-parameter model of Cole and Cherkaoui-Tadili succeeds in duplicating the major qualitative features of the spallation mass-yield curve at various energies.[13] The latter model incorporates gross averaging to accommodate both nucleon-nucleon collisions and evaporation.

In addition to the above disagreement, there are difficulties with light-fragment production $4 < A_p < 30$. Intermediate-energy production of these light fragments ($k \ll A$), for which presumably $x \ll 1$, implies $Y_A \approx xA/k(A-k) \propto 1/k$. Yet, as Cumming[14] and Panagiotou, Curtin, and Scott[15] note, experiments with 0.2–0.5-GeV protons on silver[16] suggest $Y_A \propto 1/k^{4\pm 1}$.

In his fragmentation review, Lynch notes that intranuclear cascade models used to estimate energy deposition in reactions significantly overpredict linear momentum transferred during the cascades. In this regard it is important to recognize that such calculations, like Mekjian's concept, neglect the direct ejection of fragments during the cascade. We have previously presented momentum-transfer results[17] that are indirect evidence that this oversight is unjustified in a sizable fraction of interactions leading to intermediate-mass spallation product formation. That is to say, a significant portion of light-fragment production has its origin in the reaction dynamics in addition to statistical relaxation.

A resolution to the present disagreements is to allow the tuning parameter to have different values for each initial cascade residue in recognition of the influence of residue structure and formation pathway on the final relaxation.[18] This seems to be a reasonable compromise on the use of Mekjian's multifragmentation approach. It then would become an essential component of the intranuclear cascade/statistical evaporation model, which it originally sought to replace entirely.

Our conclusion is that the only unified perspective on multifragment-evaporation nuclear reactions remains the entrenched intranuclear cascade-evaporation model. The various experimental phenomena that superficially appear inconsistent with this scheme should be addressable by reasonable and fundamentally interesting modifications which incorporate the role of light clusters in the physics of both the cascade and evaporation steps.

---

*Present address: Medical Division, Brookhaven National Laboratory, Upton, NY 11973.

[1]J. Hüfner, Phys. Rep. **125**, 129 (1985).
[2]W. G. Lynch, Annu. Rev. Nucl. Part. Sci. **37**, 493 (1987).
[3]A. J. Mekjian, Phys. Rev. C **41**, 2103 (1990).
[4]A. J. Mekjian, Phys. Rev. Lett. **64**, 2125 (1990).
[5]J. E. Finn *et al.*, Phys. Rev. Lett. **49**, 1321 (1982).
[6]D. H. E. Gross, L. Satpathy, M. Ta-chung, and M. Satpathy, Z. Phys. A **309**, 41 (1982).
[7]S. B. Kaufman, M. W. Weisfield, E. P. Steinberg, B. D. Wilkins, and D. Henderson, Phys. Rev. C **14**, 1121 (1976).
[8]A. Bujak *et al.*, Phys. Rev. C **32**, 620 (1985).
[9]S. B. Kaufman and E. P. Steinberg, Phys. Rev. C **22**, 167 (1980).
[10]M. J. Tobin and P. J. Karol, Phys. Rev. C **39**, 2330 (1989).
[11]K. Kolsky, Ph.D. dissertation, Carnegie Mellon University, 1989.
[12]T. H. Ku and P. J. Karol, Phys. Rev. C **16**, 1984 (1977).
[13]A. J. Cole and R. Cherkaoui-Tadili, Phys. Rev. C **36**, 1484 (1987).
[14]J. B. Cumming, Phys. Rev. C **32**, 1445 (1985).
[15]A. D. Panagiotou, M. W. Curtin, and D. K. Scott, Phys. Rev. C **31**, 55 (1985).
[16]R. E. L. Green, R. G. Korteling, and K. P. Jackson, Phys. Rev. C **29**, 1806 (1984).
[17]M. J. Tobin and P. J. Karol, Phys. Rev. C **38**, 267 (1988).
[18]W. A. Friedman and W. G. Lynch, Phys. Rev. C **28**, 16 (1983); **28**, 950 (1983).