FISSION AND DECAY OF HIGHLY EXCITED NUCLEI

COMPLEX FRAGMENT EMISSION IN THE \( p + Ag \) REACTION AT 160 MeV

S.J. Yennello, K. Kwiatkowski, R. Planeta, S. Rose, L.W. Woo, and V.E. Viola
Indiana University, Bloomington, Indiana 47405

Studies of complex fragments emitted in the reaction of 200-500 MeV protons with silver nuclei have indicated a predominantly non-equilibrium formation mechanism\(^1\). In order to examine the extent to which this behavior persists at lower energies, intermediate-mass fragment yields (IMF: \( 3 \leq Z \leq 14 \)) have been measured for the \( p + \text{nat}Ag \) reaction at 160 MeV. Natural silver targets of thickness 1.3 mg/cm\(^2\) were bombarded with 160 MeV protons. Fragments were detected with an axial gas-ionization chamber/310 \( \mu \)m-thick silicon surface-barrier detector telescope. At forward angles the fragment energy spectra are Maxwellian in shape, with momenta extending up to 2.5 times the beam momentum; these evolve toward more Gaussian shapes at larger angles and for heavier fragments. Coulomb peaks in the spectra were in general agreement with those predicted by fission-fragment kinetic-energy-release systematics.

For all atomic numbers the angular distributions fall off exponentially with increasing angle. As the fragment \( Z \) increases, the angular dependence of the yields becomes increasingly isotropic, with forward-to-backward ratios decreasing from \( \sim 7 \) for Li and Be to \( \sim 2 \) for F and Ne ejectiles. In Fig. 1 a rapidity plot of the invariant cross section contours in the longitudinal versus transverse momentum plane (\( p_\| \) vs. \( p_\perp \)) is shown for carbon fragments. This figure is typical of all IMF products. Constant cross-section loci (semi-circles) are drawn about momentum values corresponding to emission from an isotropic source moving with an average velocity \( \beta = 0.0056 \) (\( \beta_{cn} = 0.0054 \)). It is observed that the backward-angle data fall on these loci relatively well, whereas at forward angles the data are skewed toward much larger momenta. Thus, we infer a two-component source for these fragments, one of statistical nature that is largely responsible for fragments at back angles and one associated with a fast, precompound mechanism that accounts for most of the forward-angle yield. The relative ratio of equilibrated-to-non-equilibrated components increases with fragment charge. The interpretation is consistent with \( ^3\text{He} \) and heavy-ion data at intermediate energies\(^2\), but does not agree with the observation of Ref. 1 for higher-energy protons.

Based on the results of Fig. 1, a two-component moving source fit has been applied to these data, employing a statistical emission model for the equilibrated events\(^3\) (EQ) and a Maxwellian distribution for the non-equilibrated component (NEQ). An excellent fit to the energy spectra for all \( Z \) values and angles is found with values of \( \beta_{EQ} = 0.0054 \), \( T_{EQ} = 3.4 \text{ MeV} = T_{cn} \), \( \beta_{NEQ} = 0.04 \) and \( T_{NEQ} = 9.1 \text{ MeV} \).

Fig. 2(a) shows the cross sections for the equilibrated component of the IMF yield as a function of fragment \( Z \)-value. These results are compared with the statistical decay model of Gomez del Campo\(^4\), shown by the histogram. A value of \( J_{max} = 5h \) for the maximum angular momentum provides a good description of the data. The strong dependence of
IMF yield on angular momentum is demonstrated by the much poorer fits obtained with $J_{\text{max}} = 4$ and $6\hbar$.

Fig. 2(b) presents the cross sections for IMF formation as a function of fragment Z. The yields follow a power-law decrease, $\sigma(Z) \propto Z^{-\tau}$, where $\tau = 4.9$ provides the best fit to the data. This value is much larger than that observed at higher proton energies\textsuperscript{1,5}. These data are compared with the accreting source model of Friedman and Lynch\textsuperscript{9}, shown by the solid line in Fig. 2(b) and normalized to the $Z = 7$ yield. This model, which permits fragment emission at various stages in the time evolution of the equilibration process, provides a satisfactory fit to the data.


Figure 2. (a): Cross sections for equilibrated IMFs as a function of fragment Z. Solid line is for statistical decay model of Ref. 4 with $J_{\text{max}} = 5$. (b): Total cross sections for IMFs as a function of fragment Z. Solid line is prediction of accreting source model (Ref. 6.), normalized to $Z = 7$. 