Effects of Nuclear Deformation on Neutron Total Cross Sections

Dennis Gilbert Blondin

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EFFECTS OF NUCLEAR DEFORMATION
ON NEUTRON TOTAL CROSS SECTIONS

by

Dennis Gilbert Blondin

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment
of the
Degree of Master of Arts

Western Michigan University
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Finally, I would like to thank my wife, Elaine, for her faith, patience, and understanding during the course of this project.

Dennis Gilbert Blondin
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I. INTRODUCTION

It is well known that the ground state of certain nuclei, those with $144 \leq A \leq 190$ and $A$ greater than about 200, have permanently deformed non-spherical shapes. The magnitude and type of deformity is generally specified by a combination of deformation parameters describing the nuclear surface (St 65).

Most of the presently available information (Go 72) about nuclear deformation has been obtained using experimental techniques which are sensitive only to the charge distribution of the nucleus. It is of considerable interest to obtain experimental information on the deformation of the nuclear mass distribution as well. Although it is generally assumed that the shape of the mass distribution is the same as the shape of the charge distribution, there is no reason to believe a priori that this is so. In fact, there is some recent experimental evidence that the mass distribution may be different than the charge distribution (St 71).

The mass distribution of nuclei can be investigated by using nucleons as probes, i.e., by nucleon-nucleus scattering. However, the results of recent experiments on the scattering of protons by nuclei near 16 MeV are inconclusive (St 67).

It has been demonstrated using polarized targets that the neutron total cross section depends on the nuclear shape. Extensive experiments which have been performed using polarized $^{165}$Ho targets show that the neutron total cross section of
\(^{165}\)Ho, a deformed nucleus, depends on its orientation. This phenomenon can be understood qualitatively in terms of the nuclear Ramsauer effect, i.e., interference between neutron waves going through the nucleus and neutron waves going around the nucleus. However, measurements of this nature require monoisotopic targets which orient easily at low temperatures and high magnetic fields.

Recently, Glasgow and Foster (G1 71) have presented evidence that neutron total cross sections of nuclei which are unoriented may provide information concerning nuclear deformation. These authors compared measured total cross sections of 19 nuclei known to be permanently deformed with calculated total cross sections based on the spherical non-local optical potential of Perey and Buck (Pe 62). The large differences which are observed, up to 19 percent, were interpreted as arising from the deformation of the target nuclei.

A study of the samarium isotopes is particularly desirable for investigating the effects of nuclear deformation on the neutron total cross section because these isotopes span the region near a neutron number of 88 where the nuclear deformation changes rapidly.
Recent experimental values for the deformation parameters of some samarium isotopes are listed in Table I. It is noted that the nuclear quadrupole deformation parameter $\beta_2$ changes by nearly a factor of two, from about 0.190 to 0.351, between $^{150}\text{Sm}$ and $^{154}\text{Sm}$.

In the present work, the effects of nuclear deformation on neutron total cross sections from 1 to 15 MeV was investigated by measuring the total cross section differences between $^{152}\text{Sm}$ and $^{150}\text{Sm}$ and between $^{154}\text{Sm}$ and $^{150}\text{Sm}$. In addition, the absolute neutron total cross section of $^{150}\text{Sm}$ was measured over the same energy range. The experimental data were compared with calculated neutron total cross sections which were obtained with the local optical potential code PEREY using parameters of Perey (Ma 70), and of Becchetti and Greenlees (Be 69). Both sets of parameters are believed to be valid for spherical nuclei.
TABLE I
EXPERIMENTALLY OBTAINED GROUND STATE DEFORMATION PARAMETERS OF SOME SAMARIUM ISOTOPES

<table>
<thead>
<tr>
<th>A</th>
<th>$\beta_2$</th>
<th>$\beta_4$</th>
<th>REFERENCE</th>
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<tr>
<td>144</td>
<td>0.057, 0.055</td>
<td></td>
<td>Wo 72a</td>
</tr>
<tr>
<td>148</td>
<td>0.158</td>
<td></td>
<td>St 65</td>
</tr>
<tr>
<td></td>
<td>0.108, 0.107</td>
<td></td>
<td>Wo 72a</td>
</tr>
<tr>
<td>150</td>
<td>0.190</td>
<td></td>
<td>St 65</td>
</tr>
<tr>
<td></td>
<td>0.184</td>
<td></td>
<td>El 60</td>
</tr>
<tr>
<td></td>
<td>0.146, 0.139</td>
<td></td>
<td>Wo 72a</td>
</tr>
<tr>
<td>152</td>
<td>0.304</td>
<td>0.048</td>
<td>St 65</td>
</tr>
<tr>
<td></td>
<td>0.290</td>
<td>0.05</td>
<td>El 60</td>
</tr>
<tr>
<td></td>
<td>0.246</td>
<td>0.09</td>
<td>Ba 71</td>
</tr>
<tr>
<td></td>
<td>0.248</td>
<td></td>
<td>St 71</td>
</tr>
<tr>
<td></td>
<td>0.260, 0.262</td>
<td></td>
<td>Wo 72a</td>
</tr>
<tr>
<td>154</td>
<td>0.351</td>
<td></td>
<td>St 65</td>
</tr>
<tr>
<td></td>
<td>0.336</td>
<td></td>
<td>El 60</td>
</tr>
<tr>
<td></td>
<td>0.270</td>
<td>0.054</td>
<td>He 68</td>
</tr>
<tr>
<td></td>
<td>0.261</td>
<td>0.13</td>
<td>St 71</td>
</tr>
<tr>
<td></td>
<td>0.323, 0.294</td>
<td></td>
<td>Wo 72a</td>
</tr>
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†) All data is taken from Table 2, reference Go 72, except for that of reference St 71.
II. THEORETICAL CONSIDERATIONS

A. General

An exact treatment of the scattering of neutrons by nuclei is one in which all the interactions between the nucleons present are considered. In this case even the simplest of interaction processes is prohibitively complicated with central, spin-orbit, exchange, and tensor components for each interaction. However, the many-body interaction can effectively be reduced to a two-body neutron-nucleus interaction. In this treatment, the incident neutron sees an average potential due to the nucleons which constitute the target nucleus. This model of the scattering process is referred to as the Optical Model in reference to the representation of the nucleus by a complex potential classically analogous to refraction and absorption processes due to an index of refraction. The optical potential has a real component to represent elastic processes and an imaginary component to represent absorption and compound elastic processes. The parameters of the potentials are obtained by fitting experimental data. It is usually assumed that for a given incident particle energy and a given target nucleus the potential depends only on the space coordinate. This type of potential is called a local potential. A local potential is momentum-dependent in that the potential parameters change with incident particle energy. The optical model of the nucleus has been found to be useful for describing
the scattering of a variety of incident particles including protons, neutrons, deuterons, helium nuclei, and pions.

It has been shown (Ho 63) that when the abstract vector formulation of the many-particle problem is reduced, e.g., to a neutron-nucleus problem, the resultant potential has a non-local nature. This means that the potential depends not only on the space coordinate but also on the value of the neutron wave function over all space. Thus, the term with the local potential \( V(r) \Psi(r) \) in the Schrödinger equation describing the interaction becomes the term

\[
\int V(r, r') \Psi(r') dr',
\]

where \( V(r, r') \) is the non-local potential in the integro-differential Schrödinger equation. Mathematically, this is equivalent to a momentum-dependent potential (Ho 63). Also, it has been shown that for a given set of non-local parameters, there exists an equivalent set of local parameters (Pe 62).

B. The Local Potential

One of the local optical potentials used in this work is the one given by Becchetti and Greenlees (Be 69). Their optical potential for neutrons, \( V(r) + iW(r) \), is a combination of Woods-Saxon volume and surface derivative forms where
\[ V(r) = - V_R \left\{ (r, R_R, a_R) \right\} \quad \text{(central, real term)} \]

\[ + V_{SO} \left( \mathbf{\tau} \cdot \mathbf{\ell} \right) \lambda^2 (1/r) (d/dr) \left\{ (r, R_{SO}, a_{SO}) \right\} \quad \text{(spin-orbit term) (2)} \]

and \[ W(r) = - W_V \left\{ (r, R_V, a_V) \right\} \quad \text{(imaginary volume term)} \]

\[ + W_{SF} 4a_I (d/dr) \left\{ (r, R_I, a_I) \right\} \quad \text{(imaginary surface term) (3)} \]

and where \[ \left\{ (r, R, a) \right\} = \left[ 1 + \exp(r-R)/a \right]^{-1} \]

\[ R_i = r_i A^{1/3} \]

= the radii of a nucleus of mass \( A \).

\[ \mathbf{\tau} \cdot \mathbf{\ell} = \text{Scalar product of angular momentum operators.} \]

\[ \lambda^2 = \text{pion Compton wavelength} \]

squared \( \approx 2.0F^2 \).

All energies are in MeV, and lengths are in fermis (1F = \( 10^{-13} \) cm). The \( a_i \) are the diffuseness parameters associated with the various potential surfaces. The strength of the central, real potential is given by \( V_R \), the spin-orbit potential by \( V_{SO} \), the imaginary volume and surface terms by \( W_V \) and \( W_{SF} \). The geometry of the potential is governed by the \( R_i \) and \( a_i \).

A consistent set of Optical Model parameters were obtained by Recchetti \textit{et al.} by using a fitting routine to fit available

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differential and total cross section data for natural samples with $A > 50$ and for neutron energies less than 75 MeV. Previously obtained proton parameters were used as starting values. The energy dependence of the "best set" of neutron parameters they obtained is given by

$$V_R = 56.3 - 0.32E - 24.0(N-Z)/A,$$

$$W_V = 0.72E - 1.56$$

or zero; whichever is greater,

and

$$W_{SF} = 13.0 - 0.25E - 12.0(N-Z)/A$$

or zero; whichever is greater,

where $E$ is the incident neutron lab energy in MeV. A constant spin-orbit strength $V_{SO} = 6.2$ MeV is used. Other constant parameters are

$$r_R = 1.17$$

$$a_R = 0.75$$

$$r_I = r_I' = 1.26$$

$$a_I = a_I' = 0.58$$

$$r_{SO} = 1.01$$

$$a_{SO} = 0.75$$

Except for the inclusion of a small amount of tungsten data, these parameters were obtained by fitting data for nuclei which are believed to be spherical.

Becchetti et al. found that for $E < 10$ MeV, a correction was needed for both the differential and total absorption cross section data due to compound elastic scattering. The fit to neutron data is poorest for total cross sections for nuclei of $A < 90$. 

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C. Optical Model Calculations

The Schrödinger wave equation can be transformed into a set of radial wave equations by expanding the wave function in terms of spherical harmonics. Since the respective angular momenta of the incident particle and target nucleus couple in only two possible spin orientations, the resulting radial functions obtained in asymptotic form (Bu 60) are

\[ U_{q}^{\pm}(\rho) = F_{q}(\rho) + iG_{q}(\rho) + S_{q}^{\pm} \left[ F_{q}(\rho) - G_{q}(\rho) \right] \]  

(4)

where \( F_{q}(\rho) \) and \( G_{q}(\rho) \) are the regular and irregular solutions of the radial wave equation and the \( S_{q}^{\pm} \) are the complex elements of the scattering matrix. The total absorption cross section is given by

\[ \sigma_{A}^{-} = \frac{2\pi}{k^{2}} \sum_{q=0}^{\infty} \left\{ (q+1)(1-|S_{q}^{+}|^{2}) + \ell(1-|S_{q}^{-}|^{2}) \right\} , \]

the total elastic cross section for uncharged incident particles by

\[ \sigma_{E}^{-} = \frac{2\pi}{k^{2}} \sum_{q=0}^{\infty} \left\{ (q+1) \left| S_{q}^{+} \right|^{2} + \ell \left| S_{q}^{-} \right|^{2} \right\} \]

and the total cross section, \( \sigma_{A}^{-} + \sigma_{E}^{-} \), by

\[ \sigma_{T}^{-} = \frac{2\pi}{k^{2}} \sum_{q=0}^{\infty} \left\{ (q+1)(1-\text{Re} S_{q}^{+}) + \ell(1-\text{Re} S_{q}^{-}) \right\} \]  

(5)

Generally the wave function and scattering amplitudes are obtained through numerical integration of the radial wave equation and \( \ell \) values greater than a value \( \ell_{\text{max}} \) are not used as they contribute little to the final summations above.
D. The Non-local Potential

The non-local potential used by Perey and Buck (Pe 62) has the form

\[ V(r, r') = U \left( \frac{1}{2} \right) H \left( \frac{|r - r'|}{\beta} \right) \]

where \( \beta \) is the range of the non-locality. The potential is incorporated into an integro-differential Schrödinger equation which may be solved exactly by numerical iteration. \( H \) was taken to be a Gaussian function. The first term was similar to a local potential:

\[ -U(p) = (V + \alpha W_x) \int_S (p) + \lambda W_b (d/dp) \int_S (p) \]

where \( V \) is the real central strength, \( W_x \) is the volume absorption strength, \( W_b \) is the surface absorption strength, and \( \int_S (p) \) is a Saxon-Woods function, and where \( p = \frac{1}{2} |(r + r')| \).

A spin-orbit term is included separately in the non-local wave equation.

To facilitate the solution of the non-local wave equation, Perey and Buck redefined \( p \) as

\[ p = \frac{1}{2} (r + r') \]

The justification was that \( \bar{r} \approx \bar{r}' \) due to the short range of the non-locality. An initial set of non-local parameters was found, using the above approximation, by obtaining a fit to differential cross section data at 14 MeV for \(^{56}\)Fe. It was shown that the same parameters gave reasonable fits at energies from 4.10 to 26 MeV. When a local optical model was used to fit the same data a near perfect fit was made to the non-local...
results, implying that the results predicted by the non-local model can always be reproduced by using an equivalent local optical model.

A formula was developed which gave approximate relationships between non-local and energy dependent local parameters:

\[ U_L(r) \exp \left[ \frac{
abla^2}{2 \alpha} (E-U_L(r)) \right] = U_N(r), \]  

(9)

assuming \( \nabla_L(\bar{F}) \approx \nabla_N(\bar{F}) \), where the subscript \( L \) denotes a local function and \( N \) a non-local function. The relation was used to obtain an approximate value for \( \beta \) and the non-local potential depth \( V_N \), using local parameters found for fitting angular distribution data of \(^{208}\text{Pb} \) at neutron energies up to 80 MeV. As \( \beta \) and \( V_N \) remained essentially constant at all these energies, the full form of the non-local potential together with spin-orbit and absorption potentials with equation (9) produced a set of non-local parameters from fitting of Pb data at 7.0 and 14.5 MeV.

The above simplified non-local model gave good results for nuclei from Al to Pb at neutron energies up to 24 MeV. Comparing the non-local model of Perey-Buck with a local optical model (Fe 58) in the same neutron energy range has shown that the fixed non-local model gives as good a fit to available data as the energy dependent model.

An equivalent local set of parameters has been reported by Perey for neutron energies 1-135 MeV (Ma 70). The energy dependence of these parameters is similar to that of the
Becchetti-Greenlees parameters.

E. Nuclear Ramsauer Effect

A physical explanation of the broad maxima and minima in a neutron total cross section can be attributed to a nuclear Ramsauer effect in which the part of the wave associated with the neutron goes through the region of the nuclear potential and interferes with the part of the wave going around it. The phase difference depends on the change in the neutron wave number upon entering the nucleus. The change in wave number, \( \delta k \), is given by

\[
\delta k = \left( \frac{2M}{\hbar^2} \right)^{1/2} \left[ \left( E + U \right)^{1/2} - E^{1/2} \right]
\]

where \( M \) is the reduced mass, \( E \) is the center of mass energy, and \( U \) is the nuclear potential depth (Ho 63). It has been shown that maxima corresponding to a phase difference of \( \pi \) are predicted at about the energies at which they are observed experimentally (La 53).

If the target nucleus is non-spherical, then the path length of the neutron through the nucleus will depend on the nuclear orientation. Wong et al. (Wo 72) have pointed out that the net effect of scattering from an assembly of deformed nuclei with random orientations will be a smoothing of the total cross section.
F. Coupled-Channel Approach

Many nuclei, particularly those in the rare earth region, are permanently deformed. The polarized target work of Marshak et al. indicates that the optical model does not adequately predict measurements of highly deformed nuclei (see, for example, reference Ma 70). Calculations must be made which take into account the strong coupling of the low-lying rotational collective states. Because of the coupling terms, the Schrödinger equation describing the scattering process becomes a set of coupled differential equations.

In the formalism of coupled-channel calculations given by Tamura (Ta 65), the potential given by equations 1 and 2 is a function of the spherical coordinates of the incident particle. The nuclear radii, \( R_j \), are dependent on these coordinates according to the deformed nature of the target nucleus. If the target is an axially symmetric permanently deformed nucleus, the radius is expressed as a series of spherical functions, each with an associated strength function. The resulting potential is then expanded in terms of Legendre polynomials associated with the expression for the target radii. The resulting expression for the potential can be separated into a term of the diagonal elements of a rotation matrix, which is just the usual optical potential, and a term consisting of the off-diagonal elements representing the nuclear coupled states.
Coupled-channel calculations have been used extensively to analyze inelastic scattering data (Ta 69). Because of this ability, coupled-channel calculations are able to describe multiple-excitation processes successfully. Other calculations, such as the distorted-wave Born approximation, may become poor approximations if the interaction processes become strong. Therefore, coupled-channel calculations may be used successfully to calculate inelastic cross sections of various permanently deformed nuclei. In this application strong interaction is present, and multiple-excitation cross sections are appreciable.
III. EXPERIMENTAL DETAILS

A. General

The determination of neutron total cross section involves the measurement of the neutron flux transmitted by a sample relative to that without the sample. This flux change is related to the total cross section $\sigma_T$ by the relation

$$\frac{I}{I_0} = \exp(-N \sigma_T)$$  \hspace{1cm} (11)$$

where $I_0$ is the incident flux, $I$ is the flux after passing through the sample, and $N$ is the number of nuclei per cm$^2$ in the sample. Using the experimental arrangement shown in Figure I, the measurement of $I$ is made with the sample in place, and $I_0$ is measured without the sample. The ratio $I/I_0$ is called the transmission.

B. Geometry

The geometry of the experiment must be such that the effects of inscattering and backgrounds are minimized. This means, for example, that the ratio of the sample diameter to the source-to-detector distance must be made suitably small (Mi 63). The transmission measurements employed experimental components arranged as shown in Figure I. The source-to-detector distance, $L$, was chosen to give reasonable counting rates with the desired transmissions (Mi 63). The sample was placed so that its midpoint was a distance $L/3$ from the neutron
Figure I. Geometry used for the transmission measurements. The source represents the beam spot on the target, the detector represents the stilbene scintillation crystal, and the sample represents a longitudinal cross section of a typical oxide sample. The distance L was about 50 cm for the present measurements.
SOURCE       SAMPLE       DETECTOR

\[ \frac{L}{3} \]
target. At this position the sample completely shadowed the neutron detector from the neutron source. Although calculations (Mi 63, Fo 61) show that the \(L/2\) sample position corresponds to a minimum of inscattering, it can be shown that the correction for neutrons singly scattered into the detector from the \(L/3\) position is not appreciably larger.

The half-angle subtended by the detector at the source was 1.1 degrees.

C. Neutron Production

Monoenergetic neutrons for this experiment were obtained with the \(T(p,n)^3\text{He}\) reaction for neutron energies from 0.79 to 6.25 MeV and with the \(D(d,n)^3\text{He}\) reaction for neutron energies from 4.48 to 14.48 MeV.

The charged particle beam was provided by the WMU 12 MeV model EN tandem Van de Graaff accelerator. The absolute charged particle beam energies were obtained from calculations based on a previous calibration (Pa 71) of the analyzing magnet. The corresponding uncertainties in the absolute neutron energies ranged from less than 0.5 keV at 0.79 MeV to about 1 keV at 6.25 MeV using the \(T(p,n)^3\text{He}\) reaction, and about 0.6 keV at 4.5 MeV to about 5.0 keV at 14.48 MeV using the \(D(d,n)^3\text{He}\) reaction. These absolute uncertainties do not include the error due to the reproducibility in recycling the analyzing magnet. Nevertheless, the rms value of the
absolute energy and reproducibility uncertainties are small compared to the errors due to energy spreads in the target materials.

The target apparatus consisted of three stainless steel sections separated by glass insulators. A sketch of the target apparatus is shown in Figure II. The third section was designed to hold, with threaded target fittings, both solid target and gas target cells. The second or center section was negatively biased at 200 volts in order to suppress secondary electrons from the target and from an anti-scattering baffle in the electrically grounded first section.

Beam collimation at the target was optimized by monitoring the current on a 1/8 inch aperture tantalum collimator (see Figure II). The charged particle beam was focused with a quadrupole lens so as to minimize the collimator current. The collimator was fixed to the end of a bellows assembly used to align the target.

The solid target was a disc of titanium-tritium on a platinum backing. The titanium-tritium target1 consisted of a 3/8 inch diameter, 500 microgram per cm$^2$ titanium-tritium layer on a 9/16 inch diameter, 0.010 inch thick platinum

---

1Purchased from Amersham/Searle Corporation, Arlington Heights, Illinois.
Figure II.
Illustration of the target apparatus. Shown numbered are the three sections discussed in the text. A cross sectional view of the bellows assembly and part of the first section of the target assembly is given to show the placement of the collimator and anti-scattering baffle. The target was either a solid $^3$H-Ti target, as shown, or a gas target filled with deuterium.
ANTI-SCATTERING BAFFLE

GLASS INSULATORS

FLANGE

TANTALUM COLLIMATOR

PLEXIGLASS INSULATOR

SOLID TARGET

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backing. To minimize target heating and prevent possible tritium outgassing, the solid target was cooled by an air jet, and the proton beam current was held below 0.5 microampere.

The gas targets were cylindrical cells filled with deuterium gas. Two gas target cells were used which differed only in length: 2 cm and 4 cm. The gas cells used either tantalum or gold beam stops which were inserted and held in place against one end with a thin wire spacer. It was found that the gold contributed less background than the tantalum. A 1.25 micron thick nickel foil cemented to a tantalum washer served as the entrance window separating the gas cell from the vacuum. Thin diameter copper tubing connected the cells to a pressure gauge and a deuterium gas manifold, making it a simple procedure to vary the gas target thickness. Deuterium gas pressures of from 1/4 to 4/5 atmosphere were used in the air-cooled gas cells.

The neutron energy spread due to proton energy losses in the titanium-tritium target ranged from 58 keV at 0.79 MeV neutron energy to 20 keV at 6.25 MeV. For the gas target, the deuterium pressure was adjusted so that the total energy spread due to straggling in the nickel foil and energy loss in the gas was always less than about 70 keV. The energy uncertainty is believed to be less than 1/5 the energy loss in the target, i.e., always less than 15 keV.
D. Detection System

Because of the gamma ray background present a neutron-gamma ray discrimination system was used consisting of a stilbene crystal scintillator associated with a gamma ray discrimination circuit. The stilbene scintillator, 1.91 cm in diameter and 2.47 cm long, was optically coupled to an RCA 8575 photomultiplier tube.

The stilbene detector response to an incident neutron is slightly different from the response to an incident gamma ray. The light decay from the stilbene results from a combination of an intense fast decaying component and a less intense slow decaying component. For incident neutrons the slow component is more intense than for gamma rays. This difference in decay times of the scintillations is converted into differences in rise times of the pulses from the photomultiplier viewing the scintillations.

A simplified block diagram of the electronics is outlined in Figure III. A fast timing signal was derived from the anode of the photomultiplier. The linear signal was taken from the last dynode and was integrated and differentiated by a double delay line linear amplifier. The crossover point of the bipolar signals from this amplifier is slightly different for

\[ \text{Purchased from Harshaw Chemical Company, Cleveland, Ohio.} \]

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Figure III. 
Block diagram of gamma ray discrimination circuitry. The neutron gate, shown as a dashed line, was used only before data runs in order to demonstrate complete gamma ray discrimination on the PHA time spectrum.
neutrons compared to gamma rays due to the scintillation characteristics already mentioned. This timing difference is used to obtain neutron-gamma ray discrimination.

Since the amplitude of the dynode signal is related to the energy of the event, a low level discrimination circuit was used to bias out the low energy background pulses. A unipolar signal from the linear amplifier was used to record, on a scaler, the total number of pulses as a check on possible pile-up problems. The low level bias was set with a timing single channel analyzer (TSCA) which also sensed for the crossover point giving a negative fast logic signal used as a stop pulse for the time to amplitude converter (TAC). The anode signal, passed through a fast discriminator to obtain a fast negative timing signal, was delayed and used as a start pulse for the TAC.

The TAC output was a bipolar signal with an amplitude proportional to the time interval between the start and stop pulses. Thus, there were essentially two distinct ranges of TAC output amplitudes corresponding to the neutron and gamma ray events. A typical TAC spectrum obtained with the system is shown in Figure IV.

The window of a TSCA was placed over the neutron group enabling only the neutron events to be recorded. A second output from the TAC was delayed and used to record, on a pulse height analyzer (PHA), the neutron-gamma ray time spectrum.
The signal from the TSCA establishing the neutron window was used to gate the output of the double delay line amplifier thereby presenting on another PHA a proton-recoil energy spectrum of neutrons, as shown in Figure V, with the low energy background biased out.

The events recorded by the low-bias scalar were used as a measure of \( I \), the number of neutrons transmitted through the sample. The spectra from the analyzers were used only to optimize the detection system.

E. Samples

A standard stainless steel sample container, shown in Figure VI, was designed to hold the various samples. Adjustable end caps permitted a predetermined mass of each powdered sample to be used. The masses of the samarium samples were chosen so that the number of \( \text{Sm}_2\text{O}_3 \) molecules per sample was the same for all of the samarium samples: 40.000 grams of \(^{150}\text{Sm}_2\text{O}_3\), 40.460 grams of \(^{152}\text{Sm}_2\text{O}_3\), and 40.920 grams of \(^{154}\text{Sm}_2\text{O}_3\). The powdered samarium samples were on loan from Oak Ridge National Laboratory. A fourth powdered sample was beryllium-oxide as BeO. Solid samples included machined cylinders of metallic beryllium, carbon as \(^{12}\text{C}\), and polyethylene as \(\text{CH}_2\). The transmission was about 50 percent for the samarium-oxide samples and about 60 percent for the beryllium-oxide and beryllium samples.
Figure IV.
The output of the time to amplitude convertor (TAC) at 4.73 MeV neutron energy. The relative magnitude of the peaks and their separation will depend on the intensities and energies of the neutron and gamma fluxes and on the particular amplifier and discriminator settings used. The peak separation for this particular time spectrum is about 15 nanoseconds. The arrows indicate the TSCA acceptance window as seen by the low bias scaler. This window was set using the neutron gate indicated in Figure III.
Figure V.
The proton recoil spectrum from the stilbene scintillator at 4.73 MeV neutron energy. The arrows indicate the low and high bias respectively. This is the energy spectrum corresponding to the time spectrum of Figure IV.
Each solid sample was positioned in the center of its container with thin wire spacers. The solid carbon and polyethylene samples were used to compare our measurements with well known n-p total cross sections (Ho 71, Da 71) and with previous carbon measurements, as a check on the experimental procedures. The transmission of the polyethylene sample relative to the carbon sample was about 50 percent.

A routine was devised for the filling of the powdered oxide samples so as to prevent voids and to assure a reasonably fast transfer of the sample material from the storage container to the sample container. These oxides tend to become contaminated by adsorbing water vapor and other gases. Therefore, needless atmospheric exposure of the oxides was avoided. When not in use, the prepared sample containers were kept sealed in a desiccator.

The prepared samarium samples were weighed with a Mettler H-18 balance before transfer to the sample containers. Discrepancies were observed between our measured masses and the masses specified by Oak Ridge National Laboratory. The extra mass amounted to 121 mg of the measured $^{150}\text{Sm}_2\text{O}_3$ mass, 81 mg of $^{152}\text{Sm}_2\text{O}_3$, and 137 mg of $^{154}\text{Sm}_2\text{O}_3$. After consultation with ORNL, the mass discrepancies were attributed to water adsorbed by the samples while in their shipping containers, which were not air tight.
Figure VI. Sketch of the sample container. The end cap, open end out as shown, fits snugly into the cylinder. An air tight seal results when the two beveled flanges compress the o-ring.
F. Procedure

In order to find the uncorrected transmission for $^{150}\text{Sm}$, four samples were used: beryllium-oxide (BeO), beryllium (Be), an empty or blank sample container (BLK), and samarium-oxide ($^{150}\text{Sm}_2\text{O}_3$).

The samarium-oxide total cross section was obtained using the relation:

$$I_{^{150}\text{Sm}_2\text{O}_3}/I_{\text{BLK}} = \exp\left\{-(N_{^{150}\text{Sm}}\sigma_{^{150}\text{Sm}} + N_0\sigma_0 + N_{\text{BLK}}\sigma_{\text{BLK}}) + N_{\text{BLK}}\sigma_{\text{BLK}}\right\}$$

$$= \exp\left\{N_{^{150}\text{Sm}}\sigma_{^{150}\text{Sm}} - N_0\sigma_0\right\} \quad (12)$$

where $I_{^{150}\text{Sm}_2\text{O}_3}$ and $I_{\text{BLK}}$ are the count rates due to the respective samples, where $\sigma_{^{150}\text{Sm}}$, $\sigma_0$, and $\sigma_{\text{BLK}}$ are the total cross sections of $^{150}\text{Sm}$, natural oxygen and the empty sample container respectively, and where the $N_i$ are the respective numbers of nuclei per cm$^2$ for the various samples.

Both the beryllium-oxide and beryllium samples contained equal numbers of beryllium nuclei per unit area; thus, the oxygen cross section was obtained by subtracting the beryllium cross section from that of beryllium-oxide:

$$I_{\text{BeO}}/I_{\text{Be}} = \exp\left\{-(N_0\sigma_0 + N_{\text{Be}}\sigma_{\text{Be}} + N_{\text{BLK}}\sigma_{\text{BLK}}) + (N_{\text{Be}}\sigma_{\text{Be}} + N_{\text{BLK}}\sigma_{\text{BLK}})ight\}$$

$$= \exp\left\{-N_0'\sigma_0\right\} \quad (13)$$

where $N_0'$ is the number of nuclei per cm$^2$ in the beryllium-oxide sample.
Letting \( \frac{N_o}{N_o'} = k \),

\[
\left( \frac{I_{BeO}}{I_{Be}} \right)^k = \exp\left( -N_o \sigma_o \right)
\]

then

\[
\left( \frac{I_{Sm;O}}{I_{Sm}} \right)^k \left( \frac{I_{BeO}}{I_{Be}} \right) = \exp\left( -N_{150Sm} \sigma_{150Sm} \right).
\]  \( (14) \)

The total cross section difference between, e.g., \( ^{152}\text{Sm} \) and \( ^{150}\text{Sm} \), was determined by measuring the ratio of the transmissions for these samples. The cross section difference was then given by

\[
\sigma_{152} - \sigma_{150} = \frac{1}{n} \ln\left( \frac{I_{152}}{I_{150}} \right)
\]  \( (15) \)

where \( n \), the number of samarium nuclei per cm\(^2\) in each of the samples, is the same for all the samarium isotopes. It should be noted that the effect of the oxygen present in the samples cancels out.

In the present experiment, \( I \) was measured so as to obtain statistical uncertainties in the total cross section of less than 2% percent. Because of this requirement, the total number of counts for a particular sample was summed from several runs, each of relatively short duration. The runs were taken in a sequence of measurements in which individual samples were alternated with others in a systematic manner designed to eliminate counting inconsistances resulting from variations in target neutron yield and detector bias drift. The sequence of runs was blank container, \( ^{154}\text{Sm}, ^{150}\text{Sm}, ^{152}\text{Sm}, ^{152}\text{Sm}, ^{150}\text{Sm}, ^{154}\text{Sm}, \) blank container, shadow cone,
BeO, Be, Be, BeO, and shadow cone. The resulting transmissions were corrected for background and in-scattering effects.

Runs were normalized by integrating the charged particle beam at the target. A long counter was also used to monitor the incident neutron flux.

Hydrogen and carbon measurements were made as checks on the experimental procedure. $n-p$ total cross sections were measured at 4.99 and 8.58 MeV to an accuracy of 0.6 percent and a carbon total cross section was measured at 5.75 MeV to an accuracy of 1.2 percent. The hydrogen runs were taken concurrently with runs for the $^{154}$Sm - $^{150}$Sm cross section difference. The $n-p$ total cross sections were 1.634 and 1.074 barns at 4.99 and 8.58 MeV respectively. These cross sections were compared with computations based on Yale phase shifts (Da 71, Ho 71) and were found to agree within 0.2 and 0.1 percent respectively. The present carbon measurement of 1.055 barns at 5.75 MeV agrees with that of Fossan to within 0.45 percent.

The effect on the cross section differences due to differing amounts of oxygen in the $\text{Sm}_2\text{O}_3$ samples was investigated by performing measurements at neutron energies where the oxygen total cross section varied widely. Measurements were made at neutron energies of 2.37, 2.73, and 3.60 MeV. The oxygen total cross section at these energies is in the
No indication of any effect due to the oxygen in the samples was observed.

G. Corrections

Corrections to the transmission must be made due to background and inscattered neutrons. The background neutrons are of two types: room-scattered neutrons and neutrons in the beam direction not produced by the source reaction.

Room-scattered neutrons are those scattered into the detector from the associated equipment, walls and floor. Since these neutrons are generally scattered at large angles and are of comparatively low energy, they can be largely biased by the detection system. Room-scattered neutrons were detected by placing a 23 cm long copper shadow cone in the sample position, just shadowing the detector crystal from the course. The transmission with the shadow cone in the sample position was 0.007 at 13.9 MeV.

Neutrons in the beam direction not produced by the source reaction are low energy background caused by the charged particle beam striking collimators, control slits, and the target backing. In order to measure the background due to neutrons produced by the target backing, the solid target was replaced by an identical disc without tritium, and the gas target cells were evacuated. The background corrected count rate was obtained by subtracting the corrections.
as shown below:

\[ I_c = I_{ob} - I_{sc} - B + B_{sc} \]  \hspace{1cm} (16)

where \( I_{ob} \) is the observed count rate with the source reaction, \( I_{sc} \) is the count rate with the shadow cone and source reaction, \( B \) is the count rate with sample in with the blank target, and \( B_{sc} \) is the count rate with the shadow cone in with the blank target. \( B_{sc} \) must be added to the observed count rate because it is present in both correction terms. \( B_{sc} \) was measured to be extremely small and was therefore assumed to be zero.

A correction was made to the background corrected count rate in order to compensate for inscattering. Inscattering is the forward scattering of neutrons into the detector due to the finite area of the detector and sample: neutrons which have interacted with the sample must not be counted. The largest single-inscattering correction was 0.7 percent at 14.48 MeV. Inscattering effects due to the multiple scattering of neutrons are considerably smaller than those due to single scattering (Mi 63) and were therefore ignored.

After the above corrections were made and cross sections obtained, the absolute \(^{150}\text{Sm}\) total cross section and the cross section differences were corrected for the contribution in the cross sections due to water absorbed in the samarium samples (see section III-E). A correction term subtracted from the \(^{150}\text{Sm}\) total cross section ranged from 4.7 percent at 0.79 MeV to 1.8 percent at 14.48 MeV. The correction due
to the presence of water for the cross section difference of $^{152}\text{Sm} - ^{150}\text{Sm}$ divided by the cross section of $^{150}\text{Sm}$ varied from 0.015 at 0.79 MeV to 0.006 at 14.48 MeV. The correction due to the presence of water for the cross section difference of $^{154}\text{Sm} - ^{150}\text{Sm}$ divided by the cross section of $^{150}\text{Sm}$ varied from 0.007 at 0.79 MeV to 0.002 at 14.48 MeV. No correction was made for impurities other than water because their exact quantities were unknown. The effects of non-water impurities on the cross sections were small (see Table III).
IV. EXPERIMENTAL RESULTS

A. Total Cross Section of $^{150}\text{Sm}$

The total cross section of $^{150}\text{Sm}$ from 0.8 to 14.5 MeV neutron energy is shown in Figure VIII. The statistical uncertainties are about the same size as the data points. Presented with the data are three cross section curves calculated using the optical model. Two of these curves have been computed as described in section III-C using parameters reported by Perey (Ma 70), and by Becchetti and Greenlees (Be 69). The third curve is the result of calculations for natural samarium reported by Glasgow (G1 72, G1 71), using the non-local parameters of Perey and Buck. The data varies smoothly with energy over the energy range investigated as expected for a nucleus of this mass. The maximum near 1 MeV is a result of a predicted broad D-wave resonance (Fe 54).

Shown in Figure VII is the total cross section data of natural samarium (Sm) reported by Foster and Glasgow (Fo 71). The displayed data included only every third point of their results. The errors shown are typical and represent statistical uncertainties. Since the natural abundance of $^{150}\text{Sm}$ is only 7.4 percent of the stable samarium isotopes, exact agreement between the Sm data and the $^{150}\text{Sm}$ data is not expected. Nevertheless, there is good quantitative agreement between
Figure VII.
The total neutron cross section of natural samarium (Sm). The data is that of Foster and Glasgow (Fo 71). Every third data point of their data is shown. The error bars shown represent statistical errors only. The dashed curve was computed by Glasgow and Foster (Gl 71) using the non-local optical model parameters of Perey and Buck (Pe 62). The solid curve was computed using optical model parameters reported by Becchetti and Greenlees (Be 69).
Figure VIII.
The neutron total cross section of $^{150}$Sm. The statistical errors are about equal to the size of the data points unless shown otherwise. The solid and dashed curves are identical to those of Figure VII. The dot-dashed curve was calculated using parameters determined by Perey (Ma 70).
the two sets of data below about 7 MeV neutron energy and qualitative agreement above 7 MeV. Above 7 MeV the present measurements are about 5 percent lower than those reported by Foster and Glasgow. The structure which appears in the Sm data above 10 MeV was reported by the authors to be the result of unstable operating conditions (Fo 71). The computed cross section curves are identical to those respective curves presented in Figure VIII.

B. Total Cross Section Differences

Figure IX shows the cross section difference of $^{152}\text{Sm} - ^{150}\text{Sm}$, divided by the $^{150}\text{Sm}$ cross section, hereafter referred to as the cross section difference. The errors shown are typical and represent statistical uncertainties. Also shown are curves obtained from cross sections calculated as described in section III-B. Cross sections were computed using the parameters of Perey, and of Becchetti and Greenlees. It can be seen that the cross section difference has a minimum near 2.5 MeV and a maximum at about 8 MeV with a zero-difference crossover near 4.5 MeV. At both low and high energies, the cross section difference approaches zero. In the absence of deformation effects, the cross section difference is not expected to be zero because nuclei with different mass numbers have different radii. Thus, the computed cross section for the heavier nucleus is generally larger, as expected.
Figure IX.
The total cross section difference between $^{152}$Sm and $^{150}$Sm, divided by the cross section of $^{150}$Sm. The error bars shown represent statistical errors only. Solid and dashed curves were computed using optical model parameters determined by Becchetti and Greenlees (Be 69), and by Perey (Ma 70) respectively.
The cross section difference of $^{154}\text{Sm} - ^{150}\text{Sm}$ divided by the $^{150}\text{Sm}$ cross section is shown in Figure X. Again, the error bars represent statistical errors. The data has the same energy dependence and agrees qualitatively with the data of Figure IX. In addition to showing larger cross section differences, the crossover point of Figure X has shifted down somewhat to about 4.25 MeV. Two optical model curves using parameters of Perey, and of Becchetti and Greenlees are included in this figure. Also presented is a curve which was calculated with Becchetti parameters with the diffuseness parameters increased by 5 percent.

Figure XI shows the cross section difference of $^{154}\text{Sm} - ^{152}\text{Sm}$, divided by the $^{157}\text{Sm}$ cross section. The data exhibits the trend of Figures IX and X, although the minimum is shallower and the maximum lower. The optical model curves of Perey, and of Becchetti and Greenlees are shown here also. The data shows a relatively large amount of scatter. The reason for this scatter is that although the cross section differences of the former two figures were optimized experimentally by the sequence of sample runs, the cross section difference of this figure was not (see section III-F).
Figure X.
The total cross section difference between $^{154}$Sm and $^{150}$Sm, divided by the cross section of $^{150}$Sm. The error bars are statistical. The solid and dashed curves were computed as for Figure IX. The dot-dashed curve was computed by increasing each of the Becchetti diffuseness parameters for the $^{154}$Sm total cross section by 5 percent.
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Figure XI.
The total cross section difference between $^{154}\text{Sm}$ and $^{152}\text{Sm}$, divided by the cross section of $^{157}\text{Sm}$. The error bars are statistical. Solid and dashed curves were computed using optical parameters determined by Recchetti and Greenlees, and by Perey respectively.
C. Oxygen Total Cross Sections

 Provision was made in the sequence of data runs so that a total cross section of oxygen could be determined at each neutron energy of the present data. Table II compares some of the present oxygen results with those of other recent oxygen measurements. It is noted that the present oxygen measurements generally agree better with those of Foster and of Cierjacks than with those of Fossan. Although beryllium total cross sections were found and compared with recent beryllium measurements of Fossan, and of Foster, the present measurements were not optimized for minimum systematic equipment drift. Nevertheless, the WMU beryllium measurements agree with those of Fossan (Fo 61), and with those of Foster and Glasgow (Fo 71) to within reported statistical uncertainties in the neutron energy range 5.0 to 14.5 MeV. All comparisons were made at energies where the oxygen and beryllium cross sections are relatively flat.

D. Systematic Uncertainties

 There are uncertainties in the present measurements due to various systematic uncertainties in the sample specifications and in the transmission corrections. Table III gives a summary of the sources of systematic errors and their magnitudes in parts per thousand in the $^{150}$Sm cross section at 0.79, 4.99, and 14.48 MeV. The uncertainty in the number
<table>
<thead>
<tr>
<th>$E_n$ (MeV)</th>
<th>WMU(72)</th>
<th>Fossan(61)*</th>
<th>Foster(71)*</th>
<th>Cierjacks(68)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.730</td>
<td>1.115 ± 0.018</td>
<td>1.116 ± 0.045</td>
<td>1.18 ± 0.035</td>
<td></td>
</tr>
<tr>
<td>5.465</td>
<td>0.994 ± 0.020</td>
<td>0.98 ± 0.029</td>
<td>1.063 ± 0.021</td>
<td>1.05</td>
</tr>
<tr>
<td>6.250</td>
<td>0.936 ± 0.016</td>
<td>0.85 ± 0.017</td>
<td>0.944 ± 0.022</td>
<td>0.94</td>
</tr>
<tr>
<td>7.570</td>
<td>1.112 ± 0.018</td>
<td>1.13 ± 0.020</td>
<td>1.159 ± 0.026</td>
<td>1.09 ± 0.033</td>
</tr>
<tr>
<td>8.580</td>
<td>1.135 ± 0.018</td>
<td>1.05 ± 0.032</td>
<td>1.225 ± 0.023</td>
<td>1.07</td>
</tr>
<tr>
<td>9.500</td>
<td>1.227 ± 0.018</td>
<td>1.15 ± 0.021</td>
<td>1.166 ± 0.021</td>
<td>1.17</td>
</tr>
<tr>
<td>9.980</td>
<td>1.337 ± 0.016</td>
<td>1.24 ± 0.019</td>
<td>1.347 ± 0.019</td>
<td>1.33 ± 0.040</td>
</tr>
<tr>
<td>10.742</td>
<td>1.187 ± 0.012</td>
<td>1.14 ± 0.034</td>
<td>1.328 ± 0.015</td>
<td>1.26</td>
</tr>
<tr>
<td>12.200</td>
<td>1.581 ± 0.014</td>
<td>1.42 ± 0.017</td>
<td>1.549 ± 0.008</td>
<td>1.50 ± 0.045</td>
</tr>
<tr>
<td>12.720</td>
<td>1.555 ± 0.015</td>
<td>1.48 ± 0.045</td>
<td>1.586 ± 0.008</td>
<td>1.60 ± 0.048</td>
</tr>
<tr>
<td>13.350</td>
<td>1.642 ± 0.025</td>
<td>1.44 ± 0.011</td>
<td>1.608 ± 0.011</td>
<td>1.58</td>
</tr>
<tr>
<td>13.890</td>
<td>1.650 ± 0.037</td>
<td>1.53 ± 0.046</td>
<td>1.637 ± 0.013</td>
<td>1.65</td>
</tr>
<tr>
<td>14.480</td>
<td>1.705 ± 0.035</td>
<td>1.42 ± 0.010</td>
<td>1.615 ± 0.010</td>
<td>1.66 ± 0.050</td>
</tr>
</tbody>
</table>

†) All errors are statistical. Errors given for the Fossan and the Cierjacks data are typical and represent the 3 percent statistical uncertainty reported with their respective data.

*) These data are available in tabulated format from the National Neutron Cross Section Center, Brookhaven National Laboratory.
TABLE III
SUMMARY OF SOURCES OF ERROR IN THE $^{150}$Sm MEASUREMENT

<table>
<thead>
<tr>
<th>SOURCE OF ERROR</th>
<th>ERROR (IN PARTS PER THOUSAND)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_n$(MeV)</td>
</tr>
<tr>
<td></td>
<td>0.79</td>
</tr>
<tr>
<td>No. of Scatterers per cm$^2$</td>
<td></td>
</tr>
<tr>
<td>Sample Cross Section Area</td>
<td>0.4</td>
</tr>
<tr>
<td>Total Sample Mass</td>
<td>0.05</td>
</tr>
<tr>
<td>Impurities Other Than Water</td>
<td>1.0</td>
</tr>
<tr>
<td>Water Correction</td>
<td>12.3</td>
</tr>
<tr>
<td>Background</td>
<td></td>
</tr>
<tr>
<td>Room-Scattered</td>
<td>4.2</td>
</tr>
<tr>
<td>Target-Out</td>
<td>0.0</td>
</tr>
<tr>
<td>Inscattering</td>
<td>1.7</td>
</tr>
<tr>
<td>Total (rms)</td>
<td>13.2</td>
</tr>
</tbody>
</table>
of scatters/cm$^2$ was due to an uncertainty of 0.0005 cm$^2$ in the cross section area of the sample and an estimated uncertainty of 2 mg in the sample mass.

Effects due to other rare earths and metals in the samarium samples were determined from spectrographic analyses furnished with the samples by Oak Ridge National Laboratory. The presence of these impurities introduced uncertainties in the number of samarium scatterers per cm$^2$ and in the transmission on account of the different cross sections of the various impurities. It was determined that these two uncertainties coupled in such a manner as to yield a net uncertainty of less than 0.2 percent at any neutron energy.

The error attributed to the water assumes that this correction has an uncertainty of 25 percent. This large uncertainty was assigned to the water correction (see section III-G) because of the possibility that adsorbed gases other than water vapor, e.g., CO$_2$, may have been present. The uncertainties for both the room-scattered and target-out backgrounds were estimated by assuming a 20 percent uncertainty in the number of background neutrons. The uncertainty for inscattering was determined by assuming a 20 percent uncertainty in the inscattering correction.

Table III shows that the total rms systematic uncertainty for the $^{150}$Sm total cross section was generally about
0.7 percent or less except at the lowest energies, e.g., at 0.79 MeV where it reached 1.3 percent.

The systematic errors associated with the cross section differences are generally considerably less than those of individual cross section measurements, since the systematic uncertainties are present with the same sign for both samples (see equation 15). An exception is the uncertainty due to the water correction because different water masses were present in different samarium isotopes. The absolute uncertainty in the $^{152}\text{Sm} - ^{150}\text{Sm}$ cross section difference due to the assumed uncertainty of 25 percent in the water correction ranged from 0.0014 at 14.48 MeV to 0.0037 at 0.79 MeV. The corresponding absolute uncertainty in the $^{154}\text{Sm} - ^{150}\text{Sm}$ cross section difference ranged from 0.0005 at 14.48 MeV to 0.0018 at 0.79 MeV. Absolute uncertainties for the cross section differences arising from other sources of error listed in Table III do not contribute significantly to the absolute uncertainties given above.
V. DISCUSSION OF RESULTS

As mentioned in Chapter I, differences have been observed between calculated and experimental total cross sections for many deformed nuclei (Fo 71). Foster and Glasgow have attributed these differences to nuclear deformation.

Figure VII shows the difference between the experimental total cross section of natural samarium and the cross section computed using the spherical non-local parameters of Perey and Buck (GL 71). The maximum difference between the Sm data of Foster and Glasgow and the Glasgow-Foster calculated curve is near 8 MeV neutron energy and is about 7 percent. Also shown is a calculated curve of the $^{150}\text{Sm}$ cross section using the parameters reported by Becchetti and Greenlees (Be 69). A comparison between Sm data and $^{150}\text{Sm}$ calculations is valid since the average $A$ of natural Sm is 150.35. It is observed that the difference between the Sm data and the Becchetti curve near 8 MeV is 1 percent or less. There is no obvious reason at this time for preferring one computed curve over the other. Also, it should be noted that the present experimental results indicate the magnitude of the effect of nuclear deformation on the neutron total cross section is smaller than that suggested by the optical model calculations of Glasgow and Foster (GL 71).
Table I shows deformation parameters obtained experimentally for the samarium isotopes $^{144}\text{Sm}$, $^{148}\text{Sm}$, $^{150}\text{Sm}$, $^{152}\text{Sm}$, and $^{154}\text{Sm}$. The $\beta_2$ values given for $^{150}\text{Sm}$ in Table I indicate that this nuclide is somewhat deformed. Consequently, spherical optical potential parameters should not provide the means for a perfect fit to experimental $^{150}\text{Sm}$ data. Figure VIII shows that of three optical model curves presented, the Becchetti curve appears to fit the $^{150}\text{Sm}$ data best at least above 3 MeV. Of the two remaining calculations, the Glasgow-Foster curve fits the present $^{150}\text{Sm}$ data below 5 MeV and the Perey curve fits best above 7 MeV.

It is observed in Table I that $^{152}\text{Sm}$ and $^{154}\text{Sm}$ are considerably more deformed than $^{150}\text{Sm}$ and that $^{154}\text{Sm}$ is slightly more deformed than $^{152}\text{Sm}$. Figures IX, X, and XI show a systematic variation in the cross section difference with neutron energy among the isotopes $^{150}\text{Sm}$, $^{152}\text{Sm}$, and $^{154}\text{Sm}$. This systematic variation appears to be correlated with nuclear deformation. The maximum and minimum of the $^{154}\text{Sm} - ^{150}\text{Sm}$ cross section difference are somewhat more pronounced than the maximum and minimum of the $^{152}\text{Sm} - ^{150}\text{Sm}$, as one would expect if $^{154}\text{Sm}$ is slight more deformed. Further, the $^{154}\text{Sm} - ^{152}\text{Sm}$ cross section difference, shown in Figure XI, is seen to be the smallest of those presented, which is also in accord with an interpretation in terms of nuclear deformation. It is evident that the computed cross
section differences which are also shown in Figures IX, X, and XI, and which use only the spherical parameters of Perey, and of Becchetti and Greenlees, cannot account for the observed variations of the experimental cross section differences. It should be noted that the calculated curves take into account any size effect due to differences in $A$. Therefore, these calculated cross section differences give an indication of the magnitude of the size effect.

It has been suggested by Tamura (Ta 69) that since a nuclear matter distribution corresponding to a randomly oriented, permanently deformed nucleus will exhibit a nonabrupt falloff to zero, after a random averaging of the orientation, the associated spherical distribution will exhibit a more diffuse edge. Thus, the nuclear potential will have a more diffuse surface dependence. Figure X shows the result of increasing the value of the Becchetti diffuseness parameters 5 percent. It is apparent that the present results cannot be completely explained by a diffuseness effect.

Wong et al. (Wo 72) have suggested that deformation effects in neutron total cross sections can be accounted for with coupled-channel calculations. Figure XII shows a plot of a cross section difference involving a model, fictitious nucleus with the mass of ${}^{165}$Ho. The cross section difference is between permanently deformed and spherical nuclides of $A = 165$, divided by the spherical nucleus. Wong et al.
Figure XII.
The neutron total cross section difference between $^{165}$Ho and a fictitious spherical nucleus of the same mass, divided by the total cross section of the fictitious spherical nucleus. The total cross section values were taken from Figure 2a of reference Wo 72. The total cross section for the spherical nucleus was computed using optical model parameters of Perey (Ma 70). The total cross section for the $^{165}$Ho was found using coupled-channel calculations along with the Perey parameters.
calculated the spherical cross sections with an ordinary optical model potential using Perey parameters. The deformed cross sections were obtained by coupled-channel calculations which included the use of Perey parameters and the deformation parameter $\beta_2 = 0.25$. The calculated curve of Wong et al. qualitatively explains the present data of Figures IX, X, and XI. It is noted that, based on the interpretation of the present results, the magnitudes of the maximum and minimum of the calculated curve of Wong et al. are expected to be larger since the difference between the $\beta_2$ of the calculated curve is significantly greater than the experimental differences involving the samarium isotopes (see Table I).

In summary, the measurements reported here provide evidence that nuclear deformation does have an effect on the neutron total cross section of samarium isotopes. However, the present results indicate that the magnitude of the effect is smaller than is suggested by the optical model calculations of Foster and Glasgow. The variation of the observed magnitude of the effect with mass number is in qualitative agreement with previously determined quadrupole deformation parameters which provide a measurement of the nuclear charge distribution (see Chapter I). Further, the qualitative agreement of the energy dependence of the present results with the calculated energy dependence reported by Wong et al. suggest that their explanation of
the effect of nuclear deformation on neutron total cross sections is probably correct. At this time, T. Tamura and C. Y. Wong are fitting the present results in order to obtain a quantitative measure of the mass distribution of the samarium isotopes.
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