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TITLE FISSION IN INTERMEDIATE ENERGY HEAVY ION REACTIONS

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DISCLAIMER

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A systematic study of reaction mechanisms at intermediate energies (50 - 100 MeV/A) has been performed at the Lawrence Berkeley Laboratory's BeValac using medium weight projectiles on medium and heavy element targets. A gas and plastic phoswich detector system was employed which gave large geometric coverage and a wide dynamic response. The particles identified with the gas detectors could be character-ized into three components - intermediate mass fragments (IMF), fission fragments (FF) and heavy residues (HR). Major observed features are: the reaction yields are similar in the 50 to 100 MeV/A range, central collisions have high multiplicity of IMF's with broad angular correlations consitent with a large participant region, effects of final state Coulomb interactions are observed and give information on the size and temporal behavior of the source, true fission yields are dependent on target fissility and correlated with relatively peripheral collisions. Analysis of fission and evaporation yields implies limiting conditions for which fission decay remains a viable deexcitation channel.

1 INTRODUCTION

Intermediate energy reactions represent a transition region between the highly dissipative collective phenomena observed at low energies and the nucleon-nucleon interaction region observed at high energies. Such studies offer insight into the transition from the mean field dominated regime associated with traditional nuclear matter to a regime which consists of a mere spatial correlation of essentially individual nucleons. Since this is a transition region, a wide variety of reaction products is obtained. As a collective deexcitation channel, fission plays an important role in these investigations by providing information on the statistical aspect of the reaction. Various studies[1-5] have been performed in this region studying the reaction channels. General conclusions show a large yield for products in the fission mass region and indication for limiting momentum transfer for systems which lead to fission decay. At the intermediate energies, where the projectile nucleons are near the Fermi velocity of bound nucleons, contributions are observed from both statistical and nucleon-nucleon interaction modes. In our experiments, fission is used as the primary measure of the collective (cooperative) behavior of the excited system, while energetic nucleon emission provides information on the initial stage collision process. In addition to these decay channels, there is a large yield for the production of intermediate mass fragments (IMF). These presumably carry information on the thermal and spatial properties of the source region, and possibly on a liquid vapor nuclear matter phase transition.

2 EXPERIMENTAL

The experimental challenge faced in this field is to be able to measure an extremely wide range of interaction products with sufficient geometrical coverage to obtain the important correlations between decay products. Relatively slow moving, highly ionizing fission products and target residues must be recorded simultaneously with low ionizing intermediate mass fragments and even lower ionizing hydrogen and helium isotopes. For this purpose we have designed a "logarithmic" array, which we have named the "Pagoda", consisting of gas and scintillator components (the system is described in more detail in reference 6). Figure 1 presents a schematic diagram of the final configuration used in the experiment. It consisted of eight gas detector assemblies each of which covered 1.7 % of 4 π (total = 13.5 % of 4 π). There were four active regions in each gas module. The first was an 8 cm x 16 cm multiwire proportional counter (MWPC) operated in an "inverted Breskin"[7] configuration. It provided incident particle position information (through wires connected to tapped delay line read outs) to an accuracy of better than 1 mm and a fast timing signal (~ 400 psec FWHM). The second region was a proportional counter that was operated in the same 2.5 Torr isobutane gas environment as the MWPC's. It was electrically isolated from the multiwires by thin aluminized polypropylene windows (40-50 μgm/cm^2 coated with 10 μgm cm^2 Al) and gave linear energy response for transversing ions having losses < 200 keV. The third was another MWPC (16 cm x 16 cm) located 18 cm behind the first and provided similar position and timing response as the front counter. The fourth was a 20 cm deep ionization chamber that was isolated from the forward portions of the detector by a wire mesh supported 200 μgm cm^2 aluminized mylar foil. The ionization chamber was operated with CF_4 in the 50-300 Torr range. Behind the front six gas modules was an array of phoswich detectors. In the final configuration (as presented in Fig 1), there were 54 identical units (in 3 x 3 arrays behind the gas modules) each being a truncated pyramid that started 60 cm from the target position. The modules consisted of 1 mm fast (Bicron BC412) 26 cm slow (Bicron BC444) plastic which were optically coupled with lucite light guides to Amperex (XP 2202 [illegible] B) or Hamamatsu (R2154) phototubes. The system was capable of resolving hydrogen isotope lines and sufficiently thick to stop 200 MeV protons. The forward [illegible]

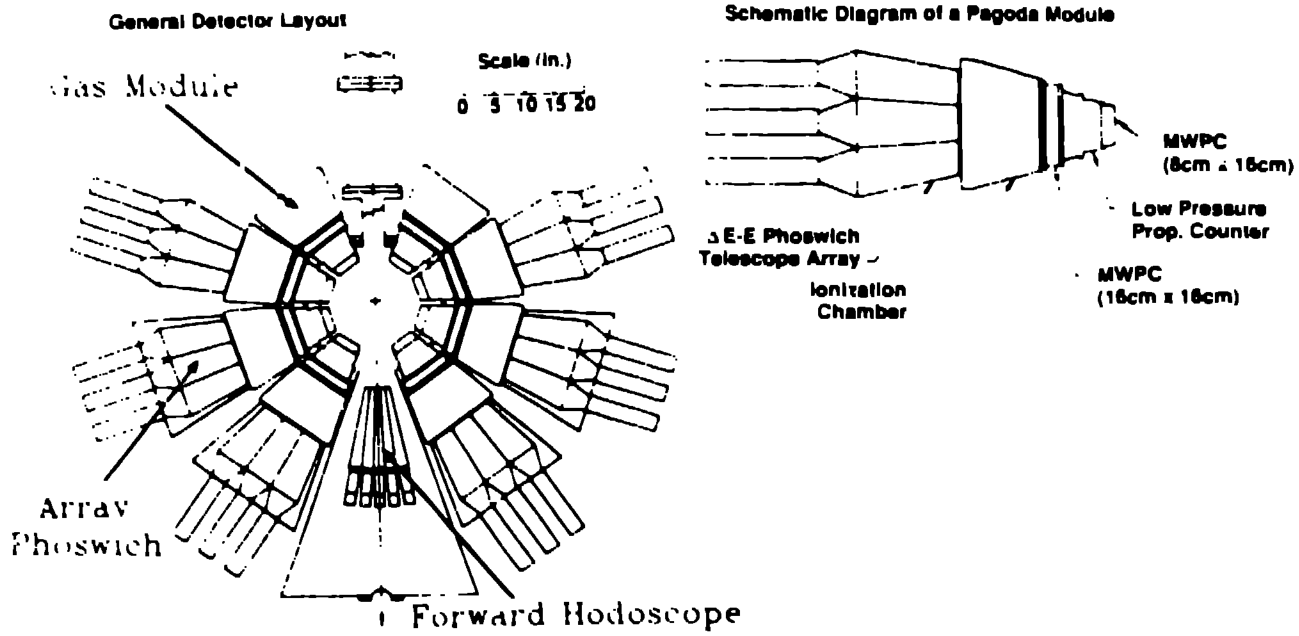

FIGURE 1.
Experimental configuration. A) top view. B) single Pagoda module detail

arrays were placed in a vacuum chamber which attached directly to the back of the ion chamber. Thus for these modules, there was no additional window introduced and particles having energies in the 2-4 MeV/A range would be detected in the fast plastic. The next two more backward gas modules were not in vacuum and were isolated from the ion chamber gas volume by a 0.9 mil mylar window. This resulted in raising the detection threshold for particles reaching the fast plastic to 6-7 MeV/A.

A forward phoswich hodoscope was also included in the Pagoda system. It consisted of a 5 x 7 array with the center element removed for the exiting beam. Each wedge shaped module had 1 mm fast/40 cm slow plastic regions and subtended 4° in both the x and y direction. The total array had an angular coverage range of ±2°-10° horizontally and ±2°-14° vertically. The Hamamatsu phototubes (R580) were located inside the forward vacuum wedge. The 40 cm slow plastic region was sufficiently thick to stop protons of over 250 MeV.

The analog signals from all detector modules were processed and digitized using commercially available electronics. The CAMAC signals were interfaced via VME into a VAX computer system for online monitoring and long term magnetic tape recording. In addition, voltages and gas pressures of detector modules were continuously digitized and monitored. A total of 14 different trigger types were used to initiate the data acquisition system and up to 402 individual analog signals were available to be sampled in each event. The total processing time for an event was a function of the number of parameters recorded in the event, but typically was 0.5-1.0 ms. The beam intensity was ~10^8 per 0.6-1.0 sec spill, and resulted in system dead times on the order of 30%. The targets were self supporting metallic foils having thickness of ~1 mg/cm²

The detector systems were calibrated with a variety of radioactive sources and beams supplied from the Los Alamos FN tandem Van de Graaff, Berkeley 88" cyclotron, and BeVaIac. Online Z identification in the phoswich detectors permitted adequate matching

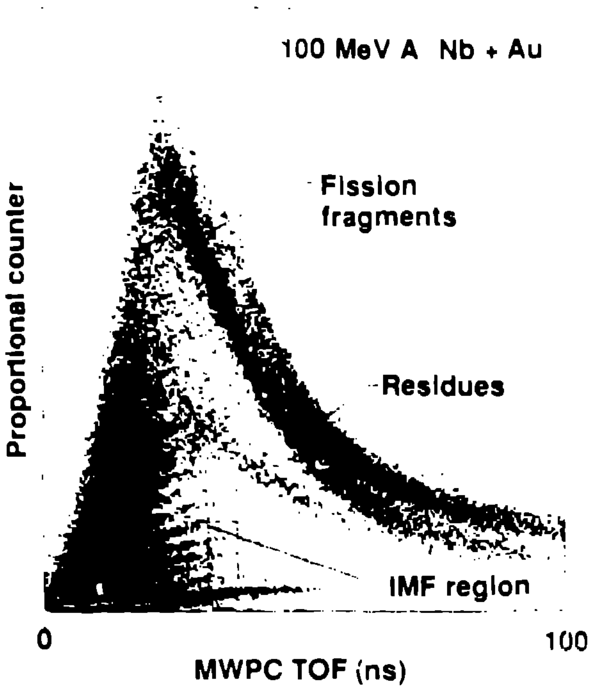

FIGURE 2
Two dimensional presentation of the front proportional counter data correlated with the transiting particles time of flight as obtained in the MWPC's. Areas of interest are identified.

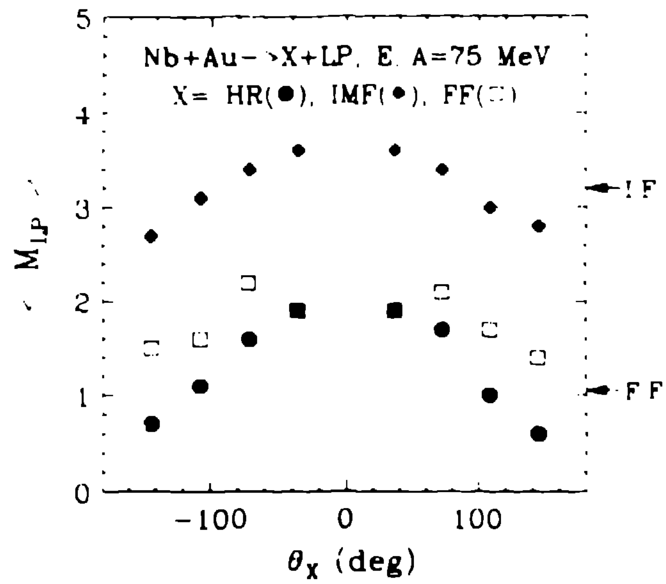

FIGURE 3
The average yield of light charged particles measured in the phoswich detectors (for the three indicated heavy reaction product types) vs the angle of the detected heavy product. The arrows on the right show the mean light particle multiplicities for the cases where two heavy products (IMF x FF or FF x FF) are recorded in the gas detectors.

of the hodoscope elements and of the arrays behind the gas modules. The gas detectors required a more concerted effort to obtain adequate calibrations. All gas units were gain matched using a ^{252}Cf spontaneous fission source. Instead of relying on range energy loss codes, we have empirically established matrices, based on our calibrations, for identifying the Z and E of ions transversing the gas detectors. Figure 2 presents the proportional counter signal versus the particle time of flight between the MWPC's and shows the system response for the higher ionizing particles.

3. RESULTS AND DISCUSSION

The data observed in the forward proportional counter (Fig 2) could be divided into three broad classes of products - intermediate mass fragments (IMF), fission fragments (FF), and heavy residues (HR). Coincidence measurements between these major groups with themselves and with light charged particles provide information on the reaction processes. Figure 3 (for the Nb + Au reaction at 75 MeV A) presents the angular correlation for the light charged particle (H and He) multiplicity observed in the phoswich detectors in coincidence with each of the groups. In all cases the [illegible] peak in the beam direction. The yield for the multiplicity of light particles is [illegible] a factor of two greater for those in coincidence with the IMF's than those with FF's or HR's. This implies a more central collision for the IMF production. The arrows on the side of the figure indicate the multiplicities of light charged particles in which there [illegible] a binary coincidence of an IMF and a FF or of a FF and a FF. The [illegible] events are associated with small light charged particle multiplicities consistent with the assumption of the modest excitation energy that would be deposited in a more peripheral collision. However, the IMF-FF data shows a multiplicity approximately a factor of three larger than that for FF-FF cases. We believe that these coincidences are the result of violent collisions in which a residue is left in the fission product mass range, but that this product is not from a binary fission decay.

Figure 4 gives additional information regarding the centrality of the reactions. The data are from the Nb + Au reaction at 50 MeV A and present observed correlations between the heavy element groups in the gas detector system and the coincident charged particle having the highest Z that is seen in the hodoscope. In the top portion of the figure, the three panels present the yield of the hodoscope Z_{max} distribution that is in coincidence with single events of the three reaction components. For the IMF yield (top middle panel) the distribution is exponentially falling as Z increases - thus indicating hard central collisions that leave little, if any, projectile residue. For the HR coincidence (top right panel) the Z distribution peaks at some intermediate value and shows that reactions leading to heavy residues are associated with intermediate reactions that still preserve significant portions of the projectile. The FF coincidences (top left panel) give a bimodal distribution of Z products in the hodoscope. The peak at high Z values is for peripheral interactions in which the projectile remains largely intact. However, the secondary peak associated with low Z values is the result of more violent collisions. We believe, as discussed above, that these events should not be associated with true binary fission, but are a resultant of a more violent collision in which a residue is left in the fission product mass range. The bottom portion of Figure 4 corroborates this assumption. When we look at the Z yield associated with events in which two fission mass products are recorded we see a correlation with only high Z yield in the hodoscope. These events are exclusively associated with reactions in which a large portion of the projectile remains intact. The other two bottom panels show that if IMF's are in coincidence with more heavy element components the hodoscope Z yield is substantially decreased and, therefore, associated with more violent collisions.

The effect of bombarding energy on product yield in the gas counters for the Nb + Au reactions is presented in Figure 5. The IMF yield is dominate, and has an integrated yield corresponding to an ≈ 8 barn cross section. The main feature of note, however, is the relatively weak dependence of the yields with bombarding energy. From this we conclude that the onset of IMF production occurs at bombarding energies below those we have studied. If we look in detail at the folding angles between binary fission products observed for the three Nb + Au reactions (Figure 6) we can obtain information on the momentum transfer associated with reactions which lead to fission. The mean folding angle is seen to be increasing as the projectile energy is raised from 50 to 100 MeV A. This gives a mean momentum transfer decrease from 1.5 to 0.9 GeV c with the increasing projectile energy. If we, as a simple approximation, ascribe the momentum transfer to the absorption of individual nucleons of the projectile, then the observed results would be consistent with a most probable excitation energy of 200-250 MeV for nuclei formed in this reaction that undergo fission.

The coincident binary product cross sections (with the requirement that each product has A > 40) for the reaction Fe + Au at 100 MeV A are presented in Figure 7 as a function of the momentum parallel to the beam axis carried by the sum of both products. The data have many features consistent with those expected from normal fission decay.

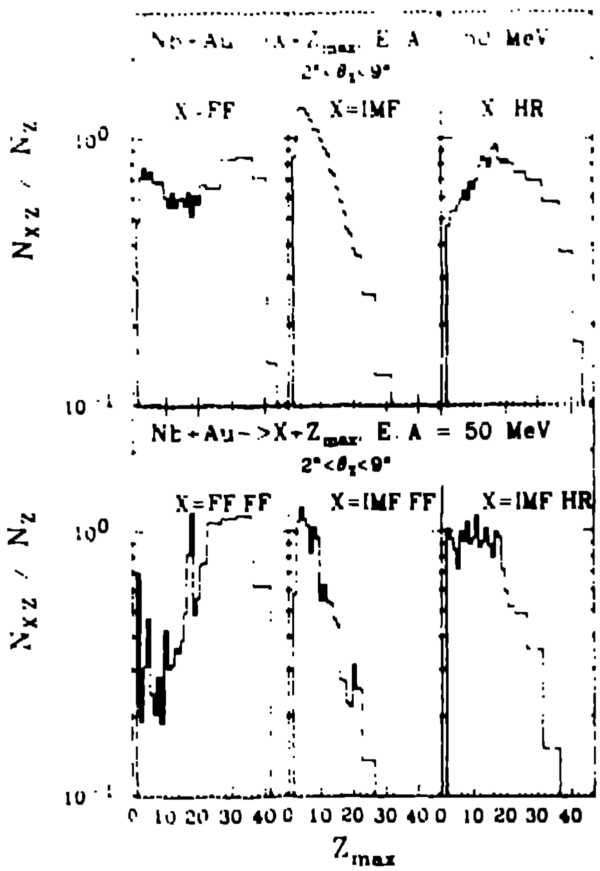

FIGURE 4
The ratio of coincident to singles spectra in the hodoscope for the indicated heavy element component vs the maximum charge measured in a hodoscope elemen (see text discussion).

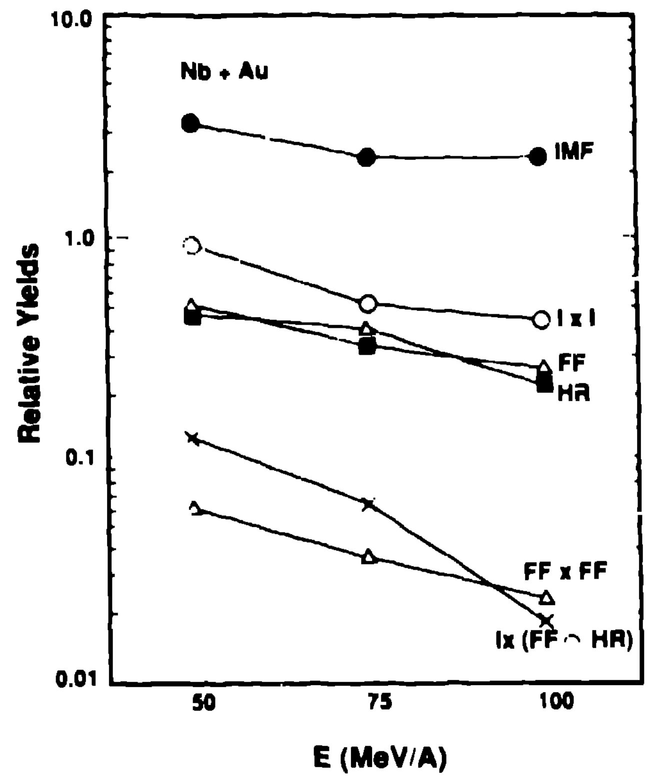

FIGURE 5
The relative yields of the indicated heavy element reaction products for the Nb + Au reaction as a function of the projectile energy.

However, for the high parallel momentum transfer region the fragment center of mass energies[8] are substantially above the Viola[9] systematics which may imply these are not statistical decay fission products. For comparison purposes we have chosen to model this data as if it were fission using a traditional and a more modern statistical approach. The results of the two models are also presented in Fig 7. In both cases the initial stages of the reaction are treated with the Yariv and Frankel intra nuclear cascade model[10].

In the first analysis, the products from the cascade are analyzed with the DFF[11] statistical decay code without considering angular momentum (see ref 8 for a more detailed discussion). This very simple approach gives remarkably good agreement with the experimental data. As a second approach, we have used a more refined effort[12]. It discards products from the cascade calculation having residual excitation energies of greater than 1 GeV on the grounds that these nuclei will not survive the fast cooling process and still remain heavy enough to have appreciable fissility. The products out of the cascade having excitation energies between 300 MeV and 1 GeV are cooled by fast nucleon emission with an assumed local temperature of 15 MeV. For the illustration shown in Fig 10, these fast particles are assumed to remove the geometrical average angular momentum (2/3 of the maximum value) from the cooling nucleus. The 300 MeV cut off is taken as a rough approximation to where statistical processes should begin. At this energy the neutron decay life time becomes comparable to the transit time of a neutron to cross the nucleus. We believe at times shorter than this the system can not be viewed as sequentially emitting particles since there is insufficient time for the emerging particles to leave the nuclear volume. From 300 MeV to 150 MeV of excitation energy the system is allowed to statistically evaporate particles (explicitly keeping track of the angular momentum) using the PACE[13] code. In this excitation energy range fission is not allowed to compete as a decay channel. This choice is made as a simple approach to the dissipative and flow dynamic effects that establish minimum times for which fission can statistically compete[14]. Below 150 MeV, fission is allowed as a decay channel in PACE using the angular momentum dependent barriers of Sierk[15] (with the relative level density parameters chosen to be $a_f/a_n = 1.03$). This choice of parameters is consistent with fitting known fission yields.

As seen in Fig 7, the simple model gives a much better fit to the experimental data. We believe this is somewhat fortuitous since a number of known features important to the fission decay process are not included (i.e. angular momentum and dissipative effects). As discussed above, we also have some reason to doubt if the high parallel momentum transfer data are from statistical fission decay and, therefore, comparison with fission models may not be justified in this region. We plan to continue our analysis and apply it to the other data sets we have experimentally measured and will report on this at a future date[12].

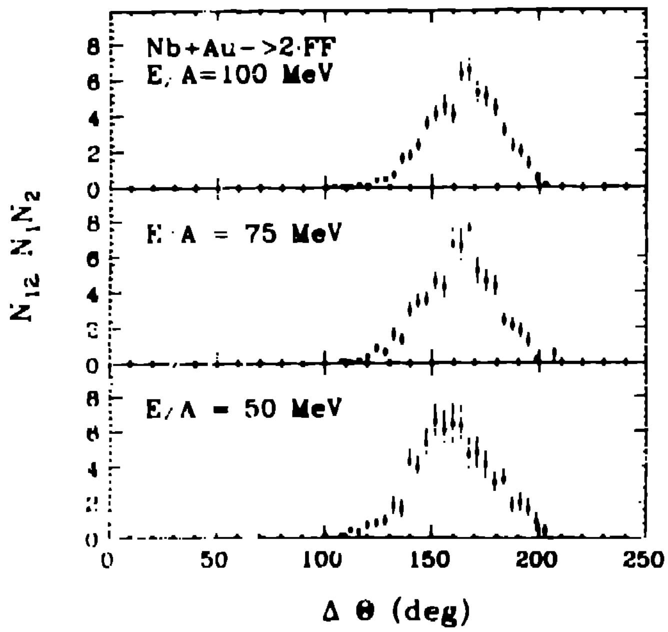

FIGURE 6
The yield of coincident fission fragments vs the folding angle between the two fragments (ratioed to the inclusive spectra to remove experimental geometrical selections) for three different projectile energies in the Nb + Au reaction

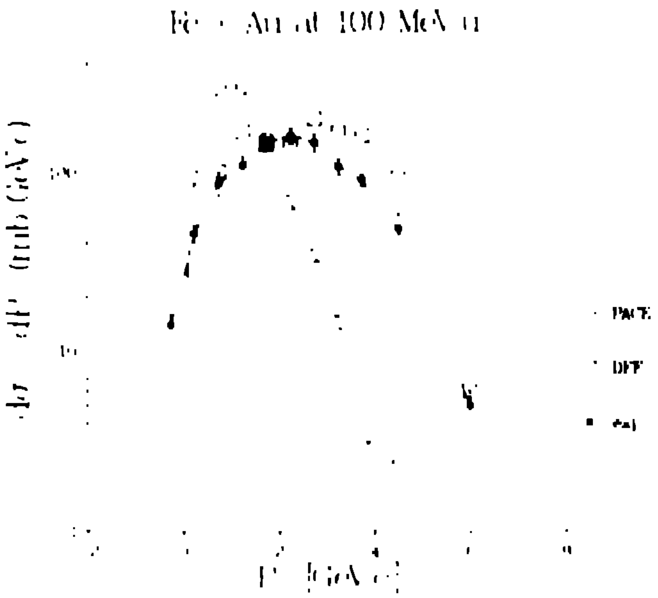

FIGURE 7
The experimental and calculated (with two models) cross sections for fission like binary decay in the 100 MeV/A Fe + Au reaction vs the parallel momentum of the decaying species. See text for additional details.