Randomly Oriented Angular Momentum in Strongly Damped Collisions

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(Received 30 October 1978)

The first three moments of the γ-ray multiplicity distribution and the out-of-plane γ-ray anisotropy have been measured simultaneously as a function of mass asymmetry for the strongly damped products of the reaction ^{63}Cu with 168-MeV ^{20}Ne. The large variance of the multiplicity appears to be associated with the small anisotropy. These results indicate a random component of angular momentum which is comparable to the aligned component induced by tangential friction.

Two of the outstanding problems in our current understanding of strongly damped collisions involve the conversion of angular momentum of relative motion into intrinsic angular momentum. While the amount of transferred angular momentum as inferred from the average γ-ray multiplicity $\langle M_\gamma \rangle$ supports the basic model of rigid rotation induced by tangential frictional forces,[1] (i) the surprisingly large values[2-4] for the width of the multiplicity distribution, σ_γ, and (ii) the small values[5,6] of the out-of-plane total γ-ray anisotropy, A, call into question the adequacy of this simple picture. Berlanger *et al.*[5] first noted the small γ-ray anisotropy in the reaction Cu + Au and suggested that twisting, bending, and/or wriggling modes, such as are introduced in the fission process, might also be present in strongly damped collisions. Wozniak *et al.*[7] then noted that the above processes could possibly account for the observed out-of-plane angular correlation for sequential fission fragments produced in strongly damped collisions of Kr + Au (Ref. 7) and Kr + Bi.[8] Small polarizations have also been observed[9] in the reaction Ar + Ag. In general, there are several possible mechanisms[10,11] in addition to the ones suggested in Refs. 5 and 7 which could introduce a nonaligned or randomly oriented angular momentum and thereby reduce the spin alignment of the fragments.

We expect that the presence of a randomly oriented angular momentum, regardless of the mechanism[5,7,10,11] by which it is generated, would also have an effect on σ_γ, thus providing a connection between the two problems mentioned above. In order to investigate this possibility it is necessary to have detailed experimental information on both σ_γ and A for the same reaction. We present here, for the first time, a simultaneous measurement of the first three moments of the multiplicity distribution *and* of the total γ-ray anisotropy as a function of mass asymmetry for the reaction ^{20}Ne + ^{63}Cu. The results indicate that A and σ_γ are related, providing support for the existence of a random component of the angular momentum. A schematic model suggests that, in order to reproduce the measured anisotropy, the random and aligned components must be comparable in magnitude. We show further that this rather surprising result can account quantitatively for the observed large variance of the multiplicity.

A 167.8-MeV ^{20}Ne beam provided by the Oak Ridge National Laboratory Isochronous Cyclotron bombarded a 1-mg/cm^2 target of ^{63}Cu enriched to 99%. A set of nine individually shielded NaI detectors (5.1 cm$\times$7.6 cm) was operated in coincidence with two heavy-ion telescopes, each consisting of a ΔE gas ionization chamber and a 1500-μm surface-barrier E detector. The telescopes were located in the horizontal plane on each side of the beam and subtended solid angles of 3 msr (20° and 26° measurements) and 9 msr (35° and 45°), respectively. The NaI counters were 10 cm from the target and their thresholds were set at 100 keV. Depending on whether zero, one, two, three, or four or more NaI detectors recorded γ rays in coincidence with one or the other of the telescopes, the digitized ΔE and E

$+\Delta E$ signals were stored in one of two sets of five 300×300 channel arrays. The energy signals from four of the NaI detectors were recorded event by event on magnetic tape. Three of these detectors were located in a plane perpendicular to the reaction plane at $\varphi = 0°$, 45°, and 90° from the vertical direction.

The average $\langle M_\gamma\rangle$, the variance $\sigma_\gamma^2 = \langle M_\gamma^2\rangle - \langle M_\gamma\rangle^2$, and the skewness $s_\gamma = \langle (M_\gamma - \langle M_\gamma\rangle)^3\rangle/\sigma_\gamma^3$ of the γ-ray multiplicity distributions as well as the anisotropy $A = [W(90°) - W(0°)]/[W(90°) + W(0°)]$ were extracted as functions of the Z of the projectilelike fragment. Only a narrow region of energy at the optimum Q-value for the strongly damped component was used. Corrections for random coincidences were less than 10%. Neutron detection adds less than 0.5 unit to $\langle M_\gamma\rangle$ and was neglected. The values of the experimental ratio σ_γ/M_γ, the skewness s_γ, and the anisotropy A are shown in Figs. 1(a)–1(c), respectively, for the projectilelike fragment detected at 45°.

The average transferred angular momentum $\langle I\rangle$ was deduced from the measured values of $\langle M_\gamma\rangle$ through the empirical relation,

$$\langle I\rangle = \langle I_0\rangle + \tfrac{3}{16}(E - E_0) + 2(\langle M_\gamma\rangle - 2),$$

for which the values $\langle I_0\rangle \sim (11-12)\hbar$ and $E_0 = 80$ MeV were obtained from measurements on equilibrated evaporation residues in the mass 60 region. In this expression, the first two terms represent the average angular momentum removed by particle emission as a function of the excitation energy E. Thus, for an excitation energy of 80 MeV, which is comparable with the Q values measured here for fully damped products, the angular momentum removed by particles is $\sim(11-12)\hbar$. The last term is the average angular momentum dissipated by γ-ray emission assuming $\langle M_\gamma\rangle - 2$ stretched $E2$ transitions and two statistical γ rays based on a study of the reaction $^{16}O + ^{58}Ni$ by Simpson *et al.*[12] The resulting values of $\langle I\rangle$, when compared to the rolling and sticking limits for this reaction, exhibit a qualitative behavior very similar to that observed by Glässel *et al.*[13] for the reaction $^{20}Ne + Ag$ and hence are not shown here. [The values of $\langle I\rangle$ for fully damped products detected at 45° decrease from $\langle I\rangle = 31\hbar$ ($\langle M_\gamma\rangle = 9.9$) to $\langle I\rangle = 19\hbar$ ($\langle M_\gamma\rangle = 7.3$) as Z increases from 3 to 16, while $\sigma_\gamma \simeq 4.0$ independent of Z.]

In contrast to systems such as Kr + Sm (Ref. 3) or Kr + Er (Ref. 4) where there is little or no fusion, the evaporation residues observed in our experiment provide an important reference point

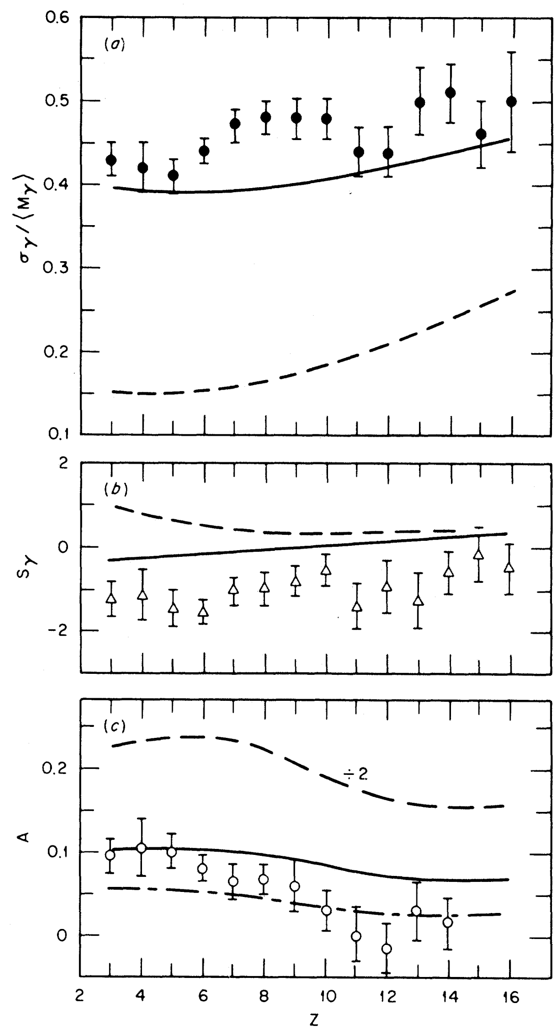

FIG. 1. (a) Relative width σ_γ/M_γ, (b) skewness s_γ of the γ-ray multiplicity distribution, and (c) out-of-plane γ-ray anisotropy A. The abscissa is the Z of the projectilelike fragment, detected at 45°. The expected values of the ordinates, assuming complete alignment at scission and corrected for the effects of subsequent light-particle emission, are indicated by the dashed curves. The expected γ-ray anisotropy (dashed curve) has been calculated assuming two dipole transitions and has been divided by 2.0 before plotting. The predicted effect on A of adding a fluctuating component I_f to the aligned component I_0 is illustrated for $I_f/I_0 = 0.9$ by the solid curve and for $I_f/I_0 = 1.2$ by the dash-dotted curve. Very similar values of $\sigma_\gamma/\langle M_\gamma\rangle$ and s_γ are predicted for $I_f/I_0 = 0.9$ and 1.2, and are therefore shown in each case by a single full curve.

in assessing the value of σ_γ for strongly damped collisions. Assuming a triangular J distribution in the compound nucleus (for which $\langle J\rangle = 40\hbar$, $\sigma_J/\langle J\rangle = 0.35$, and $s_J = -0.57$), the γ-ray multiplicity measurements show that particle emission moves the initial J distribution toward lower J values in the residual nucleus ($\langle J \rangle \simeq 19 \pm 1\hbar$) with little change in shape ($\sigma_\gamma/\langle M_\gamma \rangle = 0.30 \pm 0.02$ and $s_\gamma = -0.8 \pm 0.3$). This effect, noted previously,[3,12] is well reproduced by a statistical-model calculation[14] which yields $\sigma_\gamma/\langle M_\gamma \rangle = 0.32$ and $s_\gamma = -0.10$ after particle emission. The situation for strongly damped collisions, however, is quite different. Based on the grazing angle[15] $\theta_{c.m.}^{(1/4)} = 23.7°$ (obtained by the $\frac{1}{4}$-point method) and the value of $\sigma_{ER} = 1280$ mb, it may be assumed that incident partial waves between $l_{cr} = 60\hbar$ and $l_{gr} = 76\hbar$ lead to deeply inelastic collisions, on which basis one expects $\sigma_\gamma/\langle M_\gamma \rangle \simeq 0.07$ and $s_\gamma \simeq 0$. Correcting these values for particle emission[14] yields the dashed curves shown in Figs. 1(a) and 1(b). These values expected for $\sigma_\gamma/\langle M_\gamma \rangle$ are in sharp disagreement with the experimental data.[16] Indeed the observed values of $\sigma_\gamma/\langle M_\gamma \rangle$ for the strongly damped collisions are *even larger than those for the evaporation residues* for which all partial waves up to l_{cr} participate. This indicates that the above discrepancy does not originate with the assumption that only l values between $60\hbar$ and $76\hbar$ are involved.

In the limit of complete alignment of the fragments and stretched $E2$ transitions, the out-of-plane γ-ray anisotropy should be 1. Dipole transitions will reduce this alignment as will light-particle emission. The dashed curve in Fig. 1(c) shows the anisotropy expected after correcting for loss of alignment arising from light-particle emission and assuming that, on the average, two dipole γ rays are emitted [i.e., an incoherent mixture of (20–30)% dipole]. Particle emission and a reasonable dipole admixture clearly cannot account for the small measured anisotropy.

The individual experimental results of Figs. 1(a)–1(c) can be related through the introduction of a model. In order to preserve generality in the interpretation of the data, we use the following very simple and highly schematic picture. The intrinsic angular momentum of each fragment just after scission is assumed to consist of a component (arising from tangential friction) aligned perpendicular to the reaction plane (I_0) and a component (I_f) fixed in magnitude but random in orientation. With this assumption and a proper quantum-mechanical treatment of the combined effects of I_f and light-particle emission on the γ-ray angular distribution, the ratio of I_f/I_0 can be deduced from the measured anisotropy shown in Fig. 1(c). The result is that $I_f/I_0 \approx 0.9$, approximately independent of Z. Through use of the further assumption that the respective orientations of the random component in each fragment are uncorrelated, the values of $\sigma_\gamma/\langle M_\gamma \rangle$ and s_γ shown by the full curves in Figs. 1(a) and 1(b) are obtained. Thus, within the limitations of this simple picture, the random component of the angular momentum deduced from the measured anisotropy accounts rather well for the large variance of the multiplicity, and in the case of the skewness, reproduces the trend of the data, if not the magnitude.

Important elements of this analysis which deserve further comment are as follows:

(i) The corrections for light-particle emission are important and therefore have been investigated carefully. Although the fraction of the initial angular momentum imparted to the fragments which is dissipated by particle emission ($\sim \frac{1}{3}$ to $\frac{1}{2}$) depends upon the parameters used in the statistical-model calculation,[14] the shape of the γ-ray multiplicity distributions (i.e., $\sigma_\gamma/\langle M_\gamma \rangle$ and s_γ) *and* the loss of alignment are remarkably insensitive to reasonable variations in these parameters.

(ii) There exist, of course, different combinations of the ratio I_f/I_0 and of the amount of stretched dipole admixture compatible with the measured γ-ray anisotropy. However, the three-point ($\varphi = 0°$, 45°, and 90°) γ-ray angular correlation limits the dipole admixture compatible with the data to $\lesssim 40\%$ for which one obtains $I_f/I_0 \simeq 0.8$. A 50% dipole admixture and a ratio $I_f/I_0 = 0.5$ which still reproduce the γ-ray anisotropy fail to reproduce the γ-ray angular correlation.

(iii) The assumption that I_f has a constant magnitude is extreme, of course, and has been made only for simplicity. Relaxing this assumption would increase the deduced value of $\sigma_\gamma/\langle M_\gamma \rangle$, in better agreement with experiment. Specific models for the introduction of random angular momentum in these collisions should predict the distribution of I_f and therefore could be tested by comparison with these experimental data.

(iv) The assumption of uncorrelated orientations for the random component of the angular momentum in the respective fragments, while important for predicting $\sigma_\gamma/\langle M_\gamma \rangle$ for symmetric mass splits, has little consequence for very asymmetric fragmentation in which nearly all of the angular momentum is in the heavy partner.

In summary, the experimental results presented here, in which both the variance of the multiplicity and the γ-ray anisotropy have been measured as a function of mass asymmetry, should enable the testing of specific theoretical models for reaction mechanisms which introduce random angular momentum in strongly damped collisions. The simple quantitative analysis which we have outlined suggests both the importance of these mechanisms and their role in explaining the large variance of the γ-ray multiplicity.

This research was sponsored by the U. S. Department of Energy. Oak Ridge National Laboratory is operated by the Union Carbide Corporation for the U. S. Department of Energy.

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[1]W. U. Schröder and J. R. Huizenga, Annu. Rev. Nucl. Sci. 27, 465 (1977); M. Lefort and Ch. Ngô, Ann. Phys. (N.Y.) 3, 5 (1978).

[2]R. G. Stokstad, in *Proceedings of the Topical Conference on Heavy-Ion Collisions, Fall Creek Falls State Park, Tennessee, 1977*, CONF-770602 (National Technical Information Service, Springfield, Va., 1977), p. 56.

[3]P. R. Christensen *et al.*, Phys. Rev. Lett. 40, 1245 (1978).

[4]A. Olmi *et al.*, Phys. Rev. Lett. 41, 695 (1978).

[5]M. Berlanger *et al.*, J. Phys. (Paris) Lett. 37, L323 (1976).

[6]R. Bock *et al.*, Nukleonika 22, 529 (1977); J. B. Natowitz *et al.*, Phys. Rev. Lett. 40, 751 (1978).

[7]G. J. Wozniak *et al.*, Phys. Rev. Lett. 40, 1436 (1978).

[8]P. Dyer *et al.*, Phys. Rev. Lett. 39, 392 (1977).

[9]W. Trautmann *et al.*, Phys. Rev. Lett. 39, 1062 (1977).

[10]H. Esbensen *et al.*, Phys. Rev. Lett. 41, 296 (1978).

[11]G. Wolschin and W. Nörenberg, Phys. Rev. Lett. 41, 691 (1978).

[12]J. J. Simpson *et al.*, Nucl. Phys. A287, 362 (1977).

[13]P. Glässel *et al.*, Phys. Rev. Lett. 38, 331 (1977).

[14]Monte Carlo statistical-model code JULIAN, M. Hillman and Y. Eyal, modified by A. Gavron to couple angular momentum projection. We assume that the excitation energy and transferred angular momentum are shared by the fragments according to their masses and moments of inertia, respectively.

[15]F. E. Obenshain *et al.*, Phys. Rev. C 18, 764 (1978).

[16]We note that these values for Ne + Cu are very close to those observed for the much heavier systems Kr + Sm and Kr + Er of Refs. 3 and 4. This suggests that the present results may be relevant for heavier systems as well.

Radiative Capture of Intermediate-Energy Protons to High-Lying States in Light Nuclei

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(Received 1 December 1978)

Observations are reported from the first systematic studies of proton radiative capture at intermediate energies. In addition to captures to the ground and first few excited states, the reactions $^{11}B(p,\gamma)^{12}C$ and $^{27}Al(p,\gamma)^{28}Si$ reveal unexpectedly strong transitions to isolated high-lying states. These latter transitions could take place via "second-harmonic" giant resonances. Protons on ^{12}C produce a rich spectrum of γ rays which may arise from captures to high-lying single-particle states.

Proton radiative capture reactions at intermediate energies comprise a virtually unexplored territory. With the exception of a few studies at a single energy,[1] the only relevant information thus far has been obtained through studies of the inverse, photonuclear reactions.[2,3] Recent theoretical work[4,5] underscores the importance of such measurements for an understanding of the role of meson exchange excitation in nuclear reaction mechanisms. Information about the nucleon momentum distributions of nuclear states may also be obtained through such studies.[2,3] In initial intermediate-energy radiative capture measurements, we have observed strong primary capture γ rays not only to ground and low-lying excited states of the nuclei investigated, but to several isolated high-lying excitations as well. In this Letter, we present the evidence for this lat-

