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A PHENOMENOLOGICAL MODEL FOR PARTICLE PRODUCTION FROM THE COLLISION OF NUCLEONS AT MEDIUM ENERGIES WITH FISSILE ELEMENTS

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The addition of a detailed fission channel, including fragment mass, charge, kinetic energy, and excitation energy distributions, to the evaporation stage of the Monte Carlo computer code,[1] MECC-7, for nuclear cross sections and particle production data has been reported in an earlier paper.[2] In this code the intranuclear-cascade-evaporation model, as developed by H. W. Bertini,[3,4] and R. L. Hahn,[5] is applied to nucleon- and pion-nucleus nonelastic collisions at all incident energies between approximately 20 MeV and 3 GeV. Data regarding such collisions between medium-energy protons and uranium nuclei are of particular importance in designing the targets and shielding for facilities to produce an intense source of low-energy neutrons.[6*] In this paper significant revisions to the model described in Ref. 2 are discussed and comparison between calculated results and experimental data that were not available when Ref. 2 was published will be presented.

The statistical theory of fission originated by P. Fong[8,9] is used as a guide. Fong-type fission channel calculations for use at high energies have also been given by V. S. Barashenkov and V. D. Toneyev,[10] V. S. Barashenkov and S. Ju. Shmakov,[11] and by H. Takahashi.[12] In addition, F. Atchison[13] has recently prepared a phenomenological model.

*The fission-amended model has also been incorporated in the high-energy transport code HETC.[7]

The model described here relies heavily on experimental data of D. Epperson[14] for postevaporation average mass, total kinetic energy, and variance distributions versus A_2, the mass number of the heavy residual nucleus. We used data for 7, 10, 15, 20, 25, and 30 MeV protons incident on ^{235}U to compute the preevaporation distributions, which are shifted in A_2 (to the value A_2') by average neutron multiplicities, $\bar{\nu}_n(E_f)$ and weighted by fission probabilities, $P_f(E_f)$ obtained from the code. E_f is the excitation energy of the fissioning nucleus. Fission fragments lose kinetic energy at each evaporation step due primarily to the loss of mass.[15] In this paper we applied a $\overline{\Delta K}_E$ = 0.8 MeV correction per emitted nucleon to the average relative kinetic energy, $\bar{K}_E(A_2',E_f)$, obtained as a solution of the superposition equations of Ref. 2. The final kinetic energy distributions computed for incident protons on ^{235}U now agree fairly well with Epperson's measurements.[14] For $E_f \leq 31.5$, the total excitation energy, $\bar{E}(A_2',E)$

$$\bar{E}(A_2',E_f) \equiv E_f + \overline{\Delta E}_c(A_2',E_f)$$

of the two fission fragments at scission time is obtained by fitting a variation of Fong's mass yield formula to the calculated preevaporation mass distribution. At all higher E_f, the functions $\overline{K}_E$ and $\overline{\Delta E}_c$ defined by Eq. (1) are held constant at their E_f = 31.5 values.

The parameter, a, used in the nuclear level density formula is that given by LeCouteur and Lang,[16]

$$a = \frac{A}{B_o}\left(1 + Y_o\left(\frac{A-Z}{Z}\right)^2\right) \; ; \; Y_o = 1.5$$

and is taken to be the same for fission as for evaporation. The value of B_o is one of the most important parameters in determining neutron multiplicities as well as neutron energy spectra. It is taken to be independent of E_f, and the nuclear mass and charge numbers, A,Z. Numerical values of B_o can be varied to fit the experimental data.

In Table 1 the calculated and experimental[17] average number of emitted neutrons per fission from fission induced in ^{235}U, ^{238}U and ^{239}Pu by neutrons with energy 22.79 and 28.28 MeV are presented and compared. Calculated results are given for B_o values of 8, 10 and 15 MeV. The errors on the calculated results are the statistical errors (one standard deviation) due to the Monte Carlo nature of the calculations. For ^{235}U and ^{239}U all of the calculated results are slightly low, but the values for B_o = 8 MeV are in the best agreement with the experimental data. For ^{239}Pu both B_o = 8 and 10 MeV give results that are in reasonable agreement with the data.

Comparisons with experimental neutron multiplicities at higher energies (<3 GeV) indicate that a B_o value of approximately 10 MeV is needed to obtain agreement.[2,11] Calculated results of neutron energy spectra, average kinetic energy of residual nuclei, and residual nuclei mass distribution have also been obtained and will be presented. In particular, the residual mass distribution will be compared with experimental data. The agreement between calculated and experimental results that have been obtained give some confidence that design calculations carried out using the data obtained from this model will be reliable.

Table 1

The average number of neutrons emitted per fission for neutron induced fission in various elements

Neutron Energy MeV	Experimental	Average Number of Neutrons Emitted per Fission		
		Calculated		
		B_o = 8 MeV	B_o = 10 MeV	B_o = 15 MeV
			^{235}U	
22.79	5.493±.049	4.96±.09	4.79±.08	4.67±.08
28.28	6.080±.090	5.51±.09	5.34±.09	5.23±.09
			^{238}U	
22.79	5.513±.043	5.15±.10	4.88±.10	4.80±.10
28.28	6.137±.067	5.79±.11	5.46±.11	5.32±.11
			^{239}Pu	
22.79	6.000±.077	6.02±.08	5.93±.08	5.81±.07
28.28	6.479±.104	6.61±.08	6.49±.08	6.33±.08

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