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keV Neutron Total Cross Section Measurements at ORELA*

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Neutron total cross sections are measured at ORELA using samples as small as a few square millimeters, flight paths from 18 to 200 meters, with energy resolutions ($\Delta E/E$) from 1/300 for measurements below ~10 keV to ~1/2500 up to 200 keV and $\sqrt{E(\text{in MeV})}/1000$ above 1 MeV. A new efficient neutron detector using NE 110 has been developed for keV measurements whose efficiency is ~30% for 10 keV neutrons rising to 90% for 50 keV neutrons. Transmission measurements using iron-filtered neutron beams have been made upon thick samples of iron 4", 5", 12" and 20" to obtain accurate values of the cross-section minima. Enriched ^{54}Fe and ^{57}Fe samples have been measured to determine their contributions to the windows in natural iron.

1. Introduction

The Oak Ridge Electron Linear Accelerator (ORELA) was designed to be optimum for neutron cross section measurements in the energy region from a few keV to a few hundred keV. The time uncertainties in the moderator surrounding the fast-neutron photonuclear source and the flight times for these energy neutrons in reasonable neutron detectors determined the electron burst widths (3 to 30 nanoseconds) from the accelerator for which maximum performance was required. Peak currents of 15 amperes of 140-MeV electrons (corresponding to a peak neutron production rate of 3×10^{18} fast neutrons per second during the electron pulse) and a repetition rate of 1000 pps make ORELA one of the best available sources for most types of keV neutron cross section measurements. For total cross section measurements 3 flight stations at 18, 80 and 200 meters were constructed.

2. Neutron Detectors for Total Cross Section Measurements

In order to make transmission measurements upon small samples of enriched isotopes with high energy resolution an efficient, fast neutron detector is required to make maximum use of the high-intensity neutron source. Although neutron detectors such as a ^{6}Li glass scintillator or a ^{10}B-slab + NaI scintillator combination are suitable for neutron energies below a few keV, they have detection efficiencies for neutrons above 10 keV which are $\lesssim$ 10%. Also the fast organic proton-recoil detectors (such as Naton 136) used for MeV neutrons have efficiencies < 10% for neutron energies below 200 keV as shown in Figure 1.

In the process of testing organic scintillators for MeV neutron total cross section measurements using selected RCA 4522 5-inch photomultiplier tubes with a specially-designed tube base, it was discovered that a relatively new plastic scintillator, NE 110, was capable of detecting neutrons whose energies were only a few keV. The efficiencies measured for three of these NE 110 detectors are also shown in Figure 1. The differences for low energy neutrons were probably due to small gain differences between tubes and tube bases. It is obvious that above $\sim$10 keV this NE 110 detector has an efficiency an order of magnitude greater than that of a $\frac{1}{2}$" thick piece of highly enriched ^{6}Li glass scintillator. Neutrons can be moderated by the NE 110 scintillator and then captured by the hydrogen in the NE 110 detector producing gamma rays which are detected but the probability of this occurring is small. It is 0.1% for 100 keV neutrons, 0.2% for 25 keV neutrons, and 0.4% for 5 keV neutrons. The neutron lifetime for the sizes of scintillators used for detectors is 4.8 μsec (half-life) and it is independent of the incident neutron energy.

In making measurements with this NE 110 detector several pulse-height windows are used to minimize the contribution of room background and the hydrogen capture in the detector. For example, the lowest window which accounts for $>90\%$ of the detected neutrons below $\sim$100 keV contains $<10\%$ of the background in the detector. The backgrounds in the higher windows (>100 keV) are $\ll 1\%$ of the detected neutrons in these windows and the data can be easily corrected for their contributions.

3. Experimental Arrangements

A. Measurements for Energies < 20 keV

Transmission measurements at ORELA can be conveniently divided into two groups depending on the energy range. For neutron energies below $\sim$20 keV measurements are made using one or several $4\frac{1}{2}$" D, $\frac{1}{2}$" thick ^{6}Li glass scintillators connected together, with the accelerator operating with 10-30 nanosecond bursts. For very small samples, such as ^{244}Cm, where $\sim$tens of milligrams of material are available, sample areas of a few square millimeters are used with an 18-meter flight path. The experimental energy resolution ($\Delta E/E$) is 1/300 due to the moderation time in the neutron source and the time of flight in the detector, which is less than the Doppler broadening of resonances up to 200 eV. This resolution is sufficient to resolve $\sim$100 resonances even for nuclides with small spacings ($\sim$1 eV) such as ^{243}Am.

For samples available in $\sim$gram quantities, sufficient for sample areas $\sim$1 cm^2, an 80-meter flight path is used resulting in an energy resolution $\sim$1/1000. Below several keV, the energy resolution is less than the Doppler widths of the resonances and samples such as ^{242}Pu have been cooled to liquid nitrogen temperatures to reduce the Doppler broadening of the resonances.

B. Measurements for Energies > 10 keV

To realize the maximum energy resolution for neutrons from 10 keV to several hundred keV the linac should be operated with narrow bursts (3-5 nanoseconds). Using the 200-meter flight station the energy resolution ($\Delta E/E$) below $\sim$200 keV is determined by the moderator and detector depth and is 1/2500 and increases to $\lesssim \sqrt{E(\text{in MeV})}/1000$ above 1 MeV due to the burst width. This energy resolution is comparable to the best resolution obtained using Van de Graaff accelerators up to 2 MeV and the intensity available at ORELA is much greater. With the linac operating with 5-nanosecond bursts and 1000 pps, samples with areas of a few cm^2 have been measured using the NE 110 scintillator and the 200-meter flight station. Before this NE 110 detector was developed, this size of sample required the ^{6}Li glass scintillator at 80 meters.

4. Experimental Data

A. ^{54}Fe, ^{57}Fe

Transmission measurements have been made upon several natural elements and many isotopes in the past three years with almost all permutations of flight stations, burst widths, and detectors. The measurements on the isotopes of iron are of interest in interpreting our measurements made upon thick samples of high purity iron to determine the cross sections at the various minima. Figure 2 shows data taken using two ^{6}Li glass detectors located at 80 meters. In order to present the gross features, the data have been averaged and hence most of the narrow p-wave resonances have been lost or show up as one-point peaks. The big resonance at 29.6 keV in ^{57}Fe and the 7.9-keV resonance in ^{54}Fe contribute to the minima at 24.5-keV in natural iron. Recently, high-resolution measurements have been made upon these isotopes above 20 keV with an NE 110 detector at 200 meters.

B. Thick Samples of Natural Iron

In order to measure the total cross sections of the neutron "windows" in iron, a thick ARMCO iron filter 9½" long was inserted into a 2" collimator 8 meters from the neutron source. This thickness of iron filter will pass neutrons whose energies correspond to the energies of the minima of the iron cross-section (≤ 1 barn) and produces a beam with many intense groups of neutrons whose energy spreads vary from < 1 to 10%. Between these monoenergetic groups the counting rate drops to room background which is $\lesssim 0.1\%$ of the counting rate of the peak of the group. Time-of-flight transmission measurements were made upon three samples of high purity iron, 6", 12" and 20" long within these groups using two ^{6}Li glass detectors at the 80-meter flight station. Data obtained with the 20-inch thick sample for the lowest energy "window"are shown in Figure 3. The experimental points have been averaged in groups of 25 channels and in the region of the minimum have a statistical accuracy $\ll 1\%$. Although this high purity iron contained only 0.033% Mn and 0.03% Cu the contribution of resonances in these elements can be seen in this 24.5-keV window. To correct for the contributions of these impurity isotopes, samples of Mn and Cu about 10 times greater in thickness than that present in the 20" sample were measured with the same iron filter and the same energy resolution. The correction amounts to 0.005 to 0.015 barns at the peaks of these impurity resonances. The abundances of these impurities were checked by measuring the transmission of a 1 inch thick sample in the hundred eV region where the peak cross sections of the resonances in the impurities are ~ 100 times larger and their parameters are well known. The data obtained in this 24.5-keV window from the 12" and 6" thick samples agree very well (to $\lesssim 1\%$) with those in Figure 3. Although the energy resolution (30 nsec at 80 meters) was sufficient for a few of the low energy "windows", much better resolution was needed for most of the windows.

Another measurement was made with the Fe-filter beam using the 200-meter flight station, 9-nsec bursts from the accelerator, and the NE 110 detector with the 12" high purity iron sample. Some of the results obtained from this measurement for many windows are shown in Figures 4 and 5. Several of these windows (i.e. at 310 and 350 keV) have considerable structure in them due to p-wave resonances in ^{56}Fe or resonances in ^{54}Fe and ^{57}Fe. The points plotted above 1 barn have large errors due to the small transmission of this 12" Fe sample for these neutrons.

Recently in order to measure the windows in the MeV energy region which have minima of ~1 barn, measurements were made upon a 4" thick iron sample with a 4" thick iron filter using the 200-meter flight station, 5 nsec bursts and the NE 110 detector. Figures 6 and 7 show some of these results. Above 400 keV the resolution is ~3 points. From 200 to 400 keV the data have been averaged by 3 channels so the resolution is ~2 points. Data above 2 barns have large errors due to the low transmission for these neutrons. Table I summarizes the results obtained for the "windows" below 700 keV which are < 1 barn. The agreement between these two 200-meter runs is very good. The last column is the width where the cross section is twice that of the minimum.

The cross sections of these minima are considerably lower (up to ~50%) than the values reported by Rahn.[1] Some of the discrepancies for some of the windows arises from the insufficient energy resolution used for the Columbia measurements (~0.6 nsec/meter). Recently Block et al[2] have reported measurements made upon these iron windows and their result of 0.41 ± 0.03 barns for the 24.5-keV minima agrees with our result of 0.430 ± 0.005 barns.

C. Contributions of ^{54}Fe and ^{57}Fe to the "Windows"

In addition to the measurements upon the ^{54}Fe and ^{57}Fe isotopes mentioned earlier, transmission measurements were also made upon these isotopes using two ^{6}Li glass detectors at 80 meters with a 9½" Fe filter in the beam. This filtered beam technique enables one to make transmission measurements with high statistical accuracy for neutron energies corresponding to the windows in iron. The contributions of these two isotopes account for the observed cross sections at most of the minima. For example, for the 82.0-keV window ^{54}Fe contributes 0.22 barns and ^{57}Fe 0.23 barns, for the 137.5-keV window ^{54}Fe contributes 0.08 barns and ^{57}Fe 0.22 barns, for the 168.1-keV window ^{54}Fe contributes 0.18 barns and ^{57}Fe 0.13 barns which account for the observed cross sections. However, for a few windows such as the 128.7-keV minima ^{54}Fe contributes 0.25 barns and ^{57}Fe contributes 0.16 barns leaving a residual of .2 barns. Hence, p-wave scattering in ^{56}Fe must occur in addition to a possible contribution from the low abundant ^{58}Fe.

D. 1" Thick Sample of Natural Iron

In order to obtain accurate data for neutrons with cross sections > 2 barns, a one inch thick sample (1/N = 4.59 barns/atom) was measured using the NE 110 detector at 200 meters and 5 nsec bursts. Some of the data in the several hundred keV energy region are shown in Figure 8.

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[1]F. Rahn et al, Nucl. Sci. Eng. 47, 372 (1972).
[2]R. C. Block et al, Trans. Am. Nucl. Soc. 15, 531 (1972).

Table
Minima in the Total Cross Section of Natural Iron
200 Meters

Energy (keV)	σ_{min} (barns) 12" Fe (9½" Fe Filter) (9 nsec bursts)	σ_{min} (barns) 4" Fe (4" Fe Filter) (5 nsec bursts)	Average (barns)	Width at Twice σ_{min} (keV)
24.5	0.430 ± 0.005*	0.430 ± 0.018	0.430 ± 0.005	2.3
82.0	0.445 ± 0.010	0.460 ± 0.018	0.450 ± 0.009	1.2
128.7	0.610 ± 0.010	0.590 ± 0.013	0.602 ± 0.008	2.4
137.5	0.315 ± 0.007	0.300 ± 0.010	0.309 ± 0.006	2.0
168.1	0.310 ± 0.007	0.300 ± 0.009	0.306 ± 0.006	0.9
184.0	0.645 ± 0.010	0.662 ± 0.010	0.652 ± 0.007	4.0
219.3	0.420 ± 0.010	0.431 ± 0.011	0.425 ± 0.008	1.2
244.4	0.73 ± 0.02	0.74 ± 0.015	0.736 ± 0.013	1.3
274.0	0.490 ± 0.010	0.480 ± 0.012	0.486 ± 0.008	5.4
310.3	0.410 ± 0.012	0.399 ± 0.012	0.405 ± 0.009	1.7
312.5	0.455 ± 0.015	0.440 ± 0.015	0.448 ± 0.011	3.0
331.1	0.54 ± 0.02	0.55 ± 0.02	0.545 ± 0.014	0.5
347.0	0.88 ± 0.02	0.89 ± 0.02	0.885 ± 0.014	6
353.0	0.490 ± 0.012	0.480 ± 0.012	0.485 ± 0.009	4.6
358.3	0.560 ± 0.014	0.560 ± 0.014	0.560 ± 0.010	1.0
376.3	0.535 ± 0.014	0.52 ± 0.014	0.528 ± 0.010	4.0
437	0.75 ± 0.02	0.77 ± 0.02	0.760 ± 0.014	2.0
468	0.49 ± 0.02	0.48 ± 0.02	0.485 ± 0.014	2.7
612	0.65 ± 0.016	0.67 ± 0.016	0.660 ± 0.012	7
641	0.64 ± 0.02	0.65 ± 0.02	0.645 ± 0.014	8
652	0.56 ± 0.02	0.55 ± 0.02	0.555 ± 0.014	5

*Average of 20", 12" and 6" Fe runs with 9½" Fe filters, 30 nsec bursts, 80 meters.

Figure Captions

Fig. 1 The efficiencies of NE 110 (1 inch thick), ^{6}Li glass ($\frac{1}{2}$ inch thick) and Naton 136 scintillators in the 1- to 1000-keV neutron energy range. (ORNL Dwg. 72-1931)

Fig. 2 Total cross sections of ^{54}Fe and ^{57}Fe in the neutron energy range from 20 to 200 keV.

Fig. 3 Total cross section at the 24.5-keV window from a 20" high purity iron sample showing the contribution of the ^{54}Fe and ^{57}Fe isotopes and the resonances in Mn (.033%) and Cu (0.03%). (ORNL Dwg. 72-1665)

Fig. 4 Windows in natural iron below 300 keV obtained with a 12" iron sample.

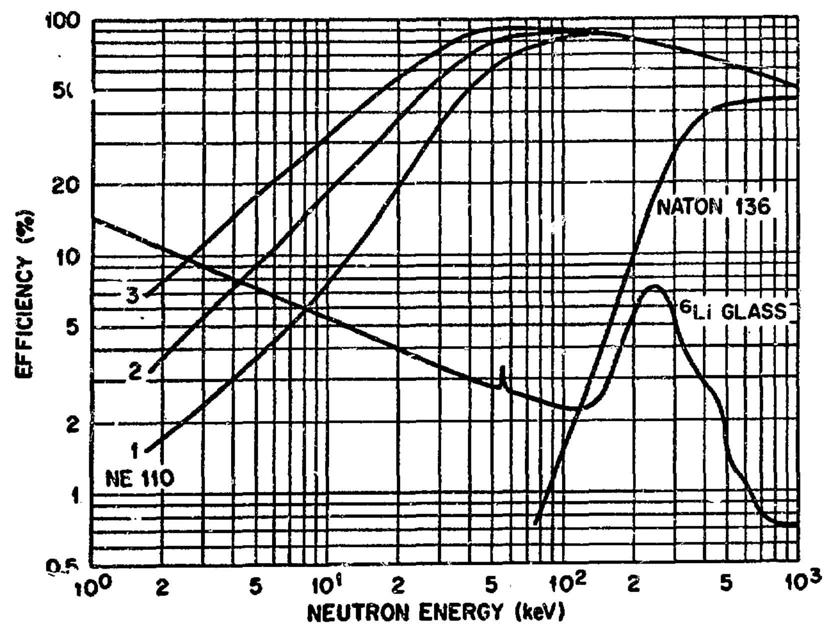
Fig. 5 Windows in natural iron above 300 keV obtained with a 12" iron sample.

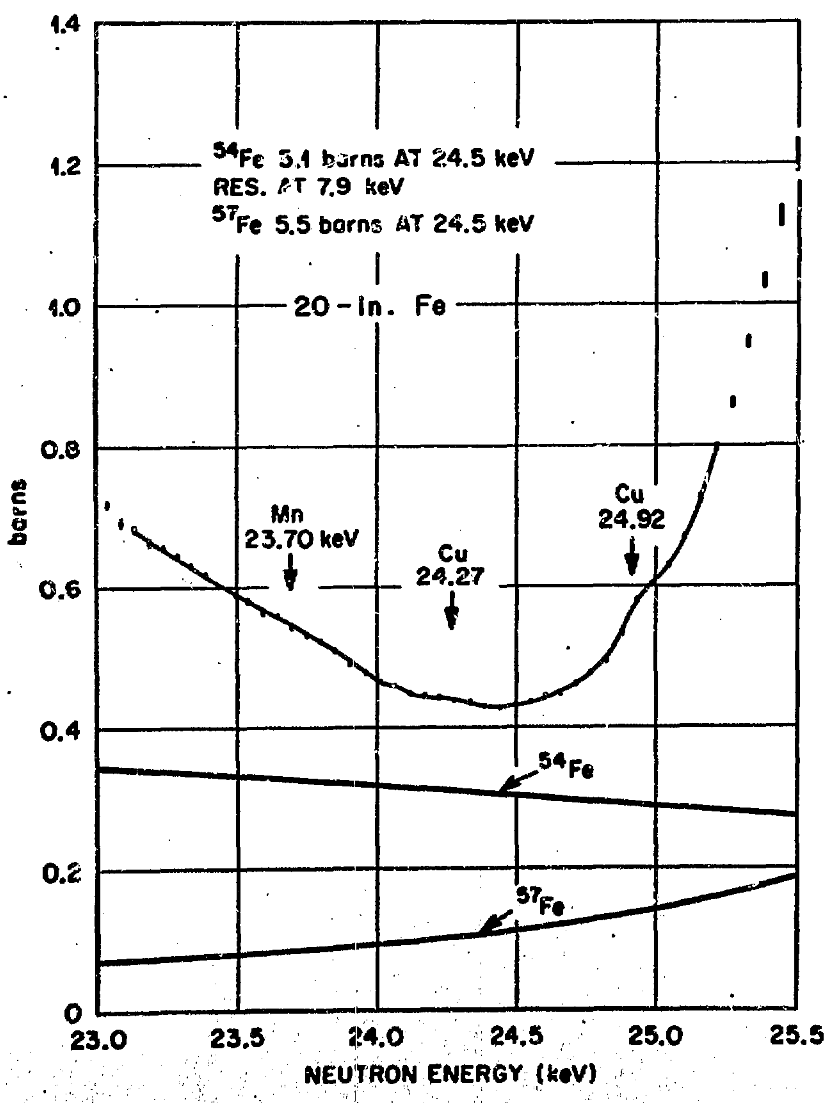
Fig. 6 Windows in natural iron below 300 keV obtained with a 4" iron sample.

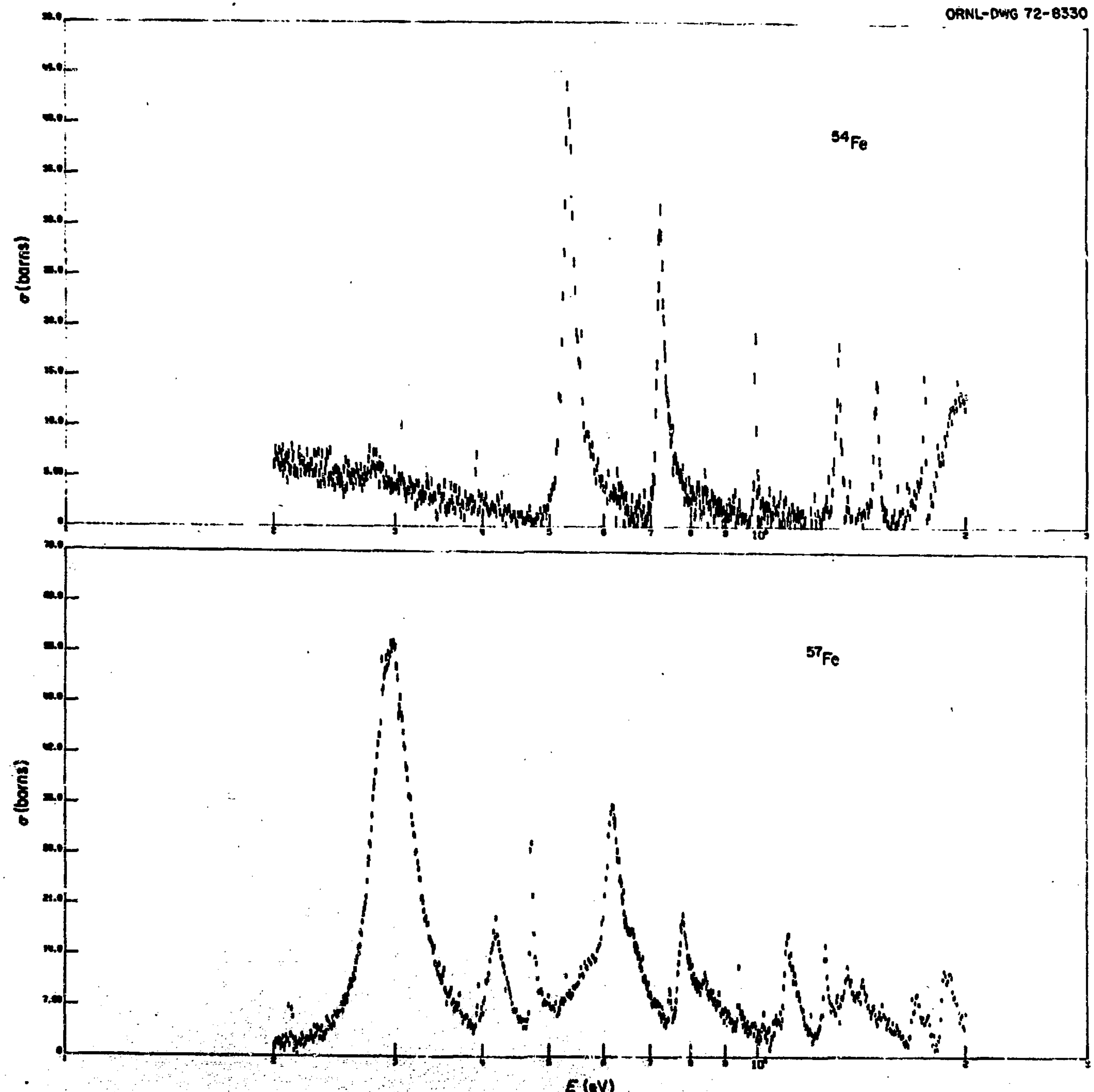
Fig. 7 Windows in natural iron above 300 keV obtained with a 4" iron sample.

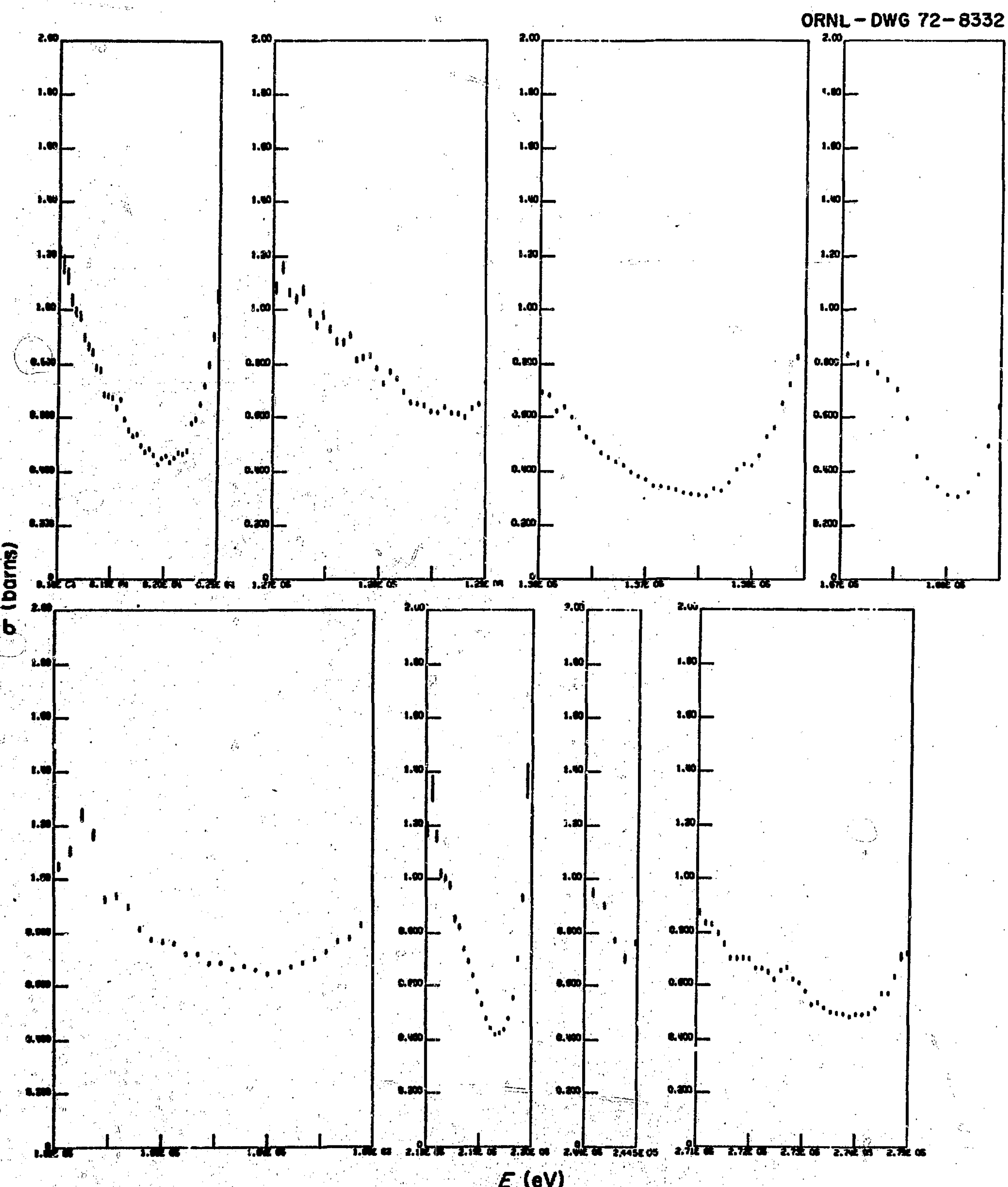
Fig. 8 Total cross section of iron in the several hundred keV energy region obtained with a 1" iron sample.

ORNL-DWG 72-8331






ORNL-DWG 72-8330
^{54}Fe
σ (barns)
^{57}Fe
σ (barns)
E (eV)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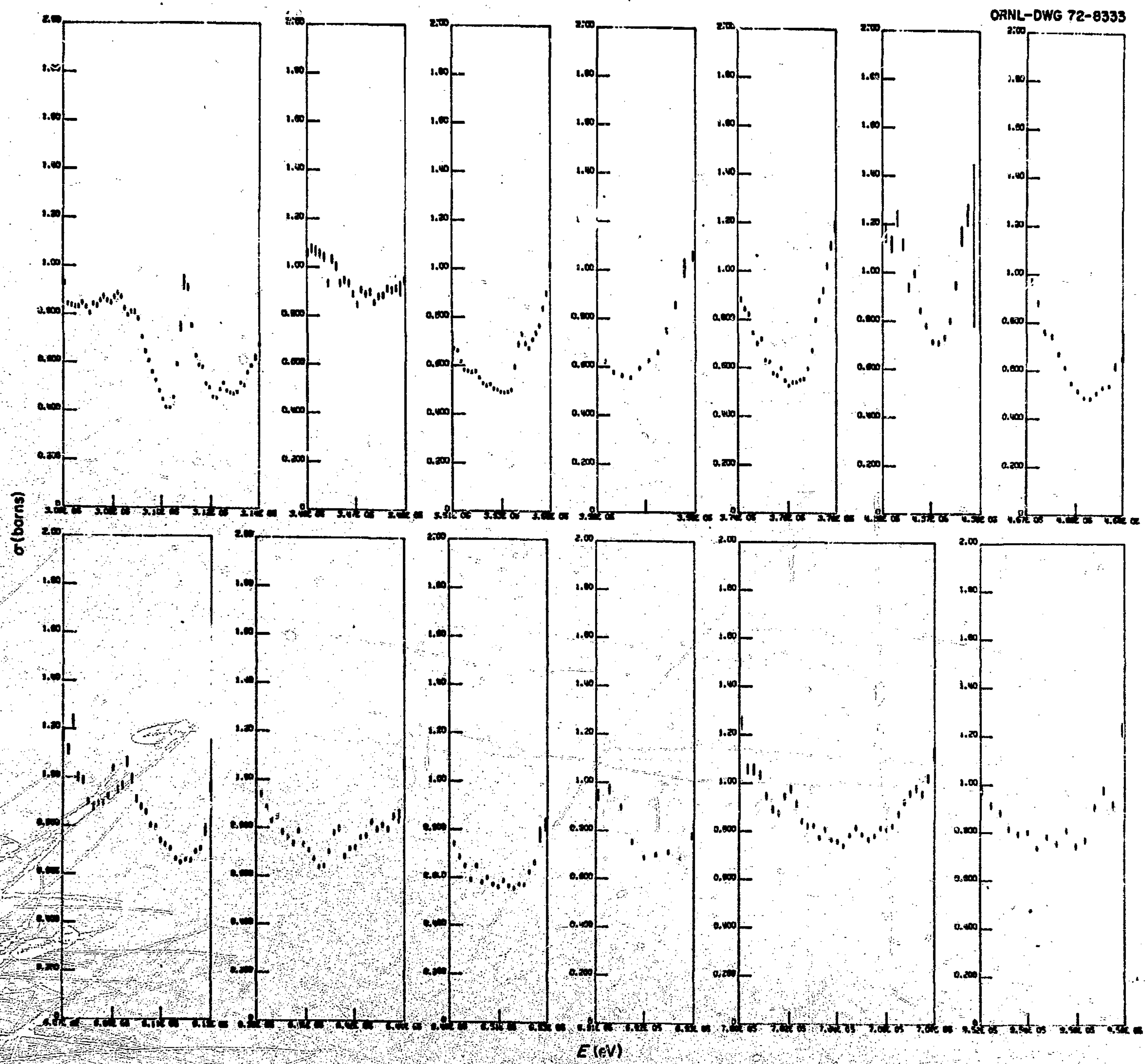
σ (barns)
E (eV)

ORNL-DWG 72-8333



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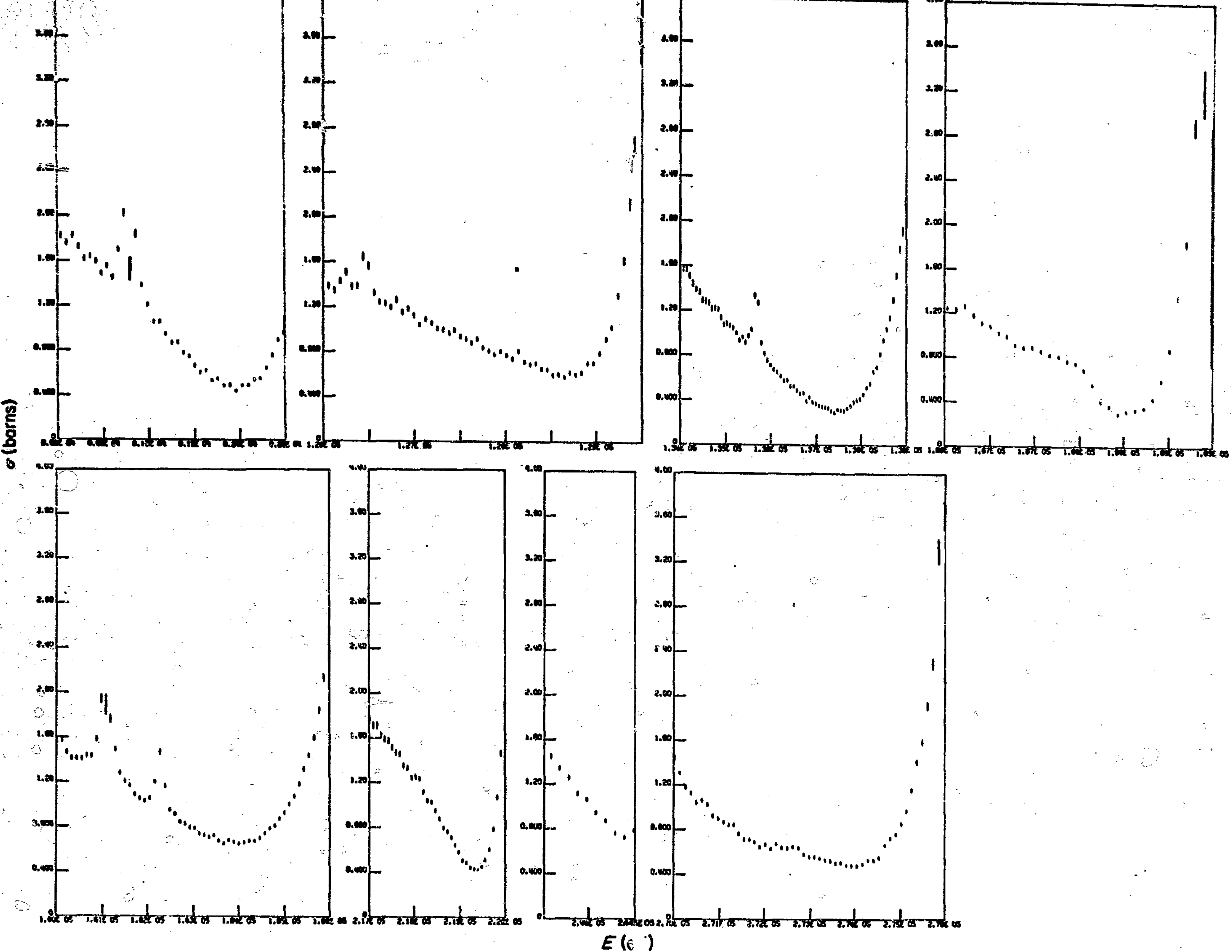

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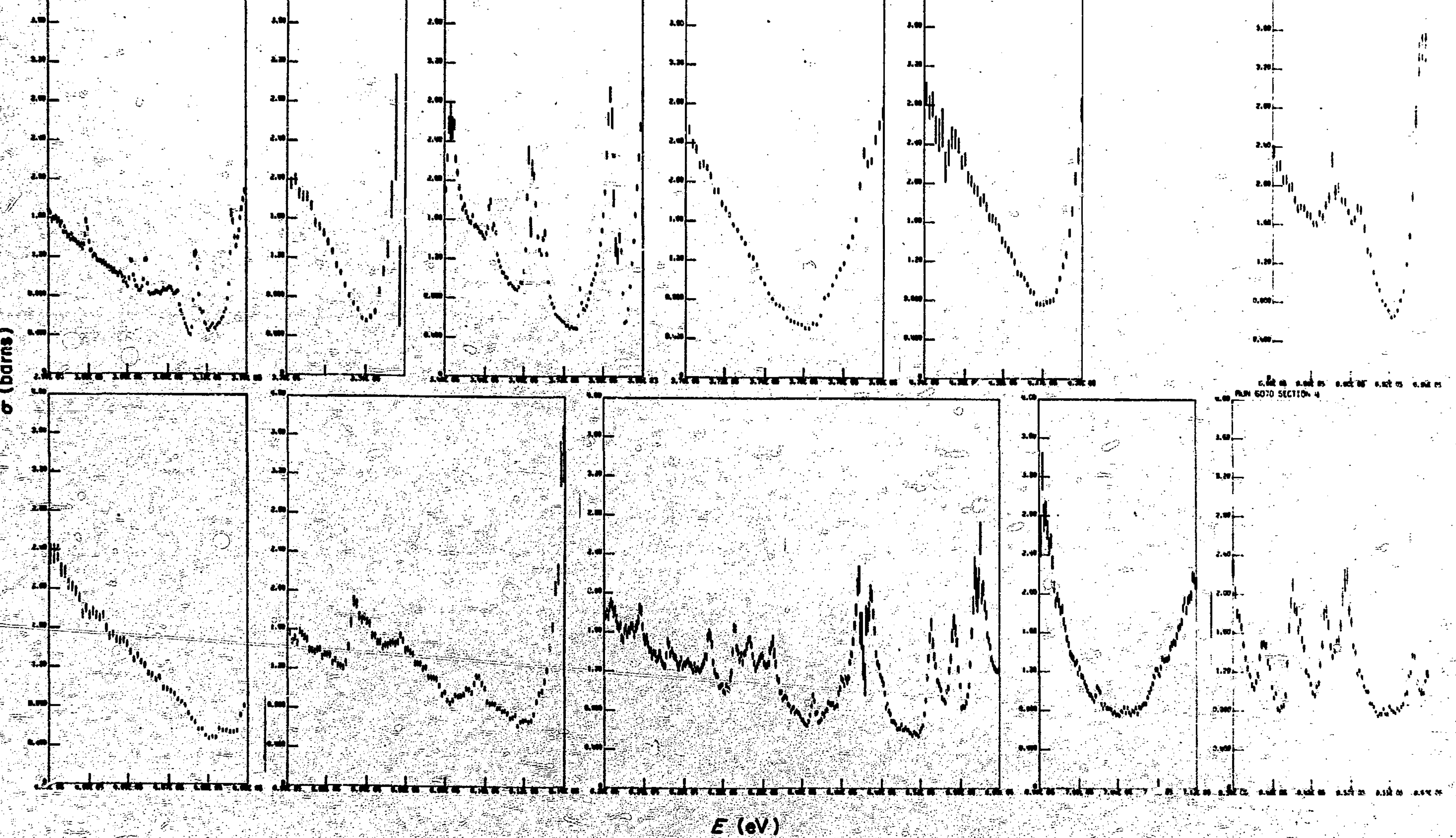

ORNL-DWG 72-8327