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EXPERIMENTAL AND CALCULATED EXCITATION FUNCTIONS FOR *DISCRETE-LINE GAMMA-RAY PRODUCTION DUE TO 1-40 MeV* NEUTRON INTERACTIONS WITH ^{56}Fe

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Abstract: Measuring cross sections for gamma-ray production from tertiary reactions is one of the ways to gain experimental information about these reactions. To this end, inelastic and other nonelastic neutron interactions with ^{56}Fe have been studied for incident neutron energies between 0.8 and 41 MeV. An iron sample isotopically enriched in the mass 56 isotope was used. Gamma rays representing 70 transitions among levels in residual nuclei were identified, and production cross sections were deduced. The reactions studied were ^{56}Fe$(n,n')^{56}$Fe, ^{56}Fe$(n,p)^{56}$Mn, ^{56}Fe$(n,2n)^{55}$Fe, ^{56}Fe$(n,d+n,np)^{55}$Mn, ^{56}Fe$(n,t+n,nd+n,2np)^{54}$Mn, ^{56}Fe$(n,\alpha)^{53}$Cr, ^{56}Fe$(n,n\alpha)^{52}$Cr, and ^{56}Fe$(n,3n)^{54}$Fe. Experimental excitation functions have been compared with cross sections calculated using the nuclear reaction model code TNG, with generally favorable results.

(Nuclear Reactions ^{56}Fe$(n,x\gamma)$ $E = 0.8 - 41$ MeV; measured $\sigma(E_\gamma\ ,\ \theta_\gamma = 125$ deg); ^{52,53}Cr, ^{54,55,56}Mn, ^{54,55,56}Fe γ-ray production. Enriched sample.)

Introduction

The U.S. National Research Council, in 1986, reporting [1] on desirable trends in physics research stated, "Experimental nuclear research is advancing toward the study of nuclei in states of higher excitation energy...." For research utilizing neutron beams, this trend has been manifest in greater interest in measurements for incident neutrons above 20 MeV, a trend already established by 1985 and discussed in reports by Rapaport [2] and by Lisowski et al. [3] at the Santa Fe Conference. We, at the Oak Ridge Electron Linear Accelerator (ORELA) had succeeded in extending the useful incident-neutron energy range of our in-beam, high-resolution gamma-ray spectrometric system [4] to obtain useful and interesting measurements for E_n to 40 MeV, and presented [5] some preliminary results at the same conference. Using this experimental system we reported [6] at the Mito conference on a systematic study of ^{10,11}B$(n,x\gamma)$ reactions for E_n up to 25 MeV which featured first measurements on the tertiary reaction ^{11}B$(n,n\alpha\gamma)^7$Li. The concept of using this system for study of previously unmeasured tertiary reactions was thus established.

The TNG statistical model code [7] has capabilities of computing all energetically available tertiary-reaction cross sections. Successful comparisons of calculated cross sections with experimental cross sections for E_n above 20 MeV should be a stringent test for applicability of the fundamental statistical-model concepts.

Experiment

The emphasis for this experiment was on the observation and measurement of tertiary reactions since there are in the literature a number of reports [8-16] on inelastic scattering gamma-ray production. The present data were also reduced for inelastic scattering gamma-ray production for incident neutron energies up to 20 MeV, primarily to serve as a measure of the reliability of the present measurements. Inelastic-scattering data for incident neutron energies between 22 and 41 MeV, however, are new, and they can be utilized to estimate total inelastic-scattering cross sections for neutron interactions with ^{56}Fe for these more energetic incident neutrons [5].

Measurements were made for incident neutron energies between 0.8 and 41 MeV. A 63-g iron sample isotopically enriched in the mass 56 isotope was used. Gamma rays representing 70 transitions among levels in residual nuclei were identified, and production cross sections were deduced for the reactions given in the abstract. Values obtained for production cross sections as functions of incident neutron energy are given in an Oak Ridge National Laboratory Report [17] which also documents additional experimental details.

Calculations

The TNG code [7] is based on a unified Hauser-Feshbach [18] (H-F) and Pre-Compound (P-C) model [19]. The H-F part is multi-step, but angular distributions can be calculated only for the binary step. The P-C part is single step and angular distributions are calculated on the basis of partial wave interference (partial relaxation of the random phase approximation in the H-F formalism). Pairing corrections and spin cutoff factors as functions of excitation energy and excitation number, based on the BCS model, for the exciton level densities in the P-C component are included [20]. Gamma-ray production cross sections for each discrete gamma ray can be calculated. Other quantities calculated include total, elastic, nonelastic, (n,γ), (n,n'), (n,p), (n,α), (n,f), $(n,2n)$, (n,np), $(n,n\alpha)$, (n,nf), ..., $(n,4n)$, ..., associated secondary-particle and gamma-ray production spectra, the angular distributions of the first outgoing particles, and the production cross sections of isomeric states.

Besides the level density parameters which affect the individual reaction cross sections, the most important parameters in the TNG calculation for ^{56}Fe are the optical-model parameters which determine directly the nonelastic cross section for E_n above 8 MeV. The parameters given by Arthur and Young [21], with some adjustment in the imaginary part [22], gave the best overall results. All other parameters were either taken from standard sources (level energies, Q-values, etc.) or were taken from an earlier global analyses [7].

Results and Comparisons

Excitation functions, both experimental and calculated, are presented for twelve discrete-line gamma-ray transitions in Figs. 1 and 2. In Fig. 1 are exhibited data for neutron-only emission reactions, while in Fig. 2 are shown data for reactions involving charged particles. The inelastic scattering data shown in Fig. 1 agree reasonably well with most of the earlier data; for the $(n,2n\gamma)$ data the agreement among the several data sets is somewhat poorer; for the $(n,3n\gamma)$ data the agreement can be improved. The agreement of the present data with

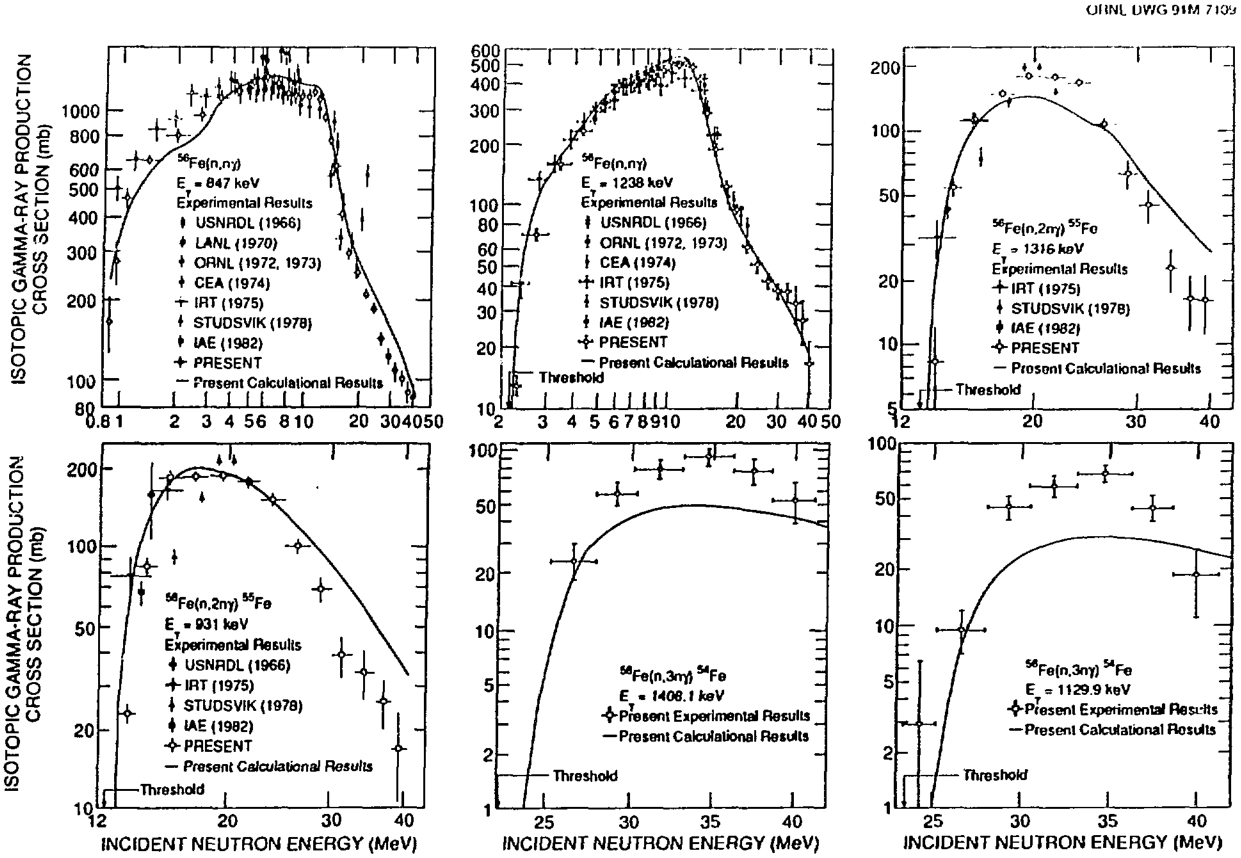

Fig. 1. Six experimental excitation functions compared with calculations. Prior data are: USNRDL (ref. 8), LANL (ref. 9); ORNL (ref. 10,11); CEA (ref. 12); IRT (ref. 13); Studsvik (ref. 14); and IAE (ref. 15).

calculation is quite good for $E_n < 20$ MeV, except for the resonance region [13,16] around $E_n \sim 2$ MeV, for $E_\gamma = 847$ keV. This good agreement may have been anticipated, however, since the parameters used in the TNG calculations were optimized to give a good accounting of data existing in 1986 [22] and were used in developing the ENDF/B-VI evaluation for iron [23].

The calculations shown for 20 MeV $< E_n <$ 40 MeV are the first to be done with this set of parameters developed for $E_n < 20$ MeV and represent an "extrapolation" of the theoretical estimates from the lower-energy calculations. Although the comparisons show somewhat larger variations for $E_n > 20$ MeV than for $E_n < 20$ MeV, this set of parameters is qualitatively correct in predicting large cross sections for reactions having large experimental values and predicting small cross sections for weakly-observed transitions. The model also does well in reproducing level-spin dependent differences observed in the measurements.

Future Work

Direct experimental knowledge of tertiary reaction cross sections is difficult to obtain, particularly if the residual nucleus is stable. Nuclear model calculations are used to obtain estimates of these important cross sections which are often the dominant generator of charged particles in the 15-MeV energy region. Gamma-ray production data provides a very useful window to these cross sections and can serve as benchmarks against which to test and improve nuclear models. The next task is to determine if improvements in calculated excitation functions for E_n above 20 MeV can be obtained through adjustments of parametric values. We plan, also, to study similar reactions for other sample nuclei; preliminary results [24] for ^{59}Co($n, x\gamma$), for example, exhibit large yields for the (n, np) and ($n, 2np$) reaction channels for E_n above 20 MeV.

Acknowledgments

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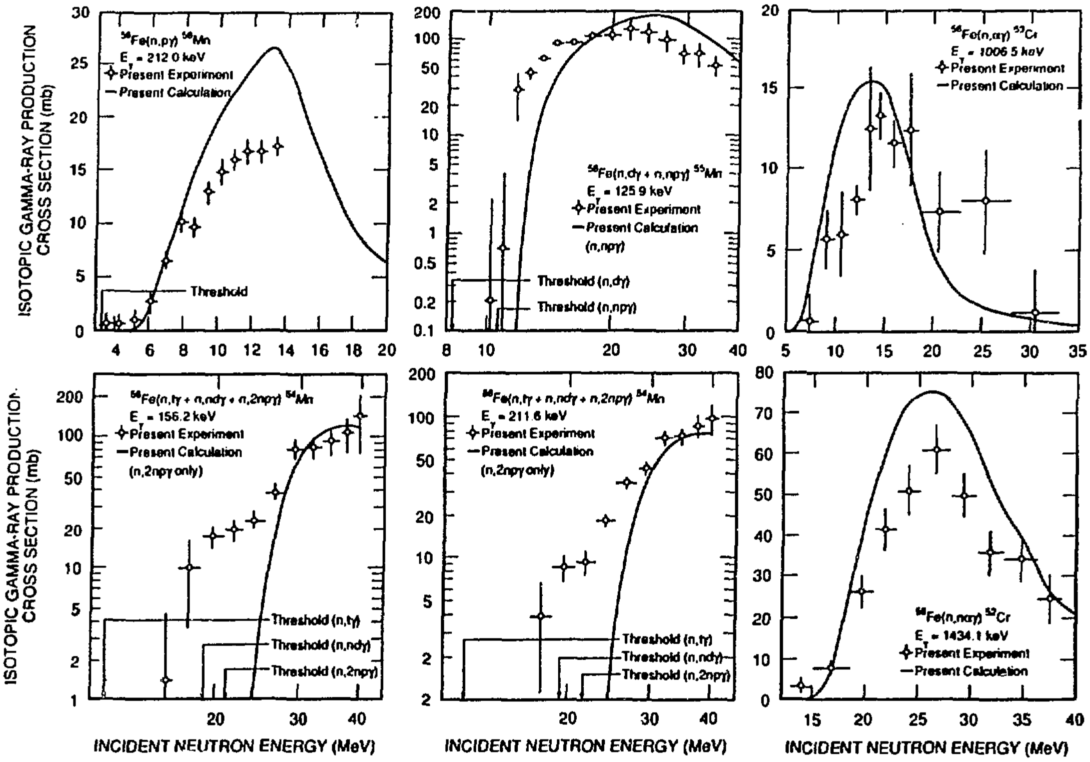

Fig. 2. Six experimental excitation functions involving secondary charged particles compared with calculations.

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