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# ORELA MEASUREMENTS TO MEET FUSION ENERGY NEUTRON CROSS SECTION NEEDS


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## ABSTRACT

Major neutron cross section measurements made at the Oak Ridge Electron Linear Accelerator (ORELA) that are useful to the fusion energy program are reviewed. Cross sections for production of gamma rays with energies $0.3 < E_\gamma < 10.5$ MeV have been measured as a function of neutron energy over the range $0.1 < E_n < 20.0$ MeV for Li, C, N, O, F, Na, Mg, Al, Si, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Nb, Mo, Ag, Sn, Ta, W, Au, Pb and Th. Neutron emission cross sections have been measured for $^7$Li, Al, Ti, Cu and Nb for $1 < E_n < 20$ MeV. Some results of recent neutron total cross section measurements from 2-80 MeV for eleven materials (C, O, Al, Si, Ca, Cr, Fe, Ni, Cu, Au and Pb) of interest to the FMIT project will be presented. Finally, future directions of the ORELA program will be outlined.


## INTRODUCTION

During the past four years a number of programs at the Oak Ridge Electron Linear Accelerator (ORELA) have provided data which are of use in the design of fusion energy devices. The purpose of this paper is to review these measurements, and to collect in one place a list of references which document these measurements. In addition, results are presented for some neutron total cross section measurements recently completed from 2-80 MeV. Finally the future directions of the ORELA fusion energy program are outlined. Besides the larger measurement programs discussed below, other measurements of importance made at ORELA include cross sections for the reactions $^{14}$N(n,charged particle) [1], $^6$Li(n,$\alpha$) [2] and $^7$Li(n,n'$\gamma$) [3].

## $(n,x\gamma)$ MEASUREMENTS

One major area in which ORELA has provided the bulk of the available cross section data is the production of gamma rays resulting from neutron-induced interactions. Cross sections for the production of gamma rays with energies of $0.3 < E_\gamma < 10.5$ MeV were measured as a function of neutron energy over the range $0.1 < E_n < 20.0$ MeV. Details of the experimental method are given in refs. 4 and 5. The measurements were made using a heavily shielded NaI detector in conjunction with the white neutron spectrum from ORELA. Incident neutron energies were determined by the time-of-flight technique over a 47-m flight path, while the gamma-ray energy distributions were obtained from pulse-height unfolding techniques using the code FERD [6]. The data have poor energy resolution compared to results using Ge(Li) detectors; however, they have the advantage of including the numerous weak transitions which appear as a continuum, a feature especially important for the heavier nuclei. Since the data span the neutron energy region of interest to ENDF/B, the data have frequently been used directly in evaluations. In addition, since they often provide cross section information for energy regions where few data exist, they are used to guide nuclear model calculations. Table 1 lists the elements on which data have been taken, the angle(s) at which data were acquired, whether or not the data have been utilized in the ENDF/B-V evaluation for the material, and the ORNL report number in which the measurement is described and numerical values of the data are given. Much of the earlier data was obtained under research sponsored by the Defense Nuclear Agency, with the more recent measurements made for the Basic Energy Sciences program to provide data useful for fusion energy problems. This series of measurements was carried out by G. L. Morgan, J. K. Dickens, G. T. Chapman, T. A. Love, E. Newman, D. C. Larson and F. G. Perey.

## $(n,xn)$ AND $(n,x\gamma)$ MEASUREMENTS

The second major measurement program which is underway is the simultaneous measurement of $(n,xn)$ and $(n,x\gamma)$ cross sections produced by neutron interactions with materials of interest to the fusion community.Details of the experimental technique are documented in refs. 7 and 8. Using ORELA as the neutron source, annular scattering samples located 47 m from the neutron source are viewed by a NE-213 scintillation detector. The average scattering angle is determined by the position of the detector along the axis perpendicular to the plane of the sample. Neutron-gamma discrimination is used to classify a given event, which is then stored in one of two pulse-height versus time-of-flight two parameter arrays (one for neutrons, one for gamma rays). Secondary neutron and gamma-ray spectra are determined by unfolding the pulse-height distributions with the code FERD [6]. These measurements provide data that have the global testing power of integral experiments while retaining enough differential character to localize the source of discrepancies with evaluated data. They are useful in providing a means of checking evaluated cross sections over wide ranges of incident and secondary energies, in addition to aiding in the development of advanced nuclear model codes. The gamma-ray-production cross sections obtained from these measurements are in good agreement with the sodium iodide results discussed previously. Results of these measurements are available for five elements to date and are listed in Table II along with the ORNL report number. G. L. Morgan and F. G. Perey initiated and carried out the measurements listed in Table II.

## HIGH ENERGY TOTAL CROSS SECTION MEASUREMENTS

The final set of experiments to be discussed are the recent high energy transmission measurements done at ORELA to help meet shielding design data needs for the FMIT project. Table III lists the elements which have been measured, the sample thicknesses, and the sample transmission in percent at 40 MeV. Two sets of measurements were done; the first set included data for H, C, O and Fe from 0.5 to 60 MeV and is documented in ref. 9. The second set of measurements cover the energy range from 2 to 80 MeV and will be discussed briefly here. The flight path was 80 m, with a NE-110 scintillator used to detect the neutrons. Corrections were made for deadtime and background effects. Samples of $CH_2$, C and Fe were rerun as checks for the H, C and Fe cross sections, and were found to be in good agreement with results from the first measurement [9]. The repetition rate was dropped from 1000/sec to 800/sec for this run, since more peak power could then be applied to the klystrons, which resulted in higher energy electrons, thus increasing the number of high energy neutrons above $\sim$50 MeV. Since ample data are available up to 2 MeV for the materials measured in this run, the bias cutoff was raised to $\lesssim$ 2 MeV neutron energy to further reduce any low energy gamma-ray backgrounds which may be present. The average run time for each material was 27 hours. Integrating the area under our data from 2-20 MeV and comparing with the integral obtained from the ENDF/B-V evaluations for these materials yielded agreement to better than 1% for all elements except Al (1.2%) and Au (1.8%). A similar comparison for hydrogen from 2-80 MeV compared with the latest results of Arndt [10] from his nucleon-nucleon phase shift analysis shows agreement to better than 1%.

Figure 1 shows a comparison of our hydrogen total cross section data from both runs, compared with the results of Arndt [10] from 2-80 MeV. Figure 2 compares our data for chromium from 15-80 MeV with all data currently available from the CSISRS data repository at BNL. The data have been suitably averaged to reduce the number of points for comparison purposes. The four data points of Peterson *et al.* [11] from 18 to 29 MeV are in good agreement with the present results. The data of Perey *et al.* [12] were also taken at ORELA using the same sample, but a different flight path, detector, data acquisition method and neutron target. These data extend to 29 MeV and are generally in good agreement with our results. The data of Cierjacks *et al.* [13] extend to 32 MeV, and are systematically lower than our data up to 21 MeV by ∿4%.

In the absence of experimental data, total cross sections have often been obtained from the optical model. Two of the more common optical model parameter sets used are those of Wilmore and Hodgson [14], and Becchetti and Greenlees [15]. We have compared the predictions of these parameter sets with our data [16], and a typical result is shown in Fig. 2 for chromium. In general, we found that cross sections predicted by the Wilmore-Hodgson set are better at lower energies, while the Becchetti-Greenlees parameters are somewhat better for higher energies.

Figure 3 compares our data for iron with data available from CSISRS from 15 to 80 MeV, along with the recent data of Zanelli *et al.* [17] from the University of California at Davis. Again the various data sets have been averaged. The data of Perey *et al.* [18], Peterson *et al.* [11] and Hildebrand and Leith [19] are generally in good agreement with our present results. The data of Cierjacks *et al.* [13] are systematically low below 21 MeV and high above 24 MeV. The data point of Deconninck *et al.* [20] lies above our averaged data while the data of Ragent [21] are generally low with the exception of the two points near 36 MeV.

Figure 4 shows a comparison of our data for nickel with other results available from CSISRS. The data of Perey *et al.* [12] and Peterson *et al.* [11] are in good agreement with our results. The data of Cierjacks *et al.* [13] appear to be slightly larger than the general trend of our data above 20 MeV, and the data point of Hildebrand and Leith [19] is slightly smaller than the trend of our data.

The data for the elements listed in Table III provide a consistent extension of the data base to higher energies where very few data are presently available. A complete report describing the measurement and results for all the elements will be published elsewhere. The total cross section work was done by D. C. Larson, J. A. Harvey, D. M. Hetrick and N. W. Hill.

## FUTURE DIRECTIONS

Current plans for future experimental work at ORELA include more simultaneous measurements of (n,xn) and (n,x$\gamma$) on materials of interest to the fusion energy program, a continuation of the high energy total cross section measurements and an exploratory program to determine the feasibility of measuring (n,charged particle) reactions over a wide range of incident neutron energies and secondary charged particle energies to complement the work going on at Livermore and Ohio University.

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TABLE I

ORNL (n,xγ) Measurements

| Element | 90° | 125° | Used in ENDF/B-V | ORNL Report |
|---|---|---|---|---|
| Li | | X | N | TM-4538 |
| C | X | X | Y | TM-3702 |
| N | X | X | Y | ORNL-4864 |
| O | | X | N | ORNL-5575 |
| F | | X | Y | TM-4538 |
| Na | | X | Y | TM-6281 |
| Mg | X | X | Y | TM-4544 |
| Al | X | X | Y | TM-4232 |
| Si | X | X | Y | TM-4389 |
| Ca | | X | Y | TM-4252 |
| Ti | | X | N | TM-6323 |
| V | | X | Y | TM-5299 |
| Cr | | X | Y | TM-5098 |
| Mn | | X | Y | TM-5531 |
| Fe | | X | Y | TM-5416 |
| Ni | | X | Y | TM-4379 |
| Cu | | X | Y | ORNL-4846 |
| Zn | | X | N | TM-4464 |
| Nb | X | | N | TM-4972 |
| Mo | | X | N | TM-5097 |
| Ag | | X | N | TM-5081 |
| Sn | | X | N | TM-4406 |
| Ta | X | X | Y | TM-3702 |
| W | | X | Y | ORNL-4847 |
| Au | | X | N | TM-4973 |
| Pb | | X | Y | TM-4822 |
| Th | | X | N | TM-6758 |

TABLE II

ORNL (n,xn) Measurements

| Element | Angle | ORNL Report |
|---|---|---|
| $^{7}$Li | 50°,126° | TM-6247 |
| Al | 127° | TM-5241 |
| Ti | 130° | ORNL-5563 |
| Cu | 130° | ORNL-5499 |
| Nb | 129° | TM-5829 |

TABLE III

ORNL Total Cross Section Measurements

| Element | Energy Range (MeV) | Sample Thickness (at/b) | Transmission at 40 MeV (%) |
|---|---|---|---|
| H | 0.5-60 | 0.8224 | 83 |
| H | 2.0-80 | 0.8224 | 83 |
| C | 0.5-60 | 0.4115 | 64 |
| C | 2.0-80 | 0.4115 | 64 |
| O | 0.5-60 | 0.5485 | 46 |
| Al | 2.0-80 | 0.4134 | 48 |
| Si | 2.0-80 | 0.3472 | 54 |
| Ca | 2.0-80 | 0.3512 | 45 |
| Cr | 2.0-80 | 0.2106 | 59 |
| Fe | 0.5-60 | 0.4296 | 34 |
| Fe | 2.0-80 | 0.4296 | 34 |
| Ni | 2.0-80 | 0.2304 | 56 |
| Cu | 2.0-80 | 0.2149 | 57 |
| Au | 2.0-80 | 0.1139 | 63 |
| Pb | 2.0-80 | 0.1653 | 48 |

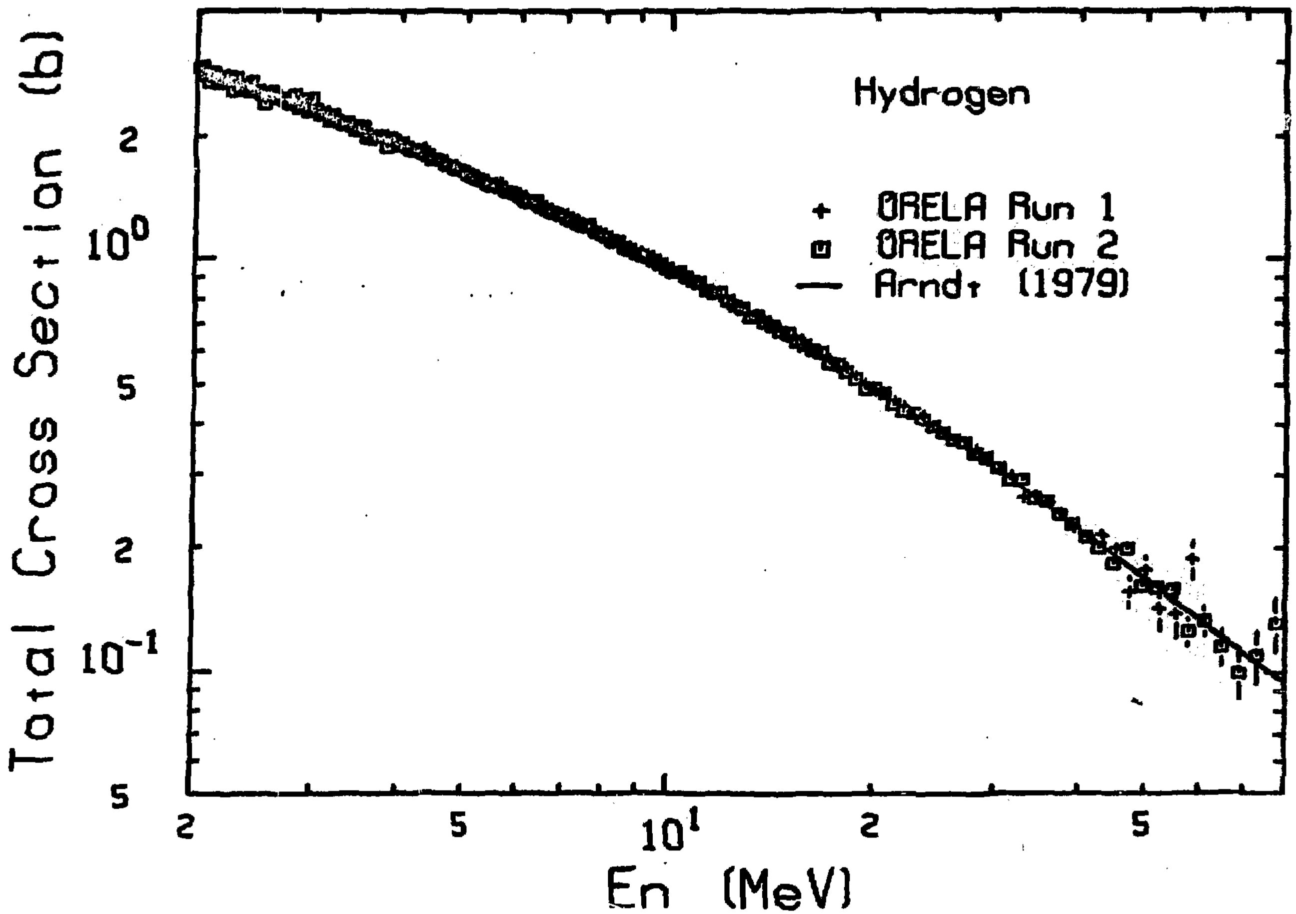
# FIGURE CAPTIONS

Figure 1. Comparison of hydrogen total cross section data for Run 1 (2-60 MeV) and Run 2 (2-80 MeV) with results of a nucleon-nucleon phase-shift analysis of ref. 10.

Figure 2. Comparison of present total cross section data for chromium with results of refs. 11-13, and predicted total cross sections from the optical model parameter sets of refs. 14 and 15.

Figure 3. Comparison of present total cross section data for iron with results of refs. 11, 13, 17-21.

Figure 4. Comparison of present total cross section data for nickel with results of refs. 11-13, 19.

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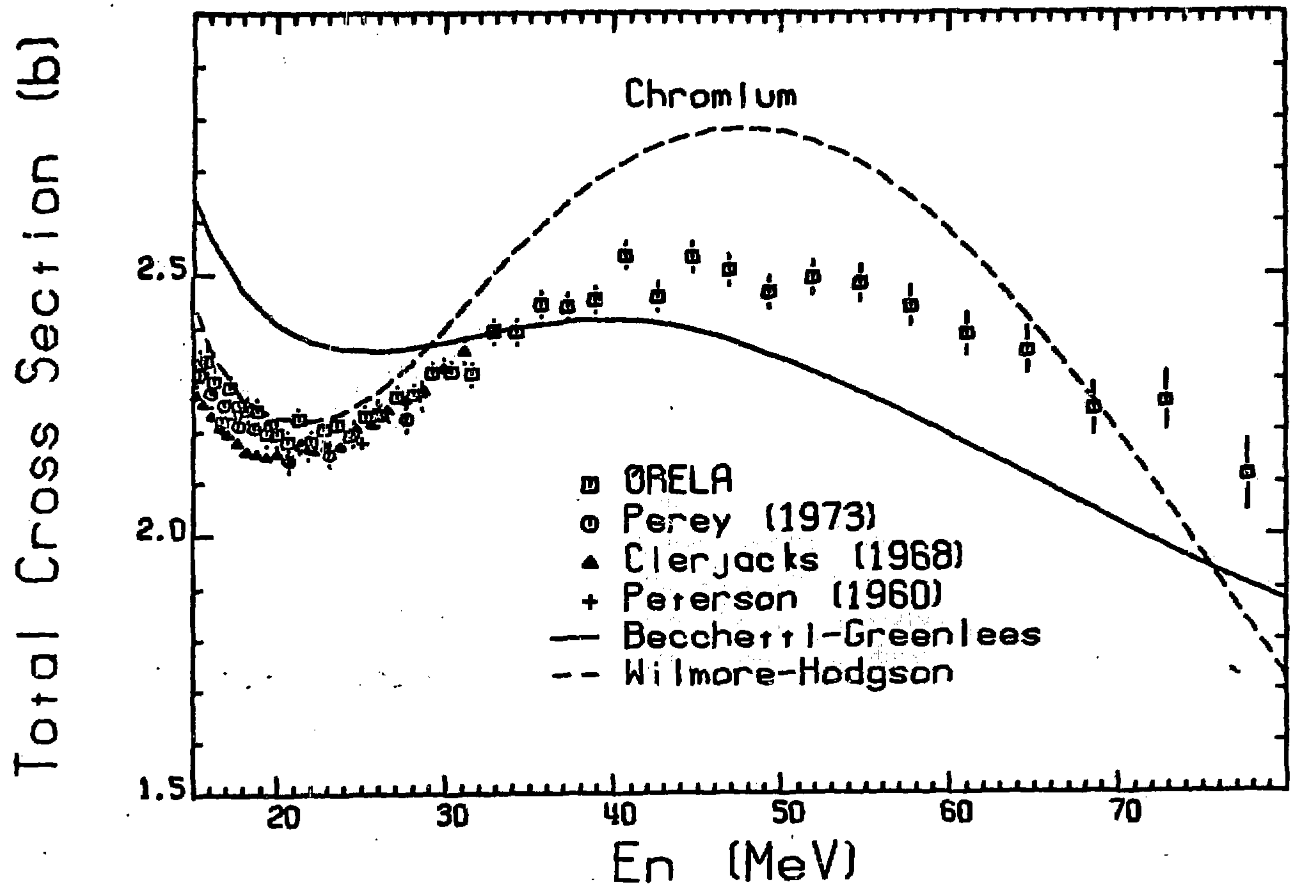


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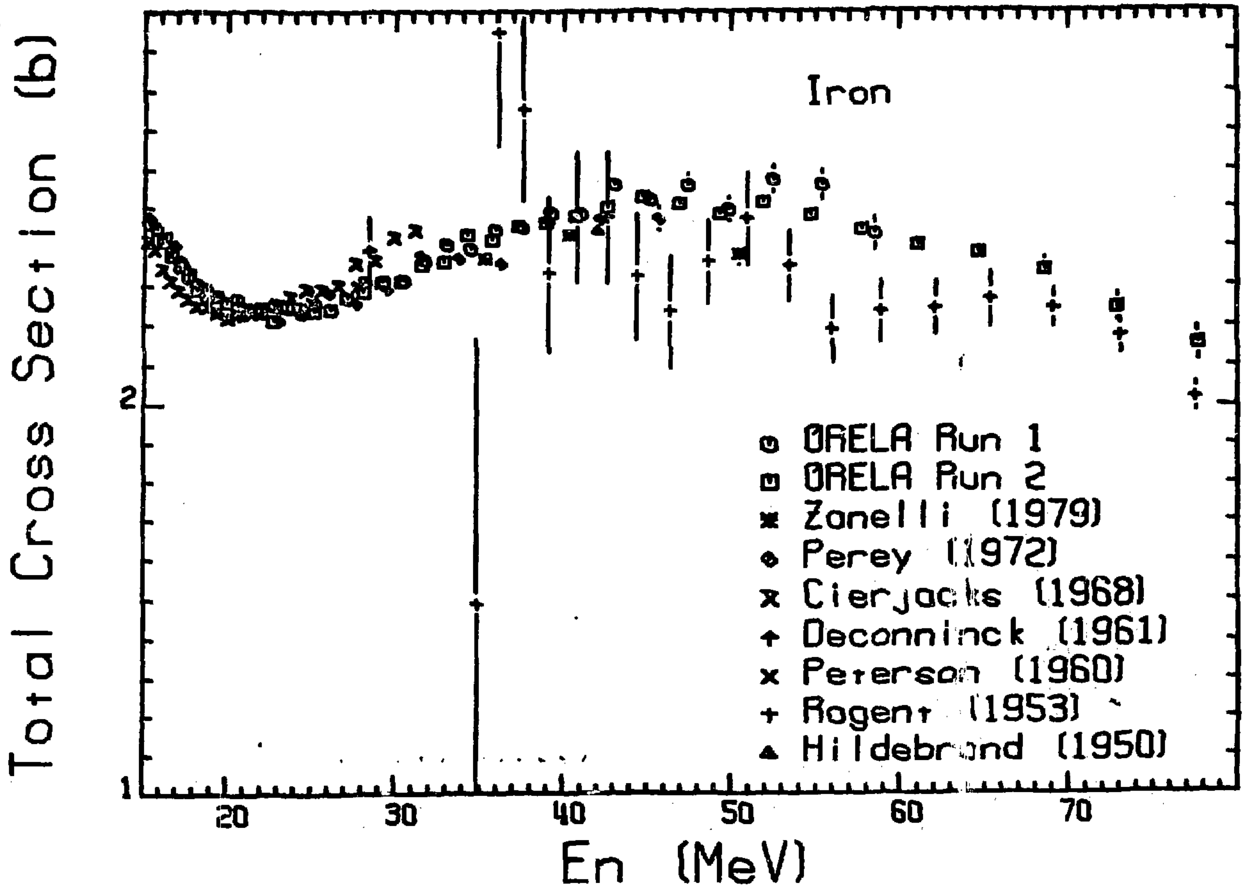


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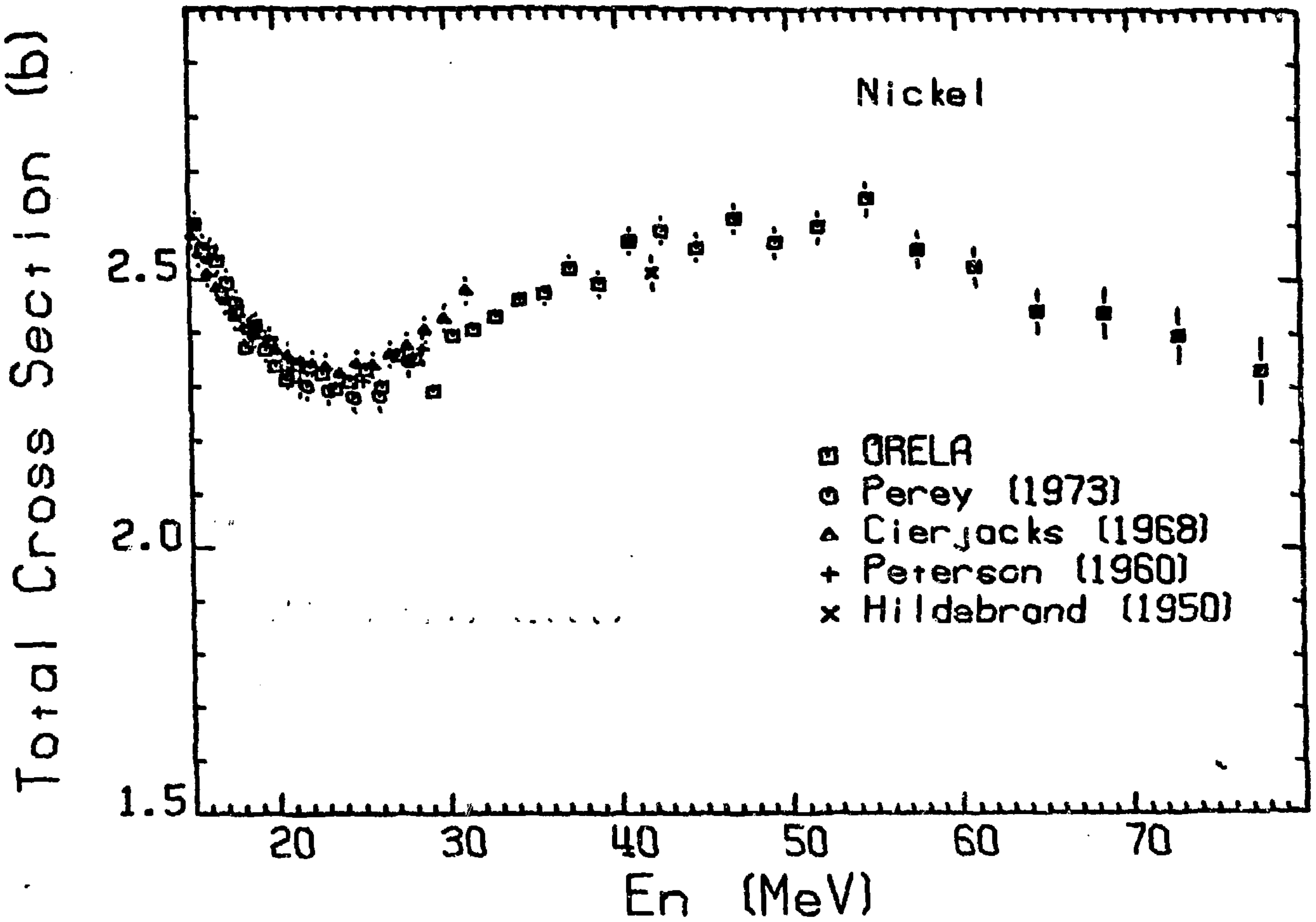


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