

THE DECAY MODES OF HIGH-SPIN COMPOUND NUCLEI PRODUCED IN  ${}^6\text{Li}$ -INDUCED FUSION REACTIONS

S.E. Vigdor, H.J. Karwowski, W.W. Jacobs, S. Kailas, P.P. Singh, F. Soga, P. Yip\*, and W. Ploughe†

In order to more stringently constrain the nuclear structure parameters involved in statistical model analyses of the decay of compound nuclei at high spin and excitation, we have initiated a program to measure the absolute cross section for all major decay modes. To date we have measured absolute total cross sections for fission ( $\sigma_{\text{fiss}}$ ), proton evaporation ( $\sigma_p$ ),  $\alpha$ -particle evaporation ( $\sigma_\alpha$ ), and neutron emission ( $\sigma_{\text{xn}}$ ) from compound nuclei formed (with  $J_{\text{CN}} \sim 30\text{-}35 \hbar$ ,  $E_{\text{CN}}^* \sim 70 - 100 \text{ MeV}$ ) in bombardment of  ${}^{181}\text{Ta}$ ,  ${}^{194,198}\text{Pt}$ ,  ${}^{197}\text{Au}$ , and  ${}^{208}\text{Pb}$  by  ${}^6\text{Li}$  beams of lab energy 75, 85, and 95 MeV. Measurements at higher energies are planned. We have also determined total fusion cross sections for these systems:

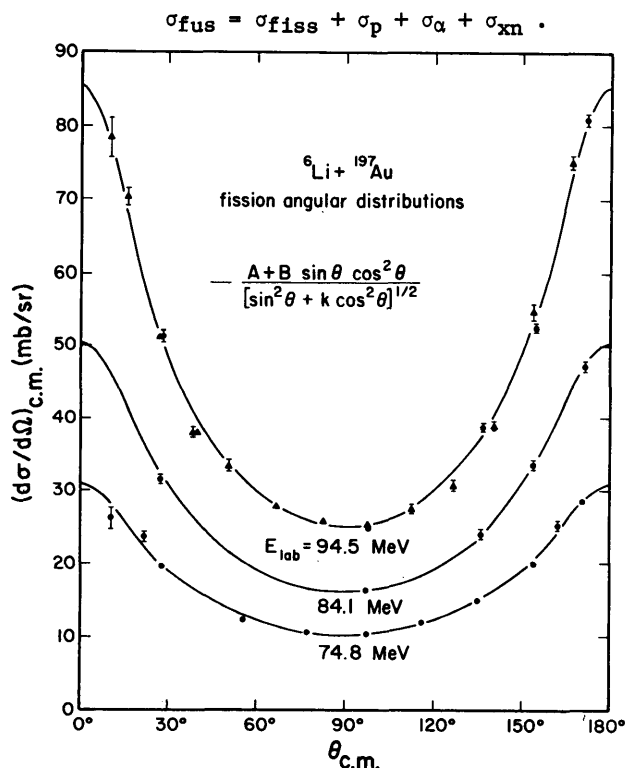


Fig. 1. Measured fission-fragment angular distributions for  ${}^6\text{Li} + {}^{197}\text{Au}$  at three bombarding energies. The curves represent the empirical formula displayed, with the parameters  $A$ ,  $B$ , and  $k$  adjusted for optimum fits.

The fission and charged-particle evaporation yields were measured with a solid-state detector telescope, in which the fission fragments were very cleanly separated from all other reaction products over the entire angular range ( $10^\circ \leq \theta_{\text{lab}} \leq 170^\circ$ ). Complete fission-fragment angular distributions exhibit a clear symmetry about  $\theta_{\text{cm}} = 90^\circ$  (see fig. 1), ruling out appreciable contributions from non-equilibrium fission or from fission following  $\alpha$ -transfer. The evaporation peaks have been clearly discerned in the  $Z=1$  and  $Z=2$  spectra (see fig. 2) over a range of backward angles ( $\theta_{\text{lab}} \geq 110^\circ$ ), over which the yields are observed to be isotropic, allowing direct determination of the total yield. The total cross section for all ( ${}^6\text{Li}, \text{xn}$ ) reactions has been determined by a new technique (see this report,

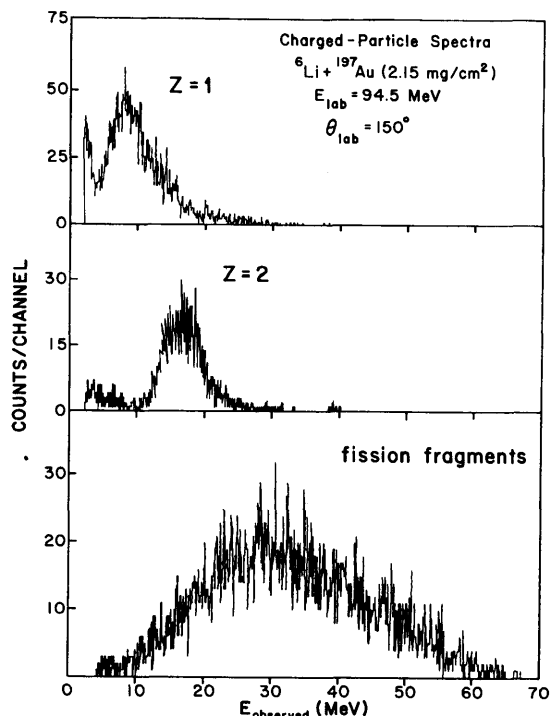


Fig. 2. Representative large-angle energy spectra for  $Z = 1$ ,  $Z = 2$ , and fission products. The evaporation peaks show up clearly in the  $Z = 1$  and  $Z = 2$  spectra. The fission spectrum is broadened considerably by straggling in the  $2.15 \text{ mg/cm}^2$  target.

p. 110) involving measurement of the yield and mean multiplicity of K X-rays characteristic of the compound nucleus Z.

Results for the decomposition of  $\sigma_{fus}$  for the five targets at two bombarding energies are shown in Fig. 3.  $\sigma_{xn}$  is the dominant contribution in all cases investigated. The charged-particle evaporation cross sections are of roughly similar magnitudes for all targets (with  $\sigma_p > \sigma_\alpha$ ), and they increase significantly with bombarding energy. Corrections (not yet applied) for multiple charged-particle emission are expected to reduce  $\sigma_p + \sigma_\alpha$  by  $< 10\%$ . The fission cross section is a rapid function of both target and energy, increasing with the spin of the compound nucleus, with Z of the compound nucleus, and for fixed Z with decreasing neutron excess, in a manner qualitatively consistent with expectations based on rotating liquid-drop model (RLDM) fission barriers.<sup>1</sup> In all cases,  $\sigma_{fus}$  accounts for  $\approx 50\%$  of the optical model total reaction cross section

$\sigma_{reac}$ . This fraction is similar to that observed in bombardment of much lighter targets with heavier ions at comparable energies per nucleon (see ref. 2), but is inconsistent with a recently proposed empirical parameterization<sup>3</sup> of all heavy-ion fusion cross sections.

A statistical model analysis of these results has been initiated, using the computer code MB-II (ref. 4), to which we have added a subroutine to calculate the fission-fragment angular distribution  $W(\theta)$ , based on the treatment of Halpern and Strutinski.<sup>5</sup> The statistical-model angular distribution calculation uses RLDM saddle-point moments of inertia and sums over contributions from all spins and all fissioning nuclei, using MB-II output to deduce the mean nuclear temperature and the contribution to  $\sigma_{fiss}$  from each spin and each chance of fission. As illustrated in fig. 4 by calculations using two different parameter sets (each constrained to give  $\sigma_{fus}$  correctly), multi-chance fission is expected to be very important in the present reactions. The fission-fragment anisotropy [ $W(170^\circ)/W(90^\circ)$ ], while relatively insensitive to changes in fission barrier height or saddle-point level density for any given fissioning nucleus, is quite sensitive to the relative importance of high-chance vs. low-chance fission, and hence provides an important additional experimental constraint on the calculations. Also indicated in fig. 4 is the non-negligible sensitivity of both  $\sigma_{fiss}$  and  $W(170^\circ)/W(90^\circ)$  to the assumed diffuseness of the compound-nucleus spin distribution.

From the calculations performed to date we conclude that the present measurements constrain the analysis much more stringently than have previous data. For example, it has been possible to adjust structure parameters to "fit" the measured energy dependence of  $\sigma_{fus}$  and  $\sigma_{fiss}$  (for one target nucleus) simultaneously, but only with very poor agreement with  $\sigma_p$ ,  $\sigma_\alpha$ , and  $W(170^\circ)/W(90^\circ)$ . We have not yet begun to compare the cal-

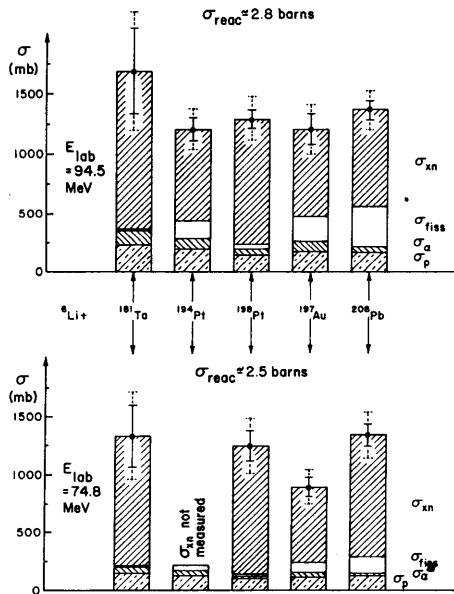


Fig. 3. Decomposition of the measured fusion cross section for five targets at two energies. ( $\sigma_{xn}$  was not measured for  $^{194}\text{Pt}$  at 74.8 MeV.) The solid error bars represent relative measurement uncertainties in  $\sigma_{fus}$ . The dashed bars include in addition a  $+10\%$  estimated systematic uncertainty in  $\sigma_{xn}$ , arising from possible deviations from a Poisson K X-ray multiplicity distribution. The overall absolute normalization uncertainty is estimated at  $\pm 10\%$ .

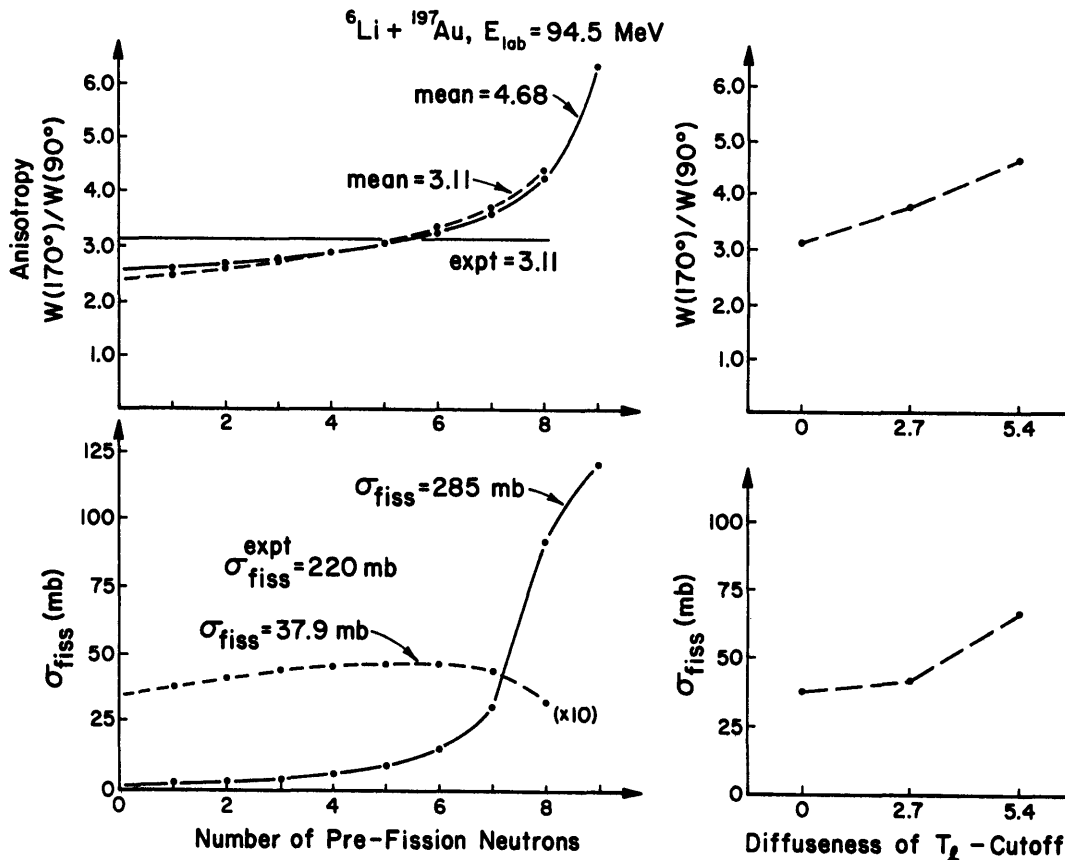


Fig. 4. Statistical-model calculations of the total fission cross section and anisotropy for  ${}^6\text{Li} + {}^{197}\text{Au}$  at  $E_{\text{lab}} = 94.5$  MeV, illustrating sensitivities to multi-chance fission and to the assumed diffuseness of the spin distribution in the compound nucleus (a diffuseness value of 2.7 is consistent with optical model partial-wave reaction cross sections). The dashed curves utilize RLDM structure parameters, neutron and fission level-density parameters  $a_n = a_f = A/7$ , and a sharp cutoff on the barrier penetration coefficients  $T_q$ ; the solid curves use fission barriers 25% smaller than RLDM values,  $a_n = A/7$ ,  $a_f = 0.95a_n$ , and a diffuse cutoff (diffuseness 2.7) on  $T_q$ . In both cases the  $T_q$  have been adjusted to reproduce the measured  $\sigma_{\text{fus}}$ .

culated and measured target-dependences. In the future, it is hoped that data of the sort presented here may provide a wide-ranging test of predictions of the shell-corrected nuclear structure at high spin (yrast and saddle-point energies, particle binding energies, moments of inertia, level densities), by using such predictions (e.g., see ref. 6) as input to the statistical model analysis.

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\*Hamilton College, Clinton, New York

†Ohio State University, Columbus, Ohio

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