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Author
Warwick, A.I.

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A.I. Warwick, A. Baden, H.H. Gutbrod, M.R. Maier,
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A.I. Warwick, A. Baden[a], H.H. Gutbrod, M.R. Maier, J. Peter[b], H.G. Ritter,
H. Stelzer, H.H. Wieman, F. Weik
Gesellschaft für Schwerionenforschung
Darmstadt 6100, West Germany
and
Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

and

M. Freedman, D.J. Henderson, S.B. Kaufman, E.P. Steinberg, B.D. Wilkins
Argonne National Laboratory
Argonne, IL 60439

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Fission and deep spallation characteristics in relativistic nuclear collisions

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Gesellschaft für Schwerionenforschung
Darmstadt 6100, West Germany
and
Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

and

M. Freedman, D.J. Henderson, S.B. Kaufman, E.P. Steinberg, B.D. Wilkins
Argonne National Laboratory
Argonne, IL 60439

Numbers of emitted fast charged particles associated with heavier nuclear fragments are employed as a graphic means of differentiating fission and spallation contributions to target fragment emission in relativistic nuclear collisions. We observe directly the violent nature of the deep spallation mechanism.

Radiochemists have studied the breakup of nuclear targets bombarded with high energy projectiles (usually protons) for many years.[1-3] More than one reaction mechanism has been perceived to contribute to the production of fragments of intermediate mass. For example, in the bombardment of U with protons at incident kinetic energies up to 2 GeV, neutron-excess fragments of mass approximately half that of the target exhibit typical fission-product kinetic energy spectra[1,2] (derived from differential range measurements). This has been interpreted as an indication of their origin in non-violent, peripheral collisions. Neutron-deficient products in this mass range, however, exhibit much lower kinetic energies and are said to arise from a deep-spallation mechanism[1-3], which is not well understood.

Multi-detector measurements of such collisions, analyzed on an event-by-event basis, are a more powerful means of studying the dynamics of the reactions, particularly if several target fragments are important in the final state. In this article we report the first results of a detailed experiment of this nature using various projectiles on a gold target. In particular, measurements of the number of fast charged particles emitted in coincidence with the heavy fragments can be interpreted dramatically and directly in terms of peripheral and violent collisions. We confine ourselves here to results for a range of fragment mass ($80 \leq A \leq 89$) where there is a large contribution from fission, and we examine the characteristics of the collisions for several different projectiles (4.9 GeV protons, 250 MeV/u neon, and 2.1 GeV/u neon).

That part of the experimental arrangement that is relevant to this report consisted of a TOF arm at $\theta \simeq 90°$ in the laboratory frame for the detection of the heavy fragments. This was made up of a large area, thin (150 $\mu g\ cm^{-2}$) avalanche detector as the start counter, and several silicon surface barrier detectors as the stop and energy measuring detectors. The target was also thin (500 $\mu g\ cm^{-2}$) and mounted at an oblique angle, 15° to the beam, giving sensitivity to the slow heavy fragments emerging at $\theta \simeq 90°$, provided their kinetic energy was greater than a threshold of about 0.2 MeV per mass unit. A second similar avalanche counter at $\theta \simeq 90°$ on the opposite side of the beam allowed the selection of data for binary or nonbinary breakup of the target residue. Studies of binary breakup kinematics[4] show that before breakup the residue moves slowly ($\beta_{||} \lesssim 0.003$) such that the 180° correlation in the centre of mass frame is approximately preserved in the laboratory frame. Surrounding the thin-walled spherical scattering chamber, an array of 80 scintillators measured the number of fast charged particles[4] associated with the fragment emission, providing a direct measurement of the degree of violence of each collision.

We are concerned here with the gross features of the reaction, those mechanisms with enough cross section to contribute significantly to the singles yield of the fragments. Thus, for example, mechanisms such as ternary fission are not discussed.

Figure 1 (for 250 MeV/u Ne + Au) shows the singles yield of fragments as a contour plot versus the fragment kinetic energy and the associated multifoldness of fast charged particles detected in the 80-fold scintillator array. (Multifoldness means simply the number of scintillators hit by a fast charged particle in coincidence with the fragment; no correction for double hits or missing solid angle is made in this report.) There are clearly two components to the yield, corresponding to two different reaction mechanisms responsible for the major yield of fragments in this mass range. The high multifoldness component (from more violent collisions) has low kinetic energy and the very low multifoldness component (from very gentle peripheral collisions) exhibits a fission-like energy spectrum, peaking at 60-65 MeV.

There is some overlap of the mechanisms when the yield is plotted as in Figure 1, but we can separate the two components in the following way. The energy spectrum at high multifoldness ($m > 10$) is taken as the shape of the low-energy high-multifoldness component and renormalized to the total yield at the lowest fragment energies (15-20 MeV) where it is the only contribution. The result is the spectrum of the low energy component; the remaining yield is the energy spectrum of the high-energy low-multifoldness component.

Figure 2 shows the results of such a procedure for several reactions. The absolute normalization of the data is uncertain by ≈30% for the 4.9 GeV/u proton and 2.1 GeV/u Ne cases, somewhat more uncertain for the case of 250 MeV/u Ne. The high multifoldness component (solid triangles) shows an exponential energy spectrum; the low multifoldness spectrum (solid squares) peaks around 60 MeV.

We now demonstrate explicitly the binary nature of the low multifoldness component by employing the second thin avalanche detector on the opposite side of the beam to the measured fragment to count the heavy partner from the binary breakup. The geometry of the detectors is such that binary events are counted if the difference in the θ angles of the two fragments lies approximately between 150° and 210° in the laboratory frame. A similar analysis has been presented by Meyer[4] using data from the forerunner to this experiment. The avalanche counters (with an appropriate software threshold) are not sensitive to alpha particles; their efficiency climbs to 100% for fragments of mass A ≃ 15 in the energy range of interest; however, the software threshold is set at about A = 30. Figure 3, for 250 MeV/u Ne + Au, shows the multifoldness distribution associated with the fragments

a) without a heavy partner firing the opposite avalanche detector (binary veto)

b) with a heavy partner (binary)

Clearly the low multifoldness component is binary and the high multifoldness component is not.

Also shown, as open circles in Figure 2, are the energy spectra of events satisfying the binary veto requirement. These spectra are essentially the same as the high multifoldness component from the separation procedure outlined above.

The high multifoldness component of the heavy fragment yield observed here comes from a reaction mechanism that has been loosely termed "deep spallation" in previous studies. This is a violent process. The residual fragments have exponentially falling energy spectra (Figure 2) with a slope parameter $\tau \approx 15$ MeV. For heavier fragments ($120 \leqslant A \leqslant 139$), where there is much less contribution from fission, the slope is steeper ($\tau \simeq 8$ MeV). The low multifoldness reaction mechanism is binary fission. The mean fast particle multifoldness associated with fission shows little energy dependence, changing from $\langle m \rangle = 2$ at 250 MeV/u to $\langle m \rangle = 3$ for 2.1 GeV/u Ne + Au. The mean multifoldness associated with spallation, however, increases from $\langle m \rangle = 8$ at 250 MeV/u to $\langle m \rangle = 15$ for 2.1 GeV/u Ne + Au.

In conclusion, we have graphically demonstrated the difference between the reaction mechanisms of fission and deep spallation by employing multifoldness measurements to observe directly the violence of the collisions associated with these two processes. We can differentiate the mechanisms both by the multifoldness technique and by observing the binary or nonbinary nature of the final state and obtain the same spectral components by both methods.

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a) Present address: Dept. of Physics, Univ. of California, Berkeley, CA 94720

b) Present address: IPN, 91406 Orsay, France

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Figure Captions

Fig. 1. Contours of fragment yield (arbitrary units) in the mass range $80 \leqslant A \leqslant 89$ at $\theta = 90°$ from the bombardment of ^{197}Au by ^{20}Ne projectiles at 250 MeV/u.

Fig. 2. Energy spectra of fragments in the mass range $80 \leqslant A \leqslant 89$ at $\theta = 90°$ from three different bombardments. The upper curves (solid circles) are the measured yield; the open circles are from nonbinary events (see text). The lower curves are the results of the multiplicity separation into the fission and deep spallation components (see text).

Fig. 3. Observed fast charged particle multifoldness distributions associated with fragments from binary and nonbinary breakup. The fragments are in the mass range $80 \leqslant A \leqslant 89$ at $\theta = 90°$ from the reaction 250 MeV/u Ne + Au.

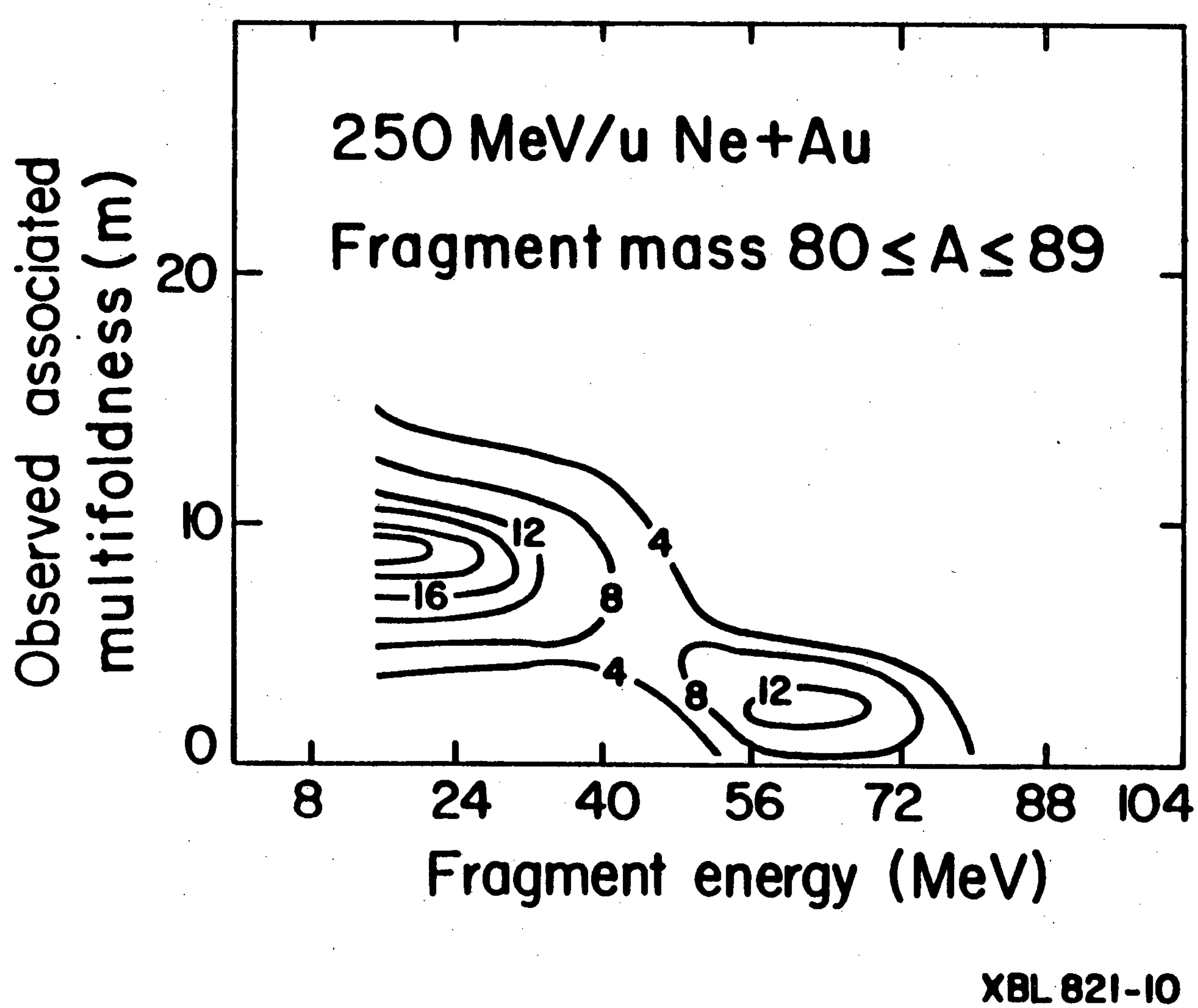

250 MeV/u Ne+Au
Fragment mass 80 ≤ A ≤ 89
Observed associated multifoldness (m)
Fragment energy (MeV)
0
10
20
8
24
40
56
72
88
104
4
8
12
16
XBL 821-10

Fig. 1

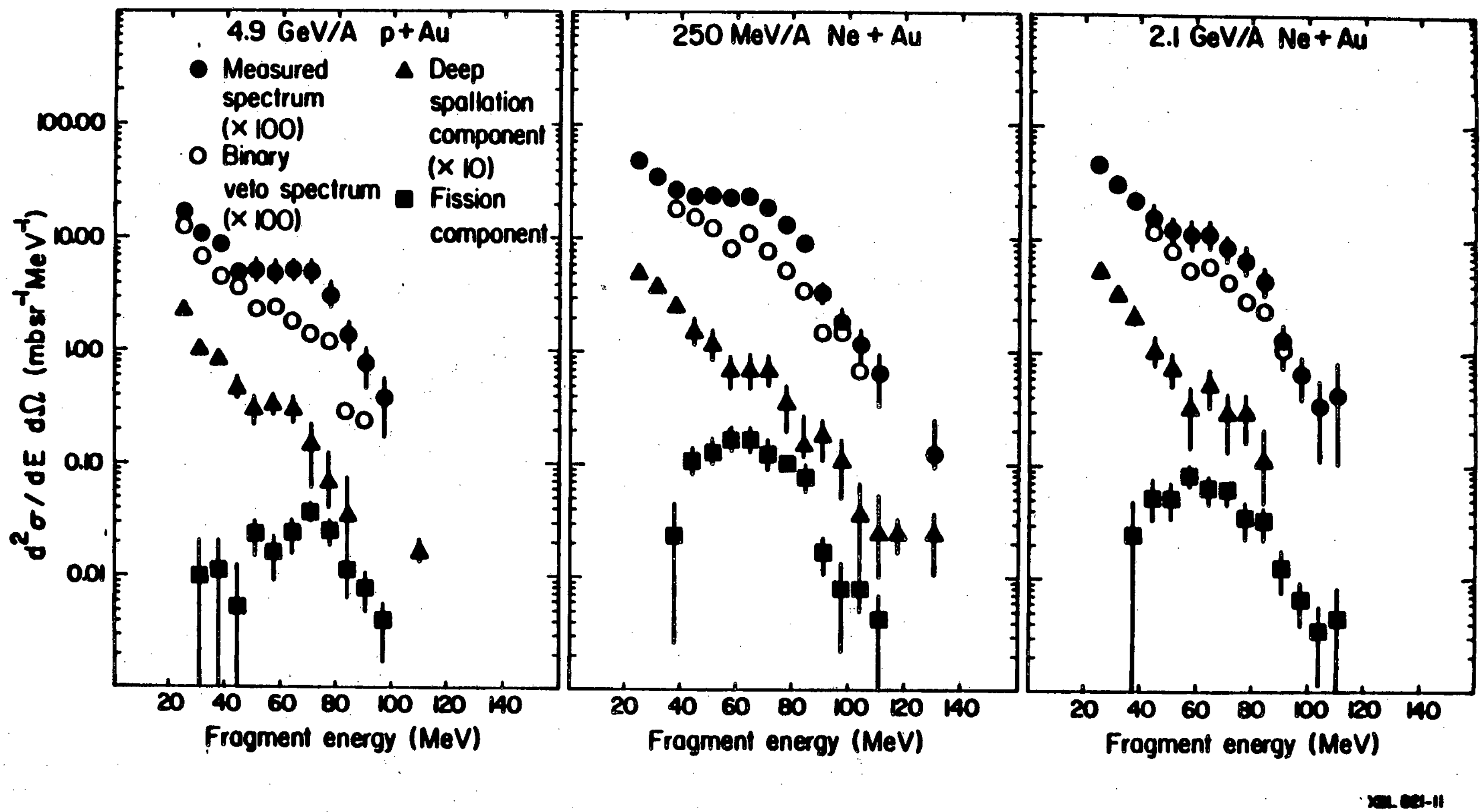
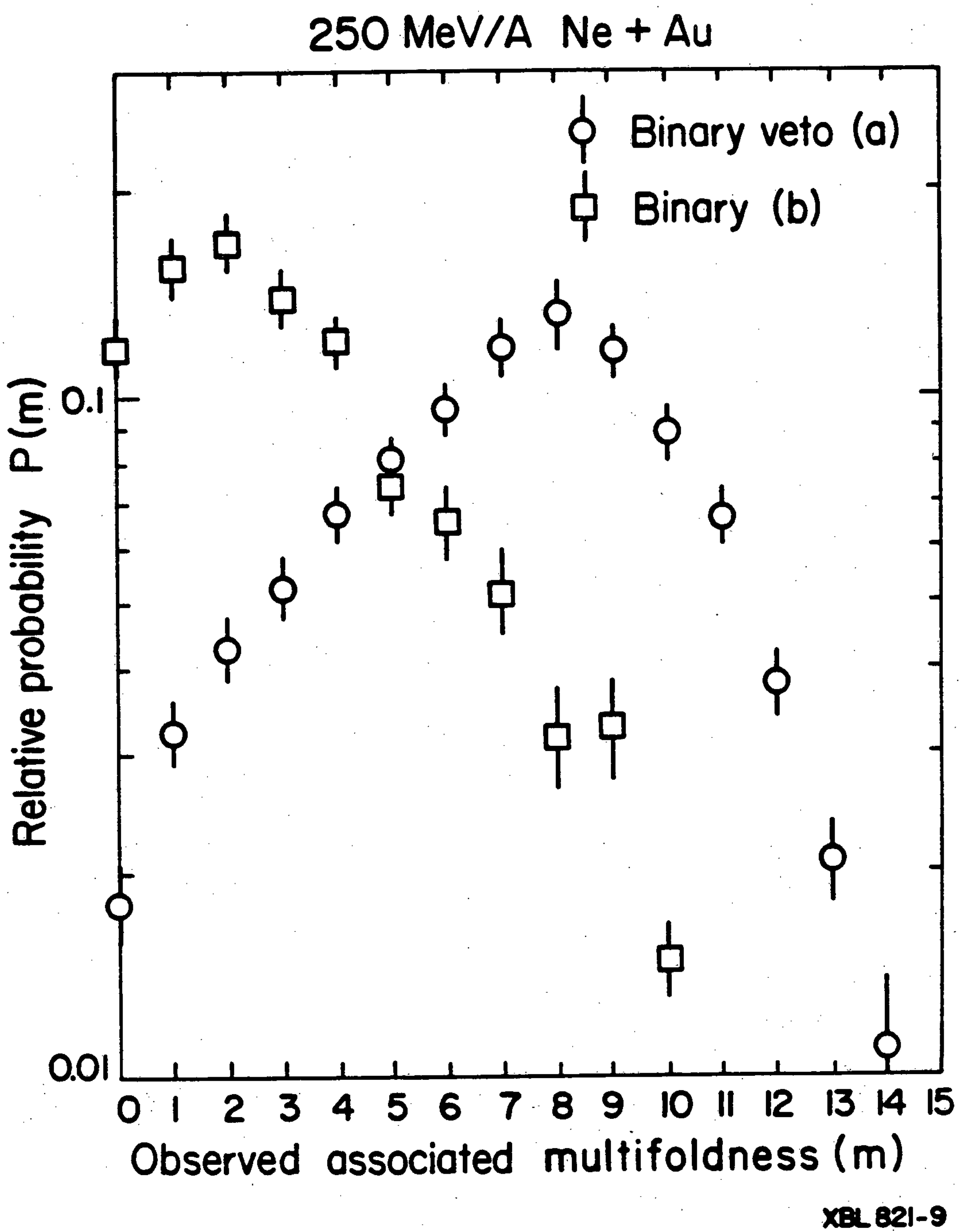

4.9 GeV/A p+Au
Measured spectrum (× 100)
Binary veto spectrum (× 100)
Deep spallation component (× 10)
Fission component
250 MeV/A Ne + Au
2.1 GeV/A Ne + Au
$d^2\sigma / dE\, d\Omega$ (mbsr^{-1}MeV^{-1})
100.00
10.00
1.00
0.10
0.01
20
40
60
80
100
120
140
Fragment energy (MeV)
XBL 861-11

Fig. 2



250 MeV/A Ne + Au
Binary veto (a)
Binary (b)
Relative probability P (m)
0.1
0.01
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Observed associated multifoldness (m)
XBL 821-9

Fig. 3