IN-BEAM GAMMA-RAY SPECTROMETRIC MEASUREMENTS OF MULTI-BODY BREAKUP REACTIONS FOR E_n BETWEEN THRESHOLD AND 40 MeV

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ABSTRACT

A system for in-beam gamma-ray spectrometric measurements to study inelastic neutron scattering has been extended to increasing incident neutron energies to study multi-body breakup reactions on light and medium-weight elements. The (n,2nγ) cross sections are generally the largest; however, reactions of the types (n,αγ), (n,npγ) and (n,3nγ) have been observed. In addition to improved understanding of reaction channels studied by other techniques, this method provides data for some reactions, e.g. $^{56}Fe(n,3n)^{54}Fe$, which have not been observed previously.

1. Introduction

The Oak Ridge Electron Linear Accelerator (ORELA) is a pulsed source of neutron having energies between thermal and about 100 MeV. About twelve years ago we set up a system for high-resolution, in-beam gamma-ray spectrometric measurements based on a germanium detector. A schematic (not to scale) drawing of the experimental arrangement is shown in Figure 1.

Originally the goal of the experiments was to obtain data for elements of interest to fusion-energy development, and the region of incident neutron energy, E_n, of interest was between about 5 MeV and 20 MeV. The upper energy of 20 MeV was also the upper energy for the ongoing ENDF/B-VI evaluation. However, interest in such data for $E_n > 20$ MeV was already developing, and we discovered (and reported)[1] that measurements using the system could be extended into the higher incident neutron energies for some of the samples of interest. What was interesting as we explored this new energy domain was the observation of gamma rays readily identified with multibody breakup reactions. It was felt that study of these reactions was important to provide guidance not only for the ongoing evaluation efforts, but also as tests for extension of existing nuclear model codes designed to calculate reaction cross sections.[2]

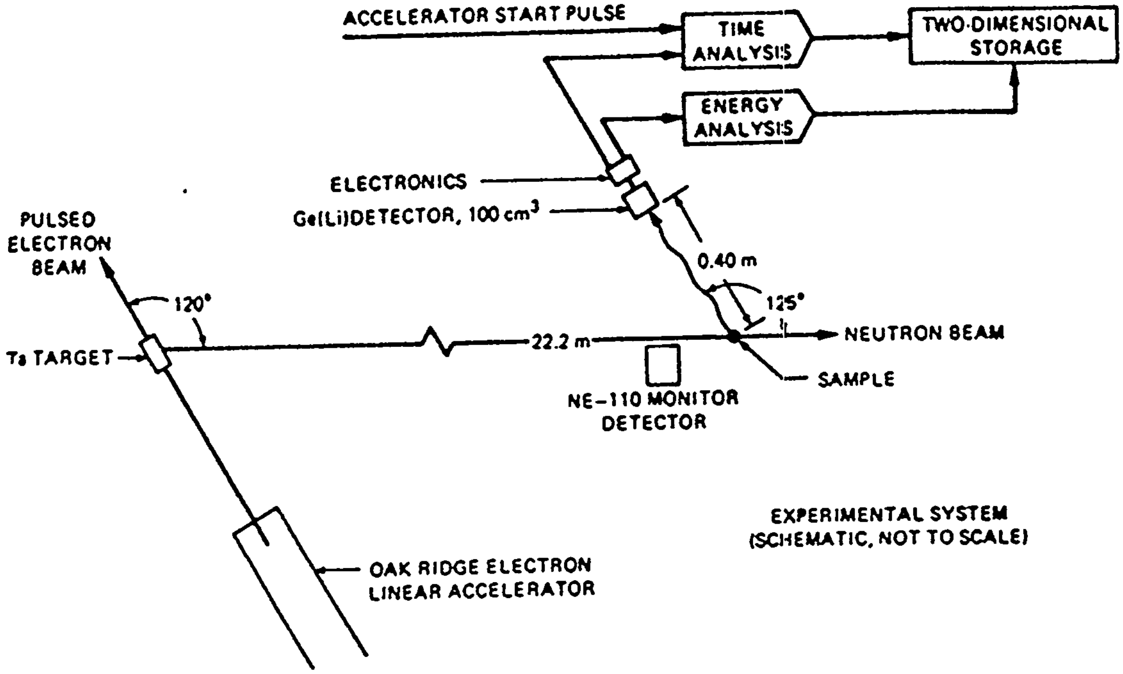

Figure 1. Schematic representation of the experimental station. Starting from the lower left of this figure, 140-MeV electrons produced by the Oak Ridge Electron Linear Accelerator (ORELA) impinged upon a tantalum converter (not shown separately) producing bremsstrahlung. Neutrons produced in the Be target by subsequent photonuclear reactions were guided to the experimental area by an evacuated, 10-m-long flight tube located at 120 degrees with respect to the incident electron beam. Collimeters were inserted into the flight tube to define the neutron beam to a diameter of 7.3 cm at the sample position. The beam traveled approximately 2 m in air before impinging on the sample. A small NE-110 scintillator intercepted approximately 1% of the incident neutron flux and was used as a beam monitor. Two types of pulses were extracted from the detector electronics. One was for energy analysis using standard very high resolution pulse-amplitude analyzing equipment. The other pulse was used for fast-timing analysis to determine the flight time of the neutron responsible for the detected gamma ray. The time-of-flight datum was correlated with the energy datum in a data-acquisition computer, which sorted and then stored events on a bulk storage disk pack.

2. Some Experimental Results and Analyses

The first set of data were obtained for a 7-gm sample of iron enriched in the isotope ^{57}Fe. A report[3] was published for most of the results of that study, primarily the cross sections for yields of gamma rays following inelastic scattering. However, interesting results were obtained for $^{57}Fe(n,2n)^{56}Fe$ reactions. The gamma-ray spectrum for E_n between 13.2 and 16.6 MeV is exhibited in Figure 2. The inset shows the level structure of ^{56}Fe. There are two point of interest: (a) the yield of the 846-keV gamma ray is substantial; and (b) gamma rays following decay of states in ^{56}Fe having $J^{\pi} = 6^{+}$ are observed with larger yields than gamma rays from decay of lower-lying states having smaller spin values not directly populated by transitions following decay of states having the larger spin values.

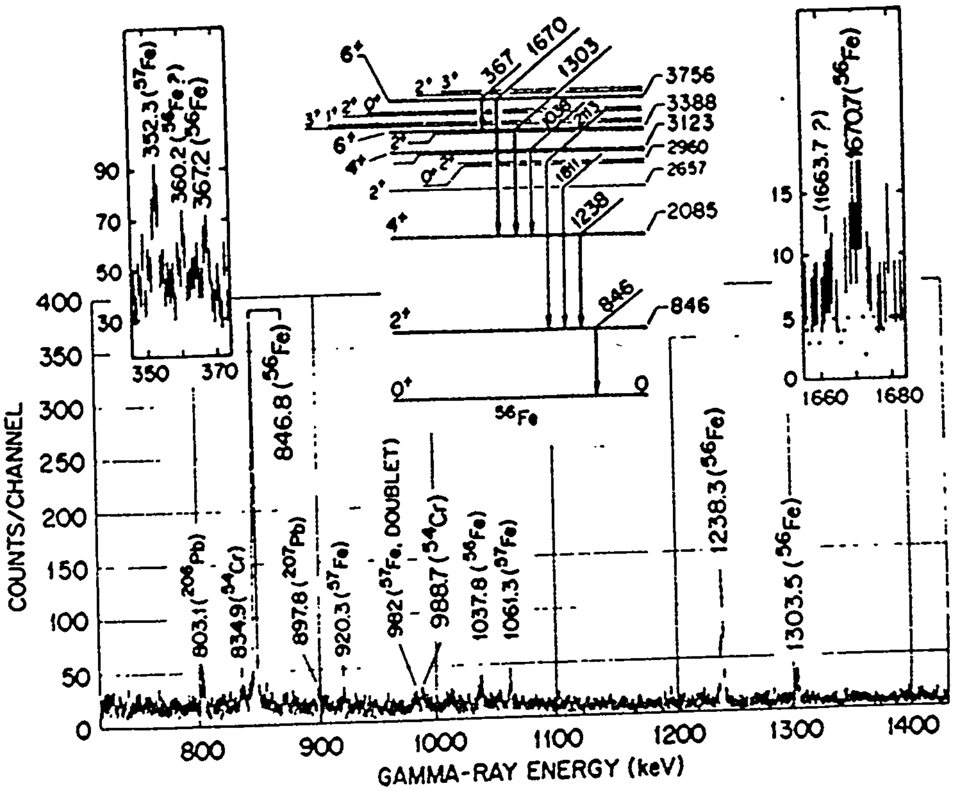

Figure 2. Spectrum of gamma rays for neutron interactions with ^{57}Fe for E_n between 13.2 and 16.6 MeV. The inset in the upper left corner exhibits data for E_γ ~ 367 keV, while the inset on the right side of the figure exhibits data for E_γ ~ 1670 keV. The level structure of ^{56}Fe is also shown, indicating the placement of the observed gamma rays associated with the ^{57}Fe(n,2nγ)^{56}Fe reaction.

The importance of the large isotopic yield of the 846-keV gamma ray (being ~ 1 b for E_n ~ 16 MeV)[3] is that this reaction increases the apparent yield of this gamma ray for an analysis of elemental Fe by a larger amount than might initially be inferred from the 2.1% isotopic abundance of ^{57}Fe in natural iron. This feature became a strong motivation for not only desiring isotopically enriched samples for experimental measurements, but also for performing evaluations[4] on each of the individual stable isotopes of Fe to obtain a more accurate picture of evaluated quantities of interest for the elemental evaluation.

The interest in the experimental observation of decay of levels having $J^\pi = 6^+$ is more physical. An explanation follows along these lines: the incident high-energy neutron may well impart a large angular momentum to the compound nucleus; however, the two emitted neutrons carry off very little angular momentum as they leave the compound nucleus, thus leaving the highly-excited residual nucleus, in this case ^{56}Fe, in a high spin state. To within the quantitative validity of this picture, it will be observed, then, that the E_γ = 846-keV photon production cross section for the ^{57}Fe(n,2n)^{56}Fe reaction represents only a small underestimate of the total cross section for this particular reaction, at least for E_n > the reaction threshold by several MeV.

The most thoroughly studied sample using this in-beam spectroscopy system has been a sample of Fe enriched to nearly 100% in the ^{56}Fe isotope. This measurement benefited by the improvement in the germanium detector from the original detector used for earlier experiments. The new detector was almost twice as efficient, and had about 10% better resolution. A typical photon spectrum, this one for E_n between 27 and 29 MeV, is shown in Figure 3. Peaks in this spectrum are identified with labels representing residual isotopes among Fe, Mn and Cr elements. Shown in Figure 4 are cross sections for the production of the E_γ = 1316-keV transition in ^{55}Fe from the $^{56}Fe(n,2n)^{55}Fe$ reaction compared with earlier measurements.[5,6,7] Similar excitations functions were determined for other multi-body reactions, and these along with some preliminary analyses have been reported.[8,9] Recently additional analyses of these data were carried out by McCollam;[10] he obtained better fits to the (n,nα) and (n,3n) experimental excitation functions, and these are exhibited in Figures 5 and 6. However, he was not able to improve on previous calculations for other measured multibody breakup reactions.

The status of measurements and analyses obtained in this experimental program is indicated in Table 1. Of the samples studied so far (excepting $^{56,57}Fe$), the high incident-neutron-energy data for ^{59}Co are the most advanced having been processed and reported[11] in preliminary form. The excitation function for the gamma-ray transitions representing $^{59}Co(n,np)^{58}Fe$ reactions is exhibited in Figure 7. As might have been anticipated *a priori* this reaction is quite dominant.

3. Future Plans

At present no future experimental effort is planned for the higher incident neutron energies. However, a considerable amount of data reduction and analysis remains to be accomplished just for the data already obtained.

4. Acknowledgments

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5. References

1. D. C. Larson, "High-Resolution Structural Material (n,xγ) Production Cross Sections for 0.2 < E_n ≤ 40 MeV," Nuclear Data for Basic and Applied Science, eds. P. G. Young, R. E. Brown, G. F. Auchampaugh, P. W. Lisowski, and L. Stewart (Gordon and Breach, New York, 1986), p. 71.

2. C. Y. Fu, Atomic Data and Nuclear Data Tables 17, 127 (1976); C. Y. Fu, "A Consistent Nuclear Model for Compound and Precompound Reactions with Conservation of Angular Momentum," in *Proc. Int. Conf. Nuclear Cross Sections for Technology, October 1979, Knoxville, Tenn.*, (Edited by J. L. Fowler, C. H. Johnson, and C. D. Bowman), p. 757, U.S. Gov't. Printing Office, Washington, DC; C. Y. Fu, *A Consistent Nuclear Model for Compound and Precompound Reactions with Conservation of Angular Momentum,* ORNL/TM-7042, Oak Ridge National Laboratory (1980).

3. Z. W. Bell, J. K. Dickens, J. H. Todd and D. C. Larson, *Nucl. Sci. Eng.* 84, 12 (1983).

4. C. Y. Fu, D. M. Hetrick, C. M. Perey, F. G. Perey, N. M. Larson, and D. C. Larson, "Description of Evaluations for ^{54,56,57,58}Fe Performed for ENDF/B-VI," in *ENDF/B-VI Summary Documentation*, comp. P. R. Rose, BNL-NCS-17541, 4th Edition [ENDF/B-VI] (1991).

5. V. J. Orphan, C. G. Hoot and V. C. Rogers, *Nucl. Sci. Eng.* 57, 309 (1975).

6. V. Corcalciuc, B. Holmqvist, A. Marcinkowski and G. A. Prokopets, *Nucl. Phys.* A307, 445 (1978).

7. Shi Xia-Min, Shen Rong-Lin, Xing Jin-Qiang and Din Da-Zhao, *Chinese J. Nucl. Phys.* 4(2), 120 (1982).

8. J. K. Dickens, J. H. Todd, and D. C. Larson, *Cross Sections for Production of 70 Discrete-Energy Gamma Rays Created by Neutron Interactions with ^{56}Fe for E_n to 40 MeV: Tabulated Data*, ORNL/TM 11671, Oak Ridge National Laboratory (1990).

9. J. K. Dickens, C. Y. Fu, D. M. Hetrick, D. C. Larson, and J. H. Todd, "Experimental and Calculated Excitation Functions for Discrete-Line Gamma Ray Production due to 1-40 MeV Neutron Interactions with ^{56}Fe," *Proc. Conf. on Nuclear Data Science and Technology*, ed., S. M. Qaim, Jülich, Germany (May 13-17, 1991).

10. K. J. McCollam, "Analysis of Fe(n,xγ) Cross Sections Using the TNG Nuclear Reaction Model Code," ORNL/TM-12358 (1993).

11. T. E. Slusarchyk, "Preliminary Cross Sections for Gamma Rays Produced by Interaction of 1-40 MeV Neutrons with ^{59}Co," ORNL/TN-11404 (1989).

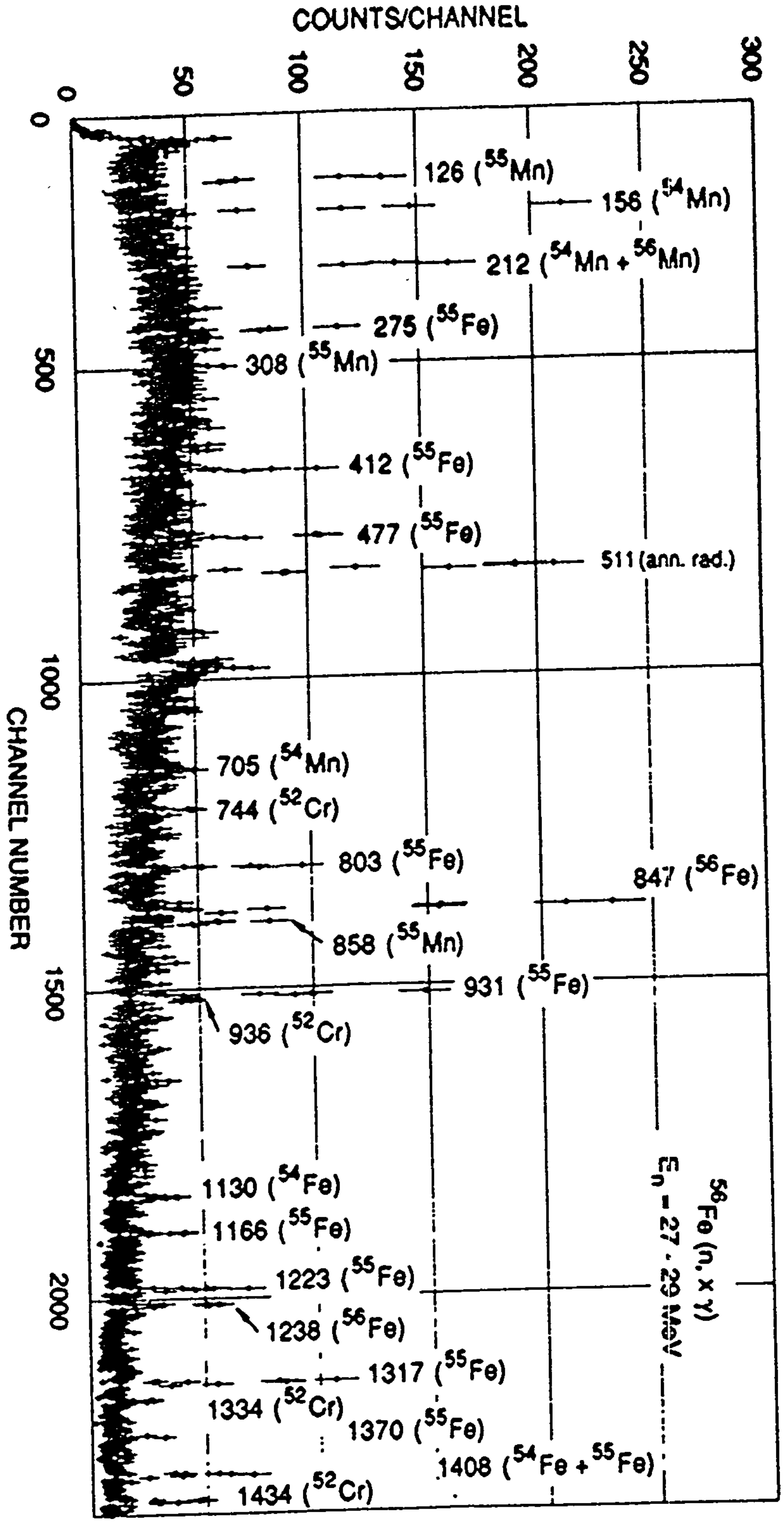

Figure 3. Pulse-height spectrum for 27 to 29 MeV neutron interactions with the ^{56}Fe sample. Gamma-ray peaks are labeled by the gamma-ray energy (keV) and the symbol of the residual nucleus. The experimental dispersion is ~ 0.6 keV/channel.

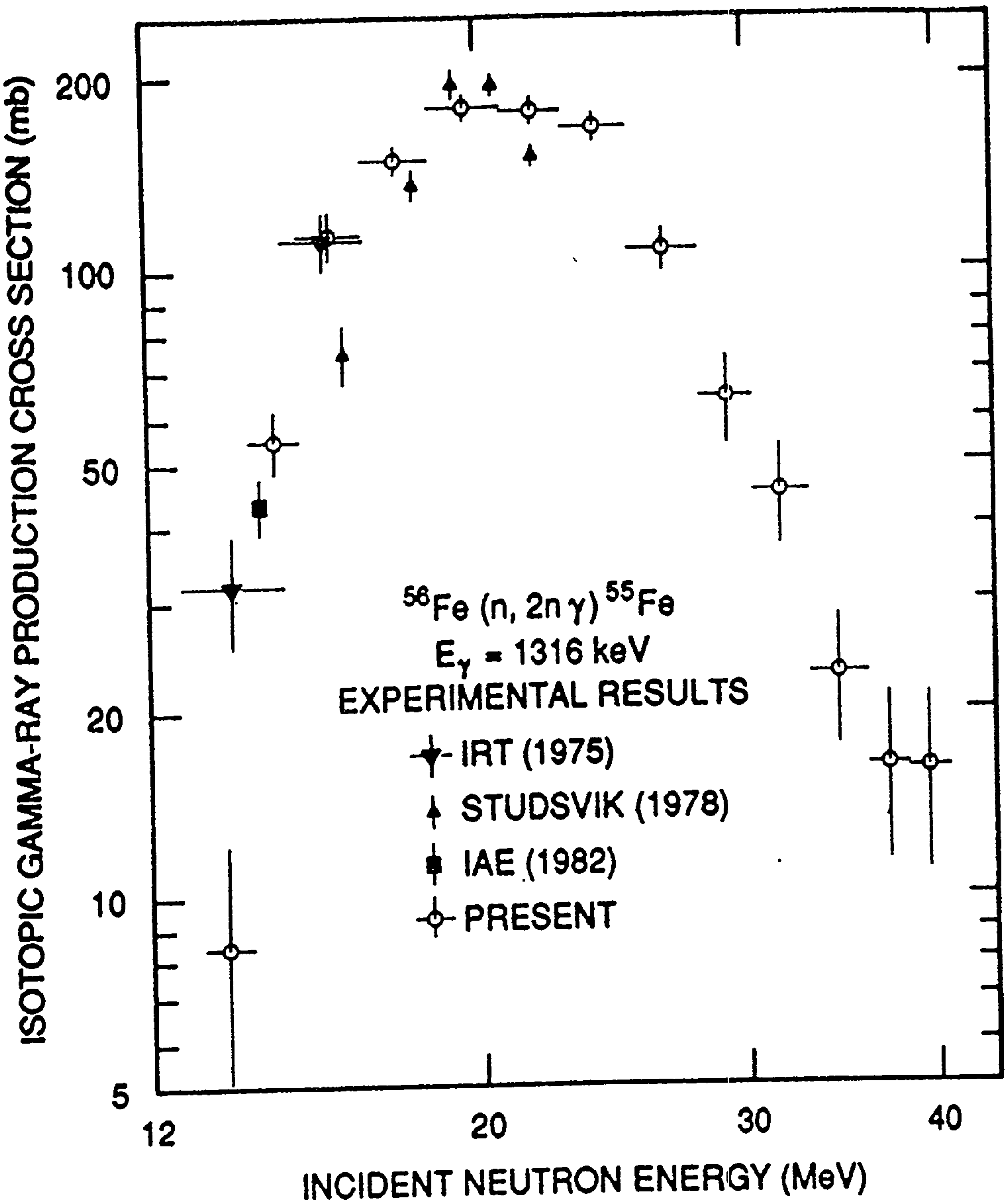

Figure 4. Isotopic cross sections for the production of the 1315-keV gamma ray. The present data (open circles) are compared with previous measurements (solid symbols) given as follows: IRT, Ref. 5, Studsvik; Ref. 6; and IAE (Beijing) Ref. 7.

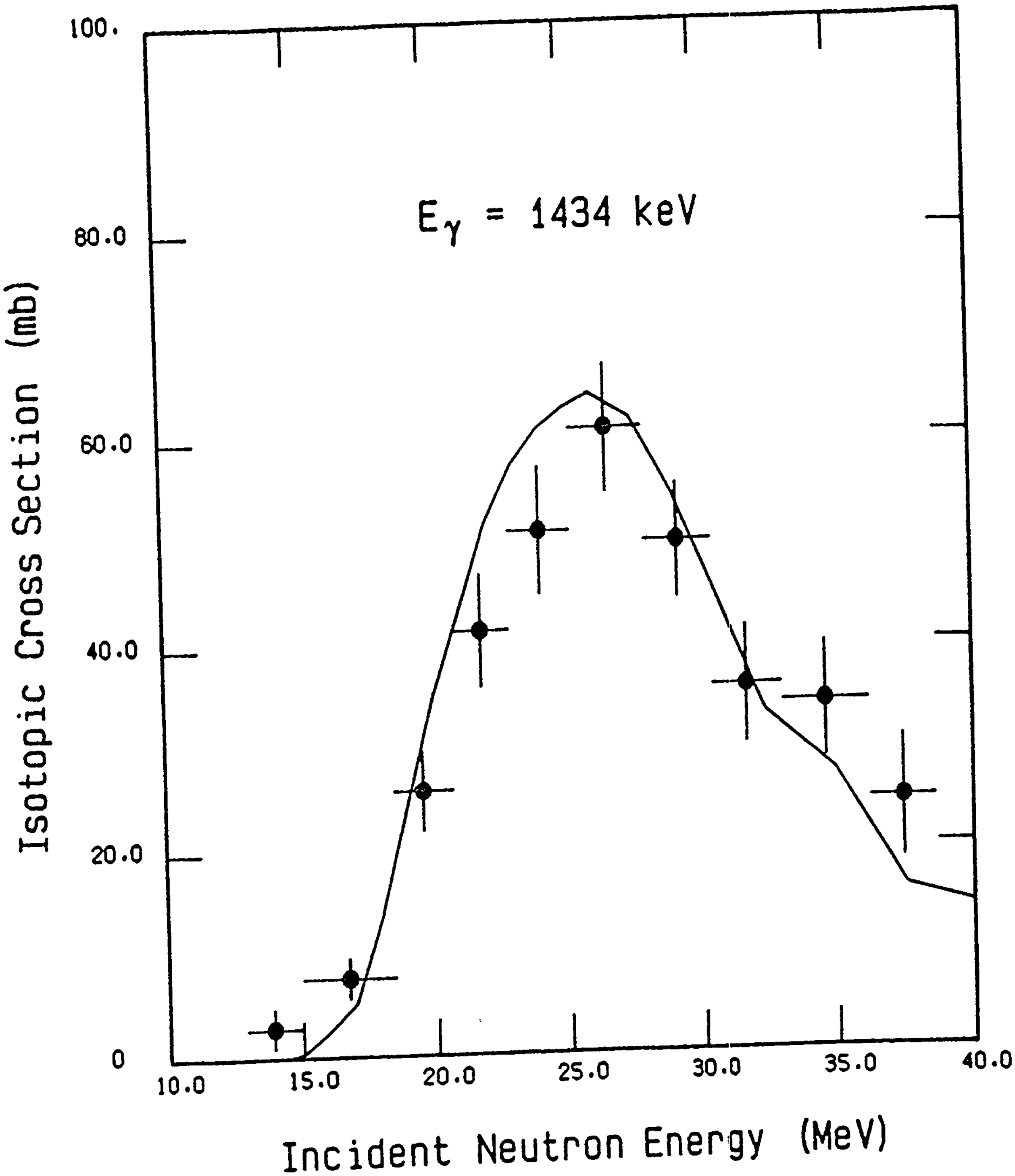

Figure 5. Excitation function for the $^{56}Fe(n,n\alpha)^{52}Cr$ reaction, E_γ = 1434 keV compared with results of a recent calculation[10] using the TNG program.[2]

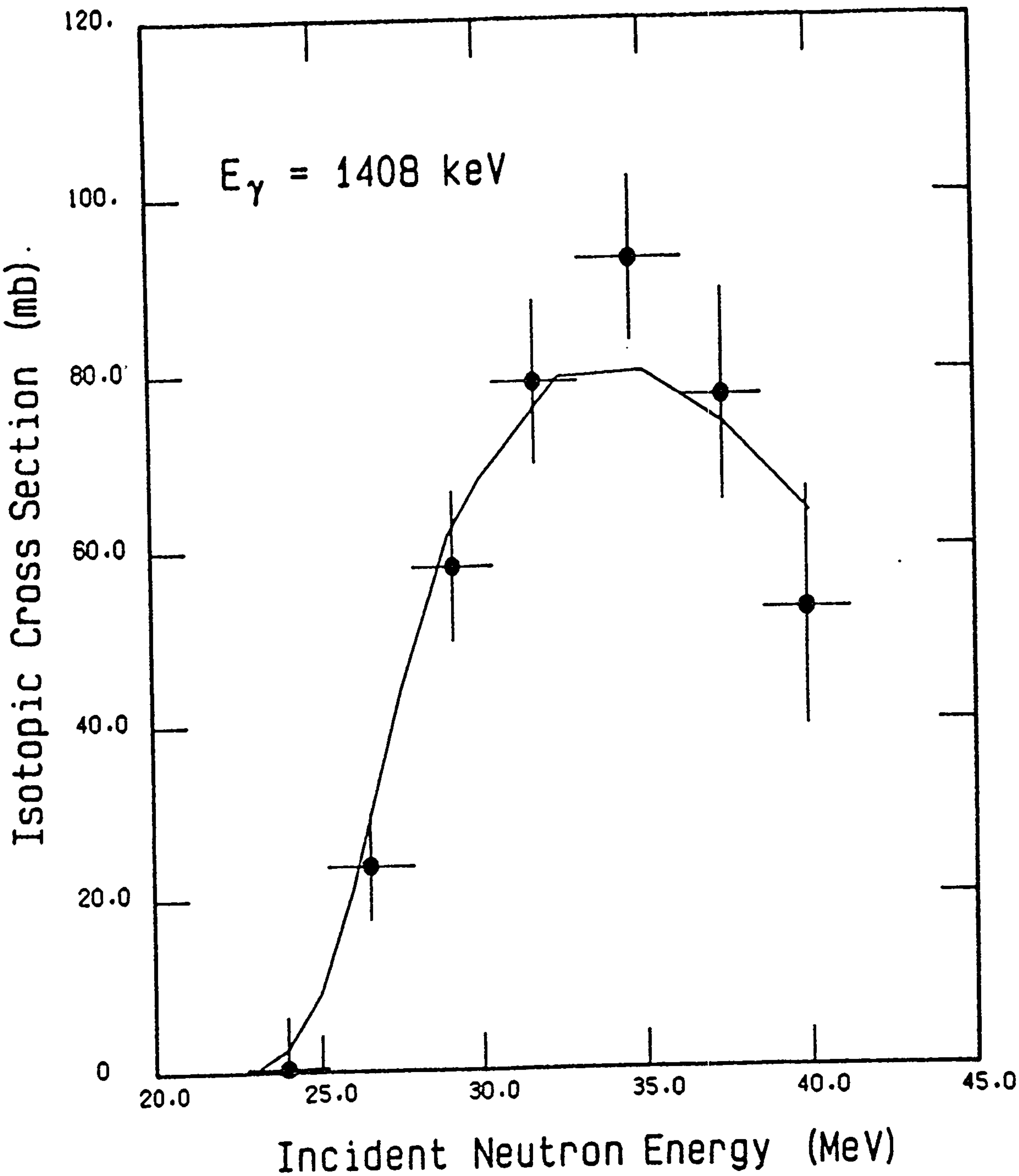

Figure 6. Excitation function for the $^{54}Fe(n,3n)^{54}Fe$ reaction, E_γ = 1408 keV compared with results of a recent calculation[10] using the TNG program.[2]

Table 1. Status of multi-body-breakup-reaction measurements and analyses at the ORELA facility

Sample	Status
^{11}B	Cross sections for $^{11}B(n,n\alpha\gamma)^{7}Li$ reported.[a]
^{51}V	Data obtained; data reduction not initiated.
^{nat}Cr	Data obtained; data reduction initiated.
^{53}Cr[b]	Data obtained; data reduction initiated.
^{54}Cr[b]	Data obtained; data reduction initiated.
^{56}Fe[b]	Cross section data reported;[c] first analyses reported;[d] further analyses reported.[e]
^{57}Fe[b]	Cross section data reported.[f]
^{59}Co	Preliminary cross section data reported.[g]
^{58}Ni[b]	Some spectral data reported;[h] data reduction not initiated.
^{nat}Ni	Data obtained; data reduction not initiated.

[a] J. K. Dickens and D. C. Larson, $^{10,11}B(n,x\gamma)$ Reactions for Incident Neutron Energies between 0.1 and 25 MeV," in *Nucl. Data for Sci. and Tech.,* Mito (Japan) May 30 - June 3, 1988, ed. S. Igarasi (Saikon Publ. Co. Ltd., Tokyo, 1988) p. 213.
[b] Sample enriched in given isotope.
[c] Ref. 8.
[d] Ref. 9.
[e] Ref. 10.
[f] Ref. 3.
[g] Ref. 11.
[h] Ref. 1.

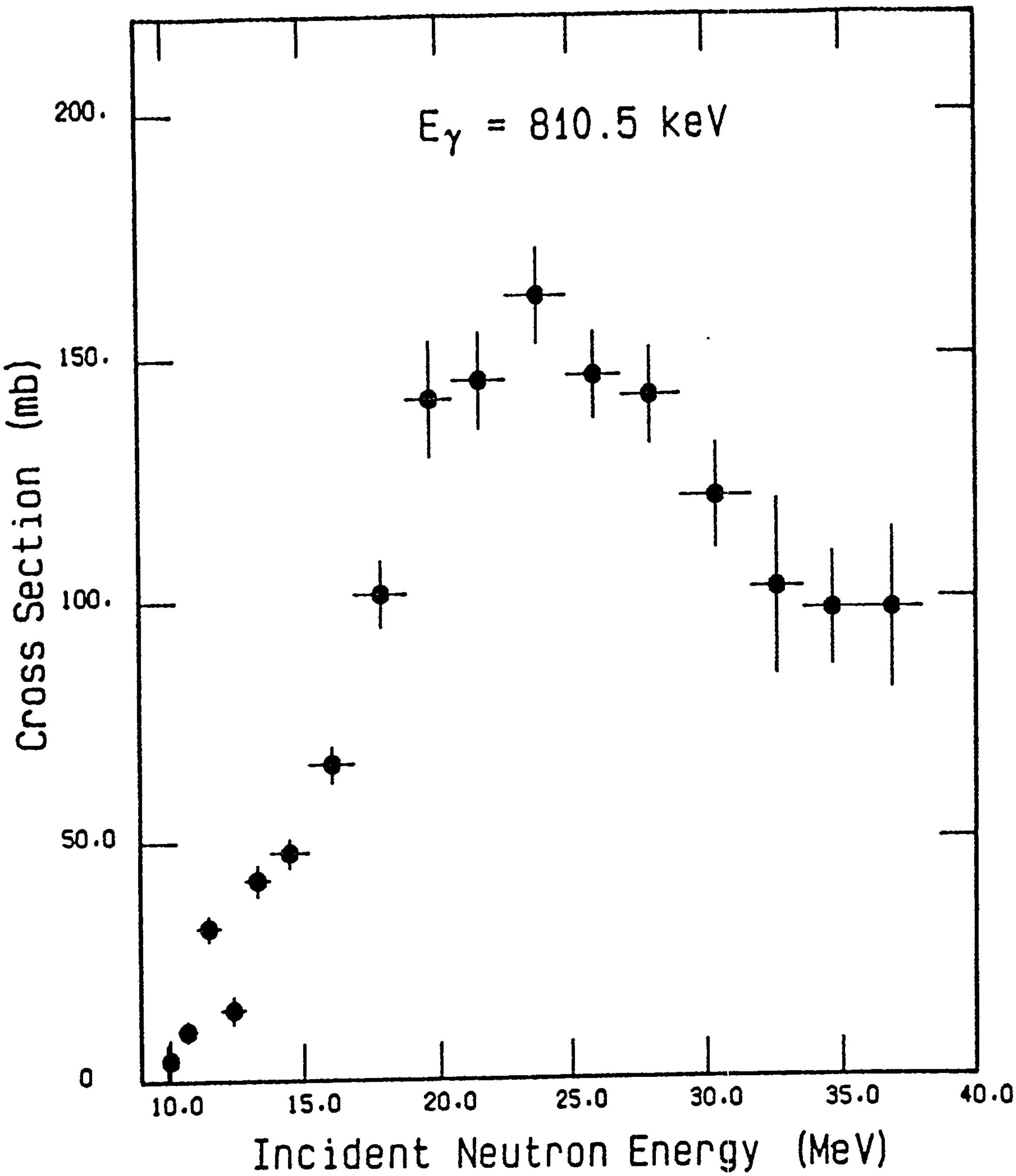

Figure 7. Preliminary excitation function for the $^{59}Co(n,np)^{58}Fe$ reaction, E_γ = 810.5 keV.