acta phys. slov. 26 (1976), No. 1

GAMMA-RAY PRODUCTION CROSS SECTIONS FOR THE ^{56}Fe(n, $n'\gamma$) REACTION FROM 2.5 TO 14.1 MeV NEUTRON ENERGIES[1]

JEAN LACHKAR*, JEAN SIGAUD*, YVES PATIN*, GÉRARD HAOUAT*,
Montrouge

Diferential production cross sections for γ rays from the ^{56}Fe(n, $n'\gamma$) reactions are presented for incident neutron energies between 2.5 and 14.1 MeV. The excitation functions of 17 γ-ray transitions were measured between 4.8 and 8.8 MeV incident energies in nine 0.5 MeV steps, and at an angle of 90 deg. Angular distributions were also measured of 13 prominent γ-rays at an 8.8 MeV neutron energy and for the 846.8 keV and 1238.3 keV γ rays at 2.5 and 14.1 MeV neutron energies.

Comparisons with previously published measurements and with the calculated cross sections of the Hauser-Feshbach formalism are presented. The agreement renders unnecessary the added contribution from a supposed continuum-like spectrum of unresolved final states. Such a contribution has been proposed in previous studies.

There are several reasons for measuring the ^{56}Fe(n, $n'\gamma$) production cross sections.

First, serious discrepancies exist between the results of the various studies of these reactions [1, 4]. A second and related problem appears to be in the analyses of those data. Although all groups adopt the statistical model as the correct approach for low incident energies, some authors require a contribution from a supposed continuum of γ-rays to unresolved final states of ^{56}Fe. Since that contribution is not a part of the measured results, its introduction can cast doubt on the effectiveness of the statistical model. To resolve this problem it is important to have a good knowledge of the ^{56}Fe level scheme; hence, extending the knowledge of that scheme is an important part of this work.

Our measurements were made for incident neutron energies E_n from 2.5 to 14.1 MeV, but we concentrated principally our effort on the range from 4.8 to 8.8 MeV. We were interested only in discrete γ-rays.

The D(d, n)^{3}He reaction is used to produce the neutron beam in the energy range 4.8–8.8 MeV. The incident deuterons are accelerated by the Tandem Van de Graaff accelerator installed at the Centre d'Études de Bruyères-le-Châtel. The beam is pulsed and benched so that 1 ns bursts at a repetition frequency of 2.5 MHz are avaliable. The average current is approximately 3μA. A 3 cm long gas target is used with a cooled entrance nickel foil (2.2 mg/cm^2 thick). The pressure of the gas in the target is 1 atm. The energy spread of the neutron beam is approximately 100 keV. At hight energy, neutrons from the D(d, n)^{3}He reaction are accompanied by neutrons from the deuteron break-up. However, for the 8.8 MeV neutron energy, the differential cross section at 0 degree of the deuteron break-up reaction is less than 10 % of the D(d, n)^{3}He reaction cross section.

The 2.5 and 14.1 MeV incident neutron beams are produced by the D(d, n)^{3}He and T(d, n)^{4}He reactions respectively, using a 550 keV Van de Graaff Accelerator and the associated particle method. The energy spreads of the neutrons are respectively 200 keV and 40 keV. The sample of natural iron is a cylinder of a diameter = 20 mm, a height = = 25 mm, set at 15 cm from the centre of the target.

Photons following the inelastic scattering of neutrons by the sample were detected by a gamma-ray spectrometer described in detail by **Chardine** et al. [6]. It is composed of a 67 cm^3 Ge(Li) detector situated inside a 305 × 305 × 80 mm hollow cylinder of NaI(Tl), split into four optically separated sectors. The central detector is a cylindrical true coaxial detector. The detector electronics allows the simultaneous recording of γ-ray pulse height spectra in two modes of operations:

1 — The Compton suppression mode in the range 0.5–8 MeV.

2 — The pair spectrometer mode for γ-ray energy above 1.1 MeV. We eliminate most of the background caused by direct neutrons with a tungsten shadow bar placed between the gas target and the spectrometer.

In order to reduce the background due to scattered neutrons and γ rays, a time-of-flight method is used. The typical flight path in nearly 1.8 m and the time resolution is 6 ns for γ-ray energies greater than 500 keV.

The neutron flux is determined using the n-p scattering cross section near 0 deg as a standard and is measured with a proton-recoil counter telescope.

For each event detected by the Ge(Li) detector, we record three pulses corresponding to the γ-ray energy, the output from the time to amplitude converter, and the gamma-ray detection mode. The data are stored on magnetic tapes, they are sorted off-line into pules height and time-of-flight spectra using a central computer. The peak positions, their F. W. H. M after shape fitting and their areas are determined with their uncertainties. The γ-ray differential production cross section is then obtained.

The gamma-ray transmission by the sample was calculated, assuming a uniform spatial distribution and parallel γ rays leaving the sample. The effects of incident flux attenuation and multiple scattering in the sample affect the measured yields in opposite directions and approximately cancel each other.

Absolute cross sections are given with an overall uncertainty varying between eight and twenty per cent.

As a first step, we associated each γ-ray transition with levels in ^{56}Fe. The level scheme proposed here is an extension of those deduced from the decay of ^{56}Co and ^{56}Mn previously reported [7, 8]. We also used results of a (p, $p'\gamma$) correlation experiment performed in conjunction with this study [5].

Neutron-induced γ-ray production measurements were undertaken for eleven energies in the range 2.5–14.1 MeV. New results of this study which extend our knowledge of the ^{56}Fe level scheme are given in another paper [4]. All the observed transitions are presented in Fig. 1.

We measured differential cross sections at 90 deg for 17 de-excitation γ rays of ^{56}Fe. Our γ-ray line data are compared with those of ORNL group of **Dickens** et al. [2] in

---

[1] Contribution presented by **D. Didier** at the International Symposium on Neutron Induced Reactions, September 2–6, 1974 at SMOLENICE, Czechoslovakia.

* Service de Physique Nucléaire Centre dÉt'udes de BRUYÈRES-LE-CHÂTEL, B. P. n° 61 — 92120 MONTROUGE, France.

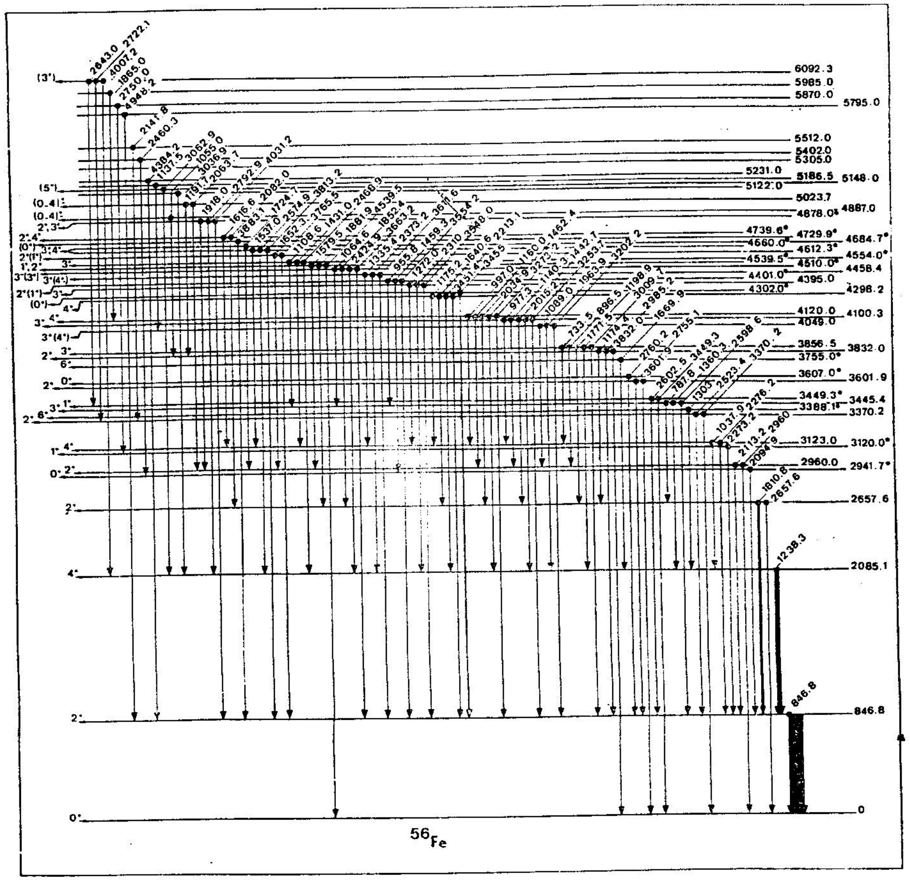

Fig. 1. Proposed level scheme of ^{56}Fe. The levels which are denoted with an asterisk have at least one characteristic determined from these measurements.

Fig. 2 after correcting their results for the isotopic abundance of ^{56}Fe in natural iron. An overall good agreement is found.

Angular distributions of the main γ rays were obtained for neutron energies of 2.5, 8.8 and 14.1 MeV. For 8.8 MeV neutron energy, the angular distributions of 13 γ rays are given in Fig. 3, where the points at 55 deg and at 90 deg of the ORNL group [2] are also plotted. The overall agreement is good. When our results are compared with those of authors other than the ORNL group [1, 3], substancial discrepancies appear.

For two incident neutron energies, 6.3 and 7.3 MeV, we have summed the cross sections of all the discrete lines present in the ^{56}Fe(n, $n'\gamma$) reaction. These results are compared to the summed line data of Dickens, Morgan and Perey [2], and to their results unfolded from white-source measurements. Our results are contained between their two kinds of measurements. Our results agree within experimental errors with their summed line data. The agreement obtained between our experimental data and our theoretical calculations renders unnecessary the large continuum contribution postulated by Orphan et al. [1] and Drake et al. [3]. Rather our data support the conclusion that, for iron an up to 7.3 MeV neutron energy, the continuum-like spectrum composed of unresolved transitions makes a small contribution, not greater than 15 % of the summed cross sections for discrete lines.

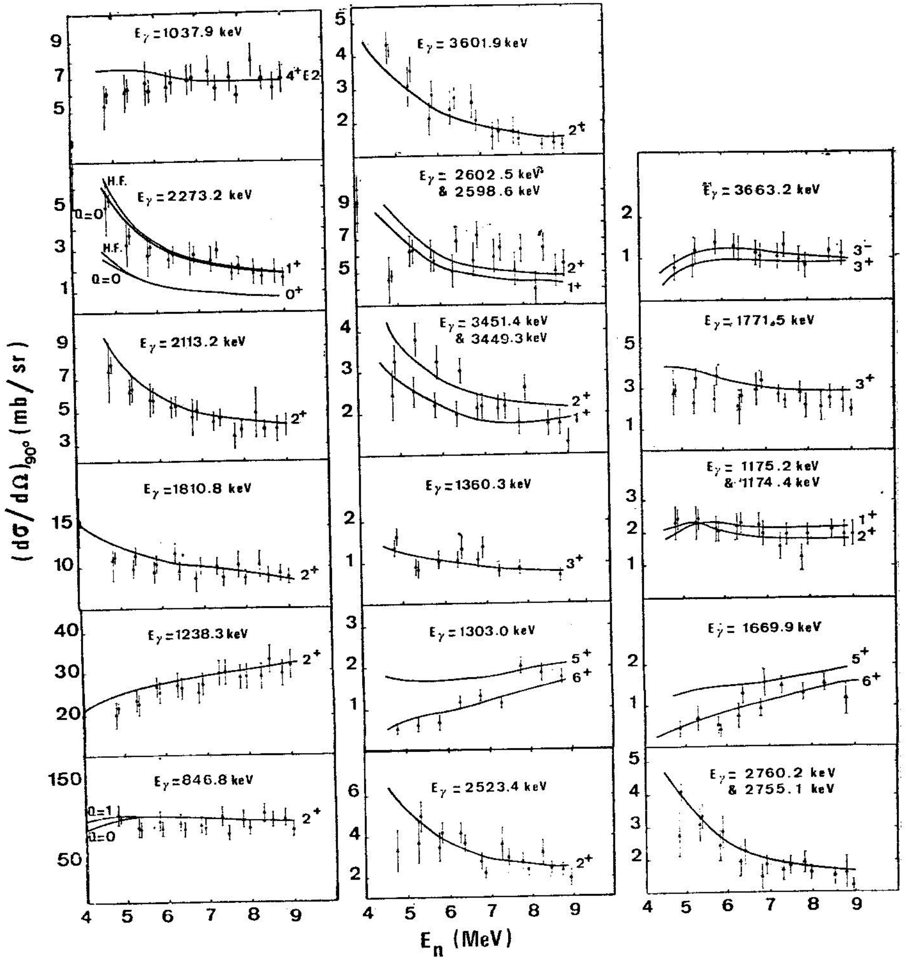

Fig. 2. Isotopic excitation functions measured at 90 deg for 17 γ-ray from the ^{56}Fe(n, $n'\gamma$) reaction. Triangles, ▲, are our measurements; points, ●, the data of Dickens et al. [2]; squares, ■, the measurements of Benjamin et al. [12]; the solid line corresponds to our theoretical calculations using several sets of spins, parities and multipole mixing ratios. The adopted spin and parity are gathered for each level in Fig. 1.

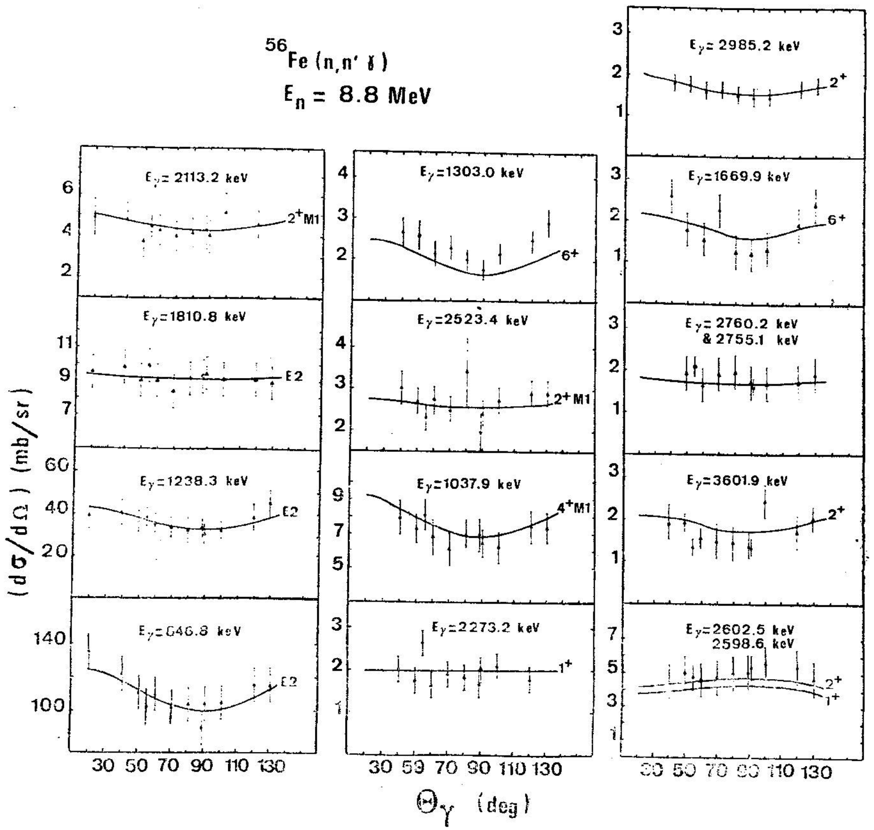

Fig. 3. Angular distributions measured for 13 γ rays for an 8.8 MeV neutron energy. The following conventions are used: triangles are our measurements, points the data of Dickens et al. [2], solid lines correspond to our theoretical calculations.

It is well established that in the lower part of this energy range the statistical model is predominant. For excitation energies reached in the compound nucleus so many resonances contribute to the reaction that the statistical hypotheses of Hauser and Feshbach [9] are well fulfilled.

In order to interpret theoretically our experimental results we have written a program giving the angular correlation function between inelastically scattered particle and de-excitation γ rays. This program enables the calculation of total and differential cross sections of inelastically scattered nucleons and following a de-excitation radiation with or without unobserved intermediate transitions, employing the statistical model.

The transmission coefficients needed in this calculation are computed from an optical model subroutine with spin — orbit coupling. We have introduced as exit channels only the levels observed in our experimental study, in preference to the method which includes a continuum of unresolved final states [10]. Owing to the good knowledge of the ^{56}Fe level scheme, a good agreement between the experimental and calculated differential cross sections at 90 deg is obtained up to 9 MeV. This can be seen in Fig. 3, where the solid curves reproduce our theoretical calculations.

Up to a 5 MeV neutron energy, we must include width fluctuation corrections [11]. The best fits to our data are obtained for a low Q value. This conclusion was previously deduced from lower energy range measurements in (n, n') experiments [11]. Theoretical angular distributions of γ rays were also calculated. Multipole mixing coefficients were deduced from this study in cases they were not known before these experiments. In our calculation we have taken into account exactly the contribution of one or two unobserved intermediate γ-ray transitions. For components which have more than two unobserved cascades, we suppose an isotropic contribution to the succeeding γ-ray angular distribution for that component. The comparison of our experimental and calculated values is presented in Fig. 3, for the neutron energy of 8.8 MeV.

Differential cross sections for the production of 17 γ-rays from the ^{56}Fe$(n, n'\gamma)$ reactions have been measured for eleven incident neutron energies in the range 2.5—14.1 MeV. They are in rather good agreement with the results of the ORNL experiments in which discrete transitions were resolved. The good agreement would seem to resolve the uncertainty about the ^{56}Fe$(n, n'\gamma)$ cross sections between 4.8 and 8.8 MeV. Moreover data at 2.5 MeV and 14.1 MeV neutron energies have been obtained in this experiment.

Angular distribution for 17 γ-rays were also recorded at 3 neutron energies: 2.5, 8.8 and 14.1 MeV. Several new levels were discovered in ^{56}Fe. Most of the measured cross sections have been compared to predictions of the Hauser-Feshbach formalism, with width fluctuation corrections included. These calculations provide a good and consistent description of the ^{56}Fe$(n, n'\gamma)$ reaction up to a 9 MeV incident energy, when all of the observed γ rays are taken into account. The agreement obtained renders unnecessary the hypothesis of a continuum contribution to unresolved levels.

REFERENCES

[1] Orphan V. F., Hoot G. C., John J., 3^{rd} *Conf. Neutron Cross Sections and Technology.* Knoxville, Tennessee, March 15—17, 1971 CONF-710301, Vol 1, 227.

[2] Dickens J. K., Morgan G. L., Perey F. G., Nucl. Sci. Eng. *50* (1973), 311.
Dickens J. K., Morgan G. L., Perey F. G., *Gamma-ray Production Due to Neutron Interactions with Iron for Incident Neutron Energies between 0.8 and 20 MeV: Tabulated Differential Cross-sections, ORNL-4798,* 1972.

[3] Drake D. M., Hopkins J. C., Young C. S., Condé H., Nucl. Sci. Eng. *40* (1970), 294.

[4] Lachkar J., Sigaud J., Patin Y., Haouat G., Nucl. Sci. Eng. (*to be published*).

[5] Lachkar J., Sigaud J., Patin Y., Haouat G., Nucl. Phys. *A 222* (1974), 333.

[6] Chardine J., Haouat G., Humeau C., Lachkar J., Sigaud J., Rapport Commissariat à l'Energie Atomique, *CEA-R-3747* (1967).

[7] Camp D. C., Meredith G. L., Nucl. Phys. *A 166* (1971), 349.

[8] Vaugham K., Pate B. D., Shapiro M. H., Nucl. Phys. *A 130* (1969), 62.

[9] Hauser W., Feshbach M., Phys. Rev. *87* (1952), 366.

[10] Bloom S. D., Green J. M., Hubbard H. W., Moszkowski S. A., Nucl. Sci. Eng. *46* (1971), 255.

[11] Moldauer P. A., Rev. Mod. Phys. *36* (1964), 1079.

[12] Benjamin R. W., Buchanan P. S., Morgan I. L., Nucl. Phys. *79* (1966), 241.

Received September 9th, 1974