

⁵⁶Fe AND ⁶⁰Ni RESONANCE PARAMETERS

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Abstract: High-resolution neutron transmission and differential elastic-scattering measurements were made for a ⁵⁶Fe-enriched iron target at the Oak Ridge Electron Linear Accelerator (ORELA). A natural iron target was used for transmission measurements below 160 keV. The data were analyzed from 5 to 850 keV. Parameters were obtained for 33 $\ell = 0$ and 242 $\ell > 0$ resonances. New ⁶Li-glass transmission data were acquired for two ⁶⁰Ni-enriched sample thicknesses. The neutron width for the 2.253-keV resonance was determined to be 59.3 ± 0.6 meV and the radiation width 553 ± 50 meV.

(⁵⁶Fe and ⁶⁰Ni transmission measurements, ⁵⁶Fe differential elastic-scattering measurements, R-matrix analyses below 850 keV, resonance parameters)

Introduction

Analysis of the ⁵⁶Fe Data

The ENDF/B-V evaluation for the resonance parameters of ⁵⁶Fe covered the energy region below 400 keV. New ORELA 200-m transmission and differential elastic-scattering measurements were used to update the resonance region and extend it to 850 keV [1]. In this note we present some of the results of this work. We also present precise resonance parameters for the 2.253-keV resonance of ⁶⁰Ni based upon new ⁶Li-glass 80-m transmission data which supersede our earlier results [2] for this resonance.

The transmission data were analyzed with the multilevel R-matrix (Reich-Moore) code SAMMY [3]. SAMMY is a constrained least-squares code which uses Bayes' theorem for the fitting process. Two main data sets were analyzed between 5 and 850 keV (see Table 1). Fit to the data was achieved with channel radii of 5.437 fm for the *s*- and *d*-wave resonances and 4.896 fm for the *p*-waves.

Data Acquisition and Data Processing for ⁵⁶Fe

In order to insure that the resonance parameters based upon the analysis of the 200-m data would produce acceptable thermal scattering cross sections, data based upon transmission measurements made with a ⁶Li-glass detector at the 17- and 80-m flight path stations were also used in the fitting process below 2 keV.

Transmission and elastic-scattering measurements were made at the 200-m flight path station by the time-of-flight technique using neutron pulses from the ORELA water-moderated tantalum target.

A sample of the fit to the total cross section data is shown in Fig. 1.

Two transmission measurements were made: one with unmoderated neutrons directly from the tantalum and the other with moderated neutrons. Two sample thicknesses and burst widths were used (see Table 1).

The differential elastic-scattering data were used as the principal tool to determine the spin and parity of the $\ell > 0$ resonances. The theoretical cross sections were calculated as a function of the incident neutron energy with the R-function code RFUNC [4] and compared to the experimental data at the six scattering angles. For a given resonance, various combinations of spins and parities were tested. The one which yielded the best agreement with the data was adopted.

The measurement with moderated neutrons was made on a natural iron sample. Transmission data from 2 to 163 keV were obtained using a 1-cm-thick NE-110 scintillator epoxy-coupled to two 12.5-cm-diameter RCA 8854 photomultipliers. The measurement on a ⁵⁶Fe sample was made with an "effective" sample enrichment of 99.92% ⁵⁶Fe and covered the energy region from ≈ 100 keV to 20 MeV. Unmoderated neutrons from the tantalum target were used. A 2.5-cm-thick NE-110 scintillator also mounted between two RCA 8854 photomultipliers was used as the detector.

The differential elastic-scattering data and theoretical curves for three of the six scattering angles are plotted in Fig. 1 from 550 to 600 keV. Figure 1 illustrates the usefulness of the differential data in assigning the spin and parity of resonances. The resonance at 561.4 keV (on top of an *s*-wave resonance) is fitted as a $p_{3/2}$ resonance in our analysis (underlined in Fig. 1, left). From the analysis of their 400-m transmission data Cornelis et al. [5] recommended a $d_{3/2}$ assignment for this resonance. With a $d_{3/2}$ assignment the fit to the transmission data is just slightly degraded but the agreement with the differential elastic-scattering data is lost as shown in Fig. 1, right. This demonstrates that the transmission data alone cannot always be depended upon to provide determination of spins and parities of $\ell > 0$ resonances.

The data were corrected for the deadtime (1104 ns) of the digitizer and for various backgrounds.

The scattering measurements, covering the ≈ 10 -keV to 5-MeV energy region, were made with filters and collimators which allowed both unmoderated and moderated neutrons to reach the sample made of 123.4 g of iron enriched to 99.87% in ⁵⁶Fe. The sample was a hollow cylinder suspended at the center of the scattering chamber. Six neutron detectors were located 19.1 cm from the center of the chamber at various angles from the direction of the incident neutron beam. Later one was placed in the direct beam to measure the product of the flux and the detector efficiency. Each neutron detector consisted of a NE-110 cylinder which was viewed at each end by RCA 8850 photomultiplier tubes.

All spectra were normalized by means of a neutron monitor detector and corrected for deadtime, constant room background, and geometrical factors to deduce a relative differential scattering cross section with an uncertainty of $\approx 5\%$.

Table 1. Summary of the 200-m data analyzed

Sample	Energy range (keV)	Burst width (ns)	Average sample thickness (at/b)
<u>Transmission data</u>			
^{nat} Fe	5 to 120	7	0.2144 \pm 0.0005
⁵⁶ Fe	120 to 850	4.5	0.2227 \pm 0.0005
<u>Differential elastic-scattering data</u>			
⁵⁶ Fe	40 to 850	6	0.0677 \pm 0.0020

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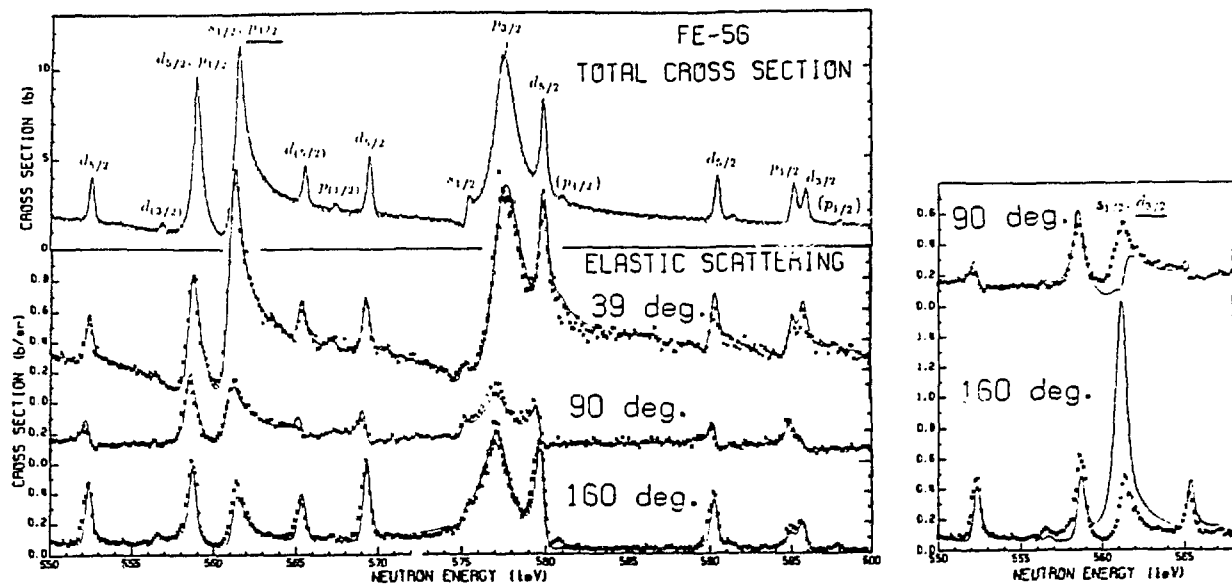


Fig. 1. Left: Sample of the fit to the total cross-section data and comparison of the elastic-scattering data at three angles with theoretical calculations. Parentheses indicate uncertain spin and parity assignments. Right: Comparison with the data when the $p_{3/2}$ resonance, at left, underlined, is changed to a $d_{3/2}$ resonance as recommended by Cornelis et al. [5]

Results for ^{56}Fe

Results of the simultaneous analyses of the transmission and differential elastic-scattering data were combined with the results of the ^{56}Fe capture data analysis of Corvi et al. [6] which extends to 350 keV. We reported parameters for 302 resonances in the 1- to 850-keV energy range [1], of which 26 were seen only in the capture data.

Thirty-three resonances were assigned as s -wave resonances. From the analysis of differential scattering data the orbital angular momentum, ℓ , of 184 resonances were definitely assigned, i.e., 76% of the $\ell > 0$ resonances analyzed in the transmission data. Eighty-five are p -wave and 99 are d -wave resonances. The spin, J , of 81% of the 85 p -wave resonances can be assigned with some degree of confidence but only 63% of the 99 d -wave resonances could be given a definite spin assignment.

The average radiation widths for the $\ell = 0, 1, 2$ resonances below 350 keV are 0.92 ± 0.41 eV, 0.45 ± 0.23 eV, and 0.75 ± 0.27 eV, respectively.

From the comparison of the distribution of the normalized reduced neutron widths of the 33 observed s -wave resonances with a Porter-Thomas distribution we conclude that up to four narrow s -wave resonances could have been missed. The average level spacing for the s -wave resonances, D_0 , is given in Table 2 and compared with values obtained from three earlier analyses [5,7,8]. The normalized distribution of the s -wave level spacings is in good agreement with a Wigner distribution.

The plot of the cumulative sum of the s -wave reduced neutron widths as a function of energy, given in Fig. 2, reveals that almost 50% of the observed strength lies in two small energy intervals that span less than 10% of the energy range analyzed. Consequently, the s -wave strength function, S_0 , based upon the total strength observed up to 850 keV is larger than the one based upon the strength observed only up to 360 keV (see Table 2). The two conspicuous large steps in the staircase plot could indicate the presence of particle vibration doorway states.

The final resonance parameter set generates the thermal capture and total cross sections recommended by Mughabghab et al. [9].

Table 2. Resonance parameter statistics for s -wave resonances compared with results of three earlier analyses

Source	Energy range (keV)	D_0 (keV)	S_0 (10^{-4})
Present work	5-850	25.4 ± 2.2	2.3 ± 0.6
Present work	5-360		1.7 ± 0.7
Cornelis et al. [5]	40-850	25.5	
Cornelis et al. [5]	240-850		2.6 ± 0.8
Cierjacks et al. [7]	450-900	19.6 ± 1.8	2.6 ± 0.8
Pandey et al. [8]	10-500	$25. \pm 5.$	2.6 ± 0.9
Pandey et al. [8]	10-200		1.9 ± 0.9

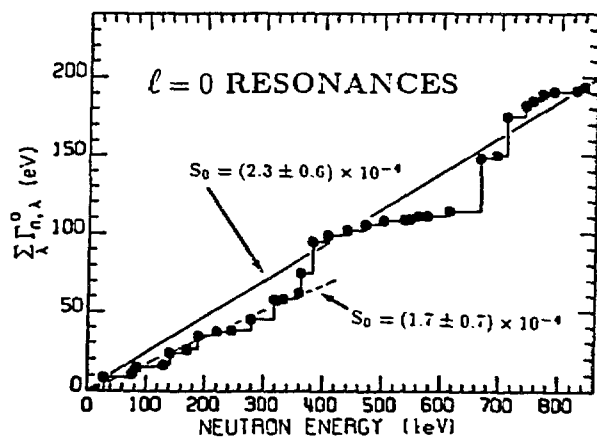


Fig. 2. Sum of the reduced neutron widths for s -wave resonances as function of incident neutron energy.

Transmission measurements have been made on two ^{60}Ni metal samples, enriched to 99.68%, using an improved two phototubes ^6Li -glass scintillation detector located at the 80-m flight-path station. This ^6Li -glass detector has a much better resolution function than the single photomultiplier detector used in the earlier measurements [2]. Also the metal samples were cast in a reducing atmosphere, whereas the samples in the earlier measurements were pressed powder which may have contained some oxide or water. The diameters of the samples were 2.54 cm with thicknesses of 0.0293 and 0.0537 atoms/barn respectively. The electron beam burst was 20 ns wide producing a beam power of 18 kw at 400 Hz. The earlier measurements had used 40-ns-wide bursts at 1000 Hz.

Since the sample thicknesses were different from those in the previous measurements, the two sets of transmission data cannot be directly compared. In the energy range from 1 to 5 keV the new data yield total cross sections that are about 0.1 barn smaller than those based upon the old data. The ORELA target moderation length and the detector resolution used in the earlier analysis is now realized to have been too small. Although the neutron width of the 2.25-keV resonance is insensitive to this resolution, it resulted in too large a value for its total width. The new transmission data for the two sample thicknesses are very consistent with each other and yield a substantially larger value for the neutron width of this resonance. Furthermore, the resonance parameter analysis of the new transmission data down to 500 eV yields the known thermal scattering cross section.

Our earlier resonance parameter analysis was updated for ENDF/B-VI using the new ^6Li -glass transmission data up to 115 keV and the old NE-110 transmission data above this energy. This analysis yields for the 2.25-keV resonance, with a $p_{1/2}$ assignment, a radiation width of 553 ± 50 meV, and a neutron width of 59.3 ± 0.6 meV (see Fig. 3). We have therefore obtained from a transmission experiment the capture area in this resonance to an accuracy of about 1%. This result should be useful in testing the consistency between transmission and capture experiments.

Conclusions

The purpose of this work was to extend the resolved resonance energy region for the ^{56}Fe ENDF/B-VI evaluation and to improve upon the low energy resonance

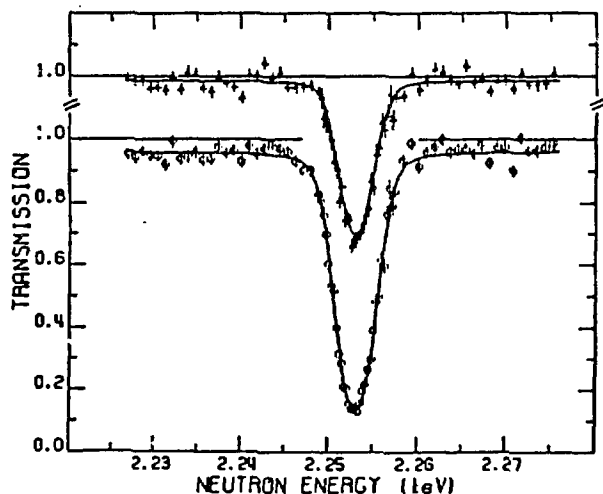


Fig. 3. Fits to the transmission data in the neighborhood of the 2.25-keV resonance.

region for ^{60}Ni , in particular the parameters of the 2.25-keV resonance.

The ^{56}Fe report [1] on which part of this publication is based gives resonance parameters for an energy range twice as large as the one covered in the previous evaluation. These resonance parameters provide a complete and accurate description of the scattering cross section from thermal to 850 keV and are consistent with the accepted values for the thermal total and capture cross sections. Our parameters were compared with those obtained at other laboratories. In general, agreement is good between our parameters and those of Cornelis et al. [5] for the resonances reported in both analyses but it is not clear why they missed 40% of the $l > 0$ resonances we observed below 240 keV and 20% above that energy. The agreement with the parameters of Cierjacks et al. [7] is very poor.

Our improved knowledge of the resonance parameters for neutron interaction with ^{56}Fe and the extension of the energy region described by those parameters are of significant importance in reactor calculations since it eliminates the need to deal with the approximate unresolved resonance formalism.

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