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Precision Measurements of ^{56}Fe Cross Sections for the 847-keV Gamma Transition

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INTRODUCTION

At the First Research Coordination Meeting of the IAEA/NDS CRP on Measurement, Calculation and Evaluation of Photon Production Data [cite{IAEA94}] an experiment to measure with high precision the cross sections of the production of the 847-keV gamma ray due to inelastic neutron scattering with iron was proposed [cite{dickens94}] and discussed. The main justification for the proposed improved precision was the need for improved calculations of radiation transport through thick iron components of nuclear reactors [cite{Fu91}], [cite{Pescarini94}]. Present evaluated data for the subject reaction in the ENDF/B-VI files [cite{Fu91}] have evaluated uncertainties $\approx 10\%$; consequently, the results of computation of deep penetration of radiation in iron can have quite large uncertainties -- larger than 100%, for example, for an attenuation of $\sim$ three orders of magnitude -- which can be a serious problem when one considers the magnitude of the radiation field inside a pressure vessel.

At the 2d Research Coordination Meeting of the IAEA/NDS CRP on Measurement, Calculation and Evaluation of Photon Production Data [cite{IAEA96}], a progress report of the proposed experiment was given [cite{dickens96}]. In it was reported that a substantial programmatic change by the sponsor resulted in the termination of full-time operation of the Oak Ridge Electron Linear Accelerator (ORELA) at the end of fiscal year (FY) 1994 putting the potential completion of the proposed experiment in some jeopardy since it had been initially anticipated that the experiment would require a minimum of six months of ORELA operation at the maximum power available during FY 1994. It was recognized that high-accuracy measurements could not be obtained concurrent with the improved incident-neutron-energy resolution of new measurements [cite{Märten95}]. So it was proposed that high-accuracy measurements could be made utilizing a "monoenergetic" neutron source, and a collaboration with scientists at the University of Kentucky Van de Graaff facility was offered. At this facility, nearly monoenergetic neutron beams are generated by pulsed protons impinging on gaseous tritium contained in a cell of 3 cm length at a pressure dictated by the experiment, usually at about a half an atmosphere. A spread in incident-neutron beam energy comes about partly by the energy loss of the protons traversing the 3-cm length and partly by kinematic spread because the neutrons are emitted at angles dictated by the size of the sample. It was anticipated that experimental data could be compared with a predicted group cross section obtained by folding the experimental neutron energy distribution with cross-section values in the current evaluations for iron.

COMPARISON OF FOUR EVALUATIONS FOR IRON FOR E_n BETWEEN 2 AND 4 MeV

Of the more than 100 experiments tabulated in the CINDA listing for photon production following neutron excitation of Fe [cite{CINDA97}], at least 80 report data in the incident-neutron energy range of 2.1 - 4.0 MeV. These data, along with Fe(n,n') data for the same incident-neutron energy range, have been subject to intensive evaluations efforts for several decades. The major evaluations are ENDF/B-VI (U. S.) [cite{Fu91}], JENDL-3.2 (Japan) [cite{JENDL94}], BROND-2 (Russia) [cite{BROND90}], and a recent evaluation from IRK (Vienna) [cite{IRK95}]. A comparison of the evaluated excitation functions for the 847-keV gamma-ray for $E_n > 2.1$ MeV (i.e. for $E_n >$ presently measured resonance-region data) should indicate how much, if any, need for new high-accuracy measurements.

All of the evaluations provide excitation functions for inelastic scattering of neutrons by ^{56}Fe and for excited states in ^{56}Fe at least to 4 MeV. To obtain the excitation function for the 847-keV gamma ray requires knowledge of the decay branching ratios for the deexcitation of excited states in ^{56}Fe . The ENDF/B-VI evaluation provides a set of evaluated branching ratios to be used with its evaluated set of individual-level cross sections. Similarly, the JENDL-3.2 evaluation provides a set of evaluated branching ratios which are somewhat different from those in the ENDF/B-VI evaluation; the cross section sets in the JENDL-3.2 evaluation are also different from those in the ENDF/B-VI evaluation. The BROND-2 evaluation provides a third, and different, set of evaluated set of cross sections; it does not, however, provide a set of evaluated branching ratios. So, for the purpose of comparison, the most recent set of evaluated branching ratios, given in the 8th Edition of the Table of Isotopes [cite{TOI96}], were used. The IRK evaluation does not provide evaluated branching ratios, and it provides evaluated excitation functions for individual excited states only for the lowest three excited states; it provides an excitation function for the 4th-to-7th excited states inclusive, and another for the 8th-14th excited states inclusive. For the purpose of obtaining an excitation function for production of the 847-keV gamma ray, "branching ratios" for deexcitation of the 4th-to-7th group were taken to be 0.992 for decay to the first-excited state and 0.008 to the ground state; for deexcitation of the 8th-to-14th group, "branching ratios" were estimated as 0.94 for decay to the first-excited state and 0.06 to the ground state. This latter estimate was needed only for the $E_n = 3.75$ MeV calculation.

For all four evaluations the evaluated inelastic scattering excitation functions combined with the (different) evaluated branching ratios were combined to obtain the "evaluated" 847-keV-gamma-ray production excitation functions, and these are shown in the figure for $2.1 \leq E_n \leq 4$ MeV. The disagreements are substantial. The closest agreement overall is for the ENDF/B-VI vis-a-vis the IRK evaluations; even so, the disagreement at $E_n = 2.7$ MeV is 5%. Indeed, it would appear that the $\pm 10\%$ overall uncertainty assigned to the ENDF/B-VI, mentioned in the Introduction, is not conservative.

Fig. 1. Evaluated Cross Sections for the Production of the 847-keV Gamma Ray Following Neutron Inelastic Scattering with ^{56}Fe .

Based upon the above discussion, it was decided that the experimental system at the University of Kentucky should be utilized to provide accurate photon-production cross sections for the incident neutron energy region $2.1 \leq E_n \leq 4$ MeV, a region in which a previous experiment [voss72] showed that the resonance structure in the excitation function of the 847-keV gamma ray is substantially damped, unlike the substantial resonance structure observed in this excitation function for $E_n \leq 2$ MeV.

Efforts have continued to determine accurately the constituency of the iron-boride sample. It was expected that the sample was a pure iron boride of chemical composition Fe_xB , where $x \approx 3$. However, because the original boron compound was B_4C , there has been some concern about possible carbon in the sample. Measurements and analyses of a transmission experiment carried out at the ORELA resulted in $x = 3.09 \pm 0.06$. Initial analyses using atomic emission spectra at Kentucky resulted in $x = 2.99$; however, this experiment is being redone so as to determine the uncertainty associated with the deduced value of x . An initial analysis of neutron backscattering carried out at the Van de Graaf facility at the University of Kentucky for the sample resulted in $x = 3.01$; the uncertainty still needs to be determined. In addition, a mass spectrum obtained at Kentucky shows the complete absence of masses 12 and 13, that is, there is no carbon in the sample. These results indicate that the multiple-scattering and neutron-attenuation calculation reported at the 2d CRP meeting, assuming a sample of iron boride having $x = 3$ and no carbon, can be used without further refinement of the model-sample constituency.

Over the past year, as time became available, gamma-ray pulse-height spectra were obtained for $1.6 \leq E_n \leq 3.9$ MeV at the Van de Graaf facility, and it was hoped that the data could be reduced in time for this report. However, it became apparent during the data reduction that there were problems in the experiment related, in some fashion, to an intermittent failure in the electronics. In addition, the background, while insignificant for a "10%" experiment, was troublesome for the accuracy needed for the present experiment. As a consequence it is planned to redesign the detector shielding and to test thoroughly the electronic system and recondition the BGO Compton anticoincidence detector before the next experimental runs.

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