MEASURED AND EVALUATED FAST NEUTRON
CROSS SECTIONS OF NICKEL AND COBALT

by

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Measured and Evaluated Fast Neutron Cross Sections of Nickel and Cobalt^a

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ABSTRACT

The provision of evaluated fast neutron data of nickel and cobalt by experimental and theoretical means is outlined with emphasis on CTR relevance. New experimental results are presented including: total cross sections, elastic and inelastic scattering cross sections and (n,p) cross sections. These measured values, previously reported experimental information and physical theory are utilized to provide comprehensive evaluated neutron data files in the ENDF/B format.

I. INTRODUCTION

Conceptual CTR energy systems can include nickel and cobalt in the form of ferrous-based alloys (1). High nickel-content alloys show attractive resistance to radiation damage. Fast neutron cross sections of these elements can appreciably influence neutron spectral distributions throughout the systems. In addition certain nickel reactions are widely employed in dosimetry measurements. This study of nickel and cobalt was undertaken as a part of the comprehensive program at the Argonne Fast Neutron Generator with the objectives of providing precise fast neutron cross sections and the derivation of comprehensive evaluated data files over the energy range 0.1 to 20.0 MeV in the ENDF/B format for CTR and other neutronic applications. Herein portions of this work are outlined and illustrated; Sec. II deals with total cross sections, Sec. III with scattering cross sections and Sec. IV with (n,X) reactions. A brief projection of future work is given in Sec. V.

II. TOTAL NEUTRON CROSS SECTIONS

Total cross sections are the essential foundation of the evaluation and of the energy-average physical models necessary for extra-

a. This work supported by the U.S. Atomic Energy Commission.

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polation and interpolation. The total cross sections are not always well known with uncertainties in magnitudes and structure particularly at energies of $\lesssim 6.0$ MeV. Therefore this program includes detailed measurements of energy-average total cross sections in the range 0.1 to $\gtrsim 6.0$ MeV with the objective of assuring a
---- precise experimental foundation essential to evaluation and the development of physical models.

The experimental resolution is good (i.e. ~ 2 keV) but not a goal in itself. Precise energy-average magnitudes are critical and attention is given to experimental procedures assuring that end (2). The resulting evaluated total cross sections are illustrated in Fig. 1. They are based upon a number of experimental values (2), particularly the high resolution results of Perey et al. (3) and Cierjacks et al. (4), adjusted to the energy-average values of the present work where necessary. Optical and coupled-channel model parameters were selected to describe these total cross sections to within a few percent from 0.1 to 20.0 MeV (5).

---- These selected potentials are specific to the particular nucleus and not necessarily of a general nature.

The high resolutions now technically available provide details of the resonances or fluctuations up to relatively high energies. The optical and coupled-channel models can also be applied to the calculation of the statistical properties of these fluctuations. The average reaction amplitudes provided by these models determine the average R-matrix parameters R and $\langle \gamma_{ue}, \gamma_{ud} \rangle / D$. The resonance spacings D are determined from resonance neutron data and the γ_{ue} are assumed to be normally distributed with zero means. This information suffices to construct a numerical statistical reaction amplitude. From this, fluctuating cross sections are computed whose statistical properties are then compared with the measured high resolution data. This statistical comparison permits a further "fine tuning" of the optical or coupled-channel model parameters. It also permits the statistical prediction of cross section fluctuations from poor resolution data.

These models provide a mechanism for physical interpolation. For example, there are no measured high-resolution cobalt total cross sections in the region 0.21 to 0.45 MeV. Energy-average interpolation over this region is provided by the optical model. Moreover, statistical fluctuating cross section can be calculated from the energy-average models and the known statistical properties of resonance widths and spacings and the R-matrix formalism (6). The results of such calculations are statistically consistent with the measured available values. They can be directly used in the evaluation process as illustrated by the cobalt results of Fig. 1. Here, the evaluation between 0.21 and 0.45 MeV is entirely based upon a theoretical interpolation which is difficult to distinguish from the adjoining experimentally-based evaluation. Moreover,

---- the statistical analysis of fluctuations guides the selection of energy-average models particularly distinguishing between spherical and coupled-channel models.

The present total cross section evaluations differ from those of ENDF/B-III (7) in both magnitude (a difference of 10% or more at some energies in the case of cobalt) and structure. The much larger fluctuations of the present evaluations should particularly influence macroscopic calculations involving penetration through thick materials as in a CTR blanket and coil shield. Moreover, the theoretical calculations indicate that the magnitudes of the fluctuations in the present evaluations may still be underestimated.

III. NEUTRON SCATTERING CROSS SECTIONS

The results of the differential elastic scattering measurements extending from 0.3 to 4.0 MeV are outlined in Fig. 2. Values from the literature (2) extend these measurements to higher energies and provide a further basis for physical models and the evaluation. Below ~ 5.0 MeV compound-elastic contributions become increasingly important while above ~ 5.0 MeV the distributions are largely due to shape scattering. A simple spherical optical model is descriptive of the cobalt results but nickel is a vibrational nucleus (8) and a coupled-channel model must be employed.

---- The effect of channel coupling is large, 50% or more at some angles and energies.

Above the region of fluctuations (e.g. ~ 2.0 MeV) the models based upon total and elastic scattering cross sections provide the evaluated elastic scattering cross sections. At lower energies fluctuations are pronounced and the evaluation is based primarily upon measured elastic scattering distributions.

Cross sections for the inelastic excitation of states in nickel at 1.33, 1.45, 2.15, 2.28, 2.48, 2.62 and 2.73 MeV and in cobalt at 1.10, 1.20, 1.30, 1.43, 1.72, 2.06, 2.16, 2.35 and 2.5 MeV were measured.

---- The experimental results were extrapolated using optical and coupled-channel models and the Hauser-Feshbach formula with width fluctuation corrections (9, 10).

The results of measurement, calculation and evaluation are outlined in Fig. 3. Where J^π values are known calculations confirm the model parameters. Where they are unknown calculation determines J^π either within limits or precisely. For example, Fig. 3 shows the results of two sets of cobalt calculations based upon alternate spectroscopic schemes (8). Neither calculation is in detailed agreement with experiment but the comparisons with experiments do resolve J^π ambiguities indicating a spectroscopic scheme consistent with a model based upon a proton hole in the $f_{7/2}$ shell strongly coupled to a spherical core with associated collective bands in the manner of Mottelson and Nilsson (11). The inelastic cobalt evaluation indicated in Fig. 3 differs from that of ENDF/B-III by a factor of more than two in some of the prominent inelastic components.

The first few excited states in the prominent isotopes of nickel are vibrational two-phonon, levels (8). Results calculated with spherical and coupled-channel (ellipsoidal) models are compared with the experimental values in Fig. 3. At these energies (< 5.0 MeV) the two calculational results do not differ appreciably. However, the direct contribution increases with energy amounting to ~ 40 mb for the excitation of the first, 2^+ , state at 14 MeV. Below ~ 3.0 MeV some inelastic cross sections calculated with the Hauser-Feshbach formula are much larger than the experimental values (e.g. the 2^+ , 1.45 MeV state in Ni-58). It is a region where fluctuation corrections should be large and, indeed,

---- the correction factor reduces the calculated result by a factor of approximately two (see WFC curve of Fig. 3).

Generally, theory, properly applied, can extrapolate measured inelastic scattering cross sections to provide improved evaluation but

---- reliable experimental values remain essential for a good quantitative evaluation.

IV. (n,X) REACTIONS

A large number of these reactions are energetically possible below 20.0 MeV in nickel and cobalt. Many of them are experimentally difficult to measure and/or very uncertain. Experiments in progress at the laboratory employed activation techniques to provide precise cross sections to incident energies of ~ 9.0 MeV. The measurements extend into the sub-threshold region that can be important in dosimetry applications. These present measurements were combined with previously reported values (2) to provide an experimental basis for the evaluations.

---- Previously reported values were selected for consistency with preference for data sets spanning wide energy ranges. A considerable amount of reported data was rejected for various subjective reasons. "Accepted" data was generally retained as originally published with no renormalization.

Thus the selection of the data base involved extensive subjective judgement.

---- The evaluations were empirically constructed from the experimental values guided where necessary by similar results in neighboring nuclei.

The evaluated results are illustrated by the Ni-58 (n,2n) and (n,p) cross sections shown in Fig. 4. These particular cross sections are relatively well defined by measured values however there are regions of uncertainty (e.g. 10-13 MeV). Many of the other energetically possible reaction channels are far less certain with discrepancies of as much as an order of magnitude between measured values or even no experimental information. Theoretical estimates can be of assistance in these instances and various theoretically calculated values reported in the literature were employed to guide the present evaluations.

V. CONCLUDING NOTE

The above measurements, calculations and evaluations are believed to provide a considerably improved data base for CTR calculations. However, there remain uncertainties and deficiencies. Particularly, these evaluations have not been validated by integral tests in a CTR-like environment nor do they contain gamma-ray production cross sections. Both of these prominent shortfalls are being mitigated through a cooperative effort with R. Howerton et al. (12) at Lawrence Livermore Laboratory.

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Figure Captions

1. Comparison of present evaluated total neutron cross sections of nickel and cobalt with those given in ENDF/B-III (7).
2. Differential elastic scattering cross sections of nickel and cobalt determined in the present measurements. Data points indicate measured values, curves a least square fit of a legendre series to the measured values.
3. Inelastic neutron excitation cross sections of nickel and cobalt. The present experimental results are indicated by $\odot$ (nickel) and $\square$ (cobalt). Other data points refer to measured values taken from the literature. The evaluated results are indicated by the solid curves. Dotted and dashed curves indicate the results of theoretical calculations as described in the text and Ref. 2. The excitation energies of the respective states are given in MeV and, in the case of nickel, the isotope is identified.
4. (n,2n) and (n,p) cross sections of Ni-58. The experimental data base is indicated by data points with the present results noted by $\odot$. The curves indicate the results of evaluations. Detailed description is given in Ref. 2.

Fig. 1

Fig. 2

Fig. 3

Fig. 4