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Neutron Cross Section Measurements Using the ORELA: $^{40}Ar(n,x)$, $^{40}Ca(n,x)$, $^{22}Ne(n,\gamma)$, $^{187}Os(n,n')$ $^{186\ 187\ 188}Os(n,nn'\gamma)$, the Stable Tellurium Isotopes (n,γ), and $^{205}T\ell(n,n\gamma)$

PROGRESS REPORT

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ABSTRACT

The research performed during this reporting period consisted primarily of (1) measurement, analysis, and publication of the $^{187}Os(n,n')$ cross section near 30 keV, (2) measurement and analysis of the $^{148,149,150}Sm(n,\gamma)$ cross sections, (3) development and publication of a significantly better approximation to the average neutron scattering function as determined by total cross section measurements at the Oak Ridge Electron Linear Accelerator (ORELA), and (4) providing support for the neutron capture facility at ORELA as in the corrections made to the $^{60}Ni(n,\gamma)$ data discussed in a paper included with this report.

The major result[1] of the $^{187}Os(n,n')$ cross section measurement was the 30 keV average value for that cross section $\overline{\sigma}_{nn'} \approx 1.5 \pm 0.2$ b and the implication that the duration of stellar nucleosynthesis, as derived from the $^{187}Re \rightarrow ^{187}Os$ beta decay, is estimated to be $(8.9 \pm 2.0) \times 10^9$ year consistent with an earlier estimate reported by Winters and Macklin[2]. The Sm(n,γ) measurement has already resulted in an estimate of the importance of branching in the s-process in the samarium mass region. We estimate the average neutron density during s-process nucleosynthesis in the vicinity of the solar system to be $\lesssim (1.1 {}^{+0.7}_{-0.6}) \times 10^8$ neutrons/cm^3. In the optical model analysis of neutron total cross sections, we continue to find that orbital angular momentum dependent well depths are required if the spherical optical model is used to describe the neutron-nucleus interaction at low neutron energies.

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I. Introduction

The past year's research activity has resulted in three (3) publications, one (1) paper in press, one (1) paper submitted for publication, six (6) conference papers, two (2) technical memoranda, and four (4) manuscripts in various stages of preparation. During this time I have spent five months at the Institut für Kernphysik II, Karlsruhe, West Germany, participating in a neutron cross section measurement and during the spring (1983) semester carried a full (two courses plus two laboratories) teaching load. This has made for an exciting and busy professional life. Since the preprints, reprints, and abstracts included with this report discuss in detail the work which has been performed during this reporting period, only brief discussions of the various components of the work will be reported here. I estimate that approximately 80% of the research proposed to the United States Department of Energy for the two-year period 1982-83 has been completed.

II. $^{148,149,150}Sm(n,\gamma)$

Collaborators: R.R. Winters (DU) and F. Kappeler (IAK)

These measurements have been completed and the resulting cross sections are shown in figures 1-3. The measurements were made at the Institut für Kernphysik II (Karlsruhe, West Germany) Van de Graaff. The neutron source is the $^{7}Li(p,n)$ reaction. The gamma ray detectors are two C_6D_6 liquid scintillators mounted on either side of the capture sample. This system has very low backgrounds as is demonstrated in figure 4. The graphite spectrum (fig. 4) measures the sensitivity of the system to sample-scattered neutrons and, as can be seen, the correction for this effect is also small.

Other corrections which must be made in converting observed samarium capture yields to cross sections and their contributions to the overall uncertainty in the measured cross section are presented in Table I.

Correction/Uncertainty	^{148}Sm	^{149}Sm	^{150}Sm	Ratio
Background subtraction	1.3%	<0.1%	0.2%	yes
Sensitivity to scattered neutrons	<0.5	<0.5	<0.5	yes
Sample self-screening/multiple scattering	$\lesssim 2$	$\lesssim 2$	$\lesssim 2$	50%
Coincidence count rate	1	2	0.6	yes
γ-ray attenuation	1	1	1	50%
Pulse height weighting uncertainty	2	2	2	yes
Isotopic composition	1.3	<0.1	0.2	yes
Normalization	2.5	2.5	2.5	no
Uncertainty estimate	4.5	4.4	4.0	

Table I. Sources of Corrections and their contribution to the overall uncertainty in the results of our Sm(n,γ) cross section measurements.

It is to be noted that these are among the most carefully measured neutron capture cross sections of importance to astrophysics ever reported. Such precision is required by data needs in both nuclear reactor technology and astrophysics.

IIA. Astrophysics: s-process Nucleosynthesis

As was discussed in the proposal leading to these measurements, samarium provides a nearly unique test for the current notions of s-process stellar nucleosynthesis. As can be seen from figure 5, ^{148}Sm and ^{150}Sm are both shielded from the r-process of nucleosynthesis. The "local approximation" for the s-process current $N_S\langle\sigma_\gamma\rangle$ (s-process abundance x Maxwellian averaged neutron capture cross section) is constant through the samarium mass region, so that

$$N_S(148)\ \langle\sigma_\gamma(148)\rangle = N_S(150)\ \langle\sigma_\gamma(150)\rangle$$

or

$$R \equiv \frac{N_S(148)\ \langle\sigma_\gamma(148)\rangle}{N_S(150)\ \langle\sigma_\gamma(150)\rangle} = 1 \qquad (1)$$

We have averaged the cross sections shown in figures 1 and 3 using a Maxwellian weighting function characterized by a range of temperatures expected to be typical of the site of s-process nucleosynthesis, the interiors of giant red stars. The results are presented in figures 6 and 7. The observed abundances and T = 30 keV average cross sections are presented in Table II.

Isotope	$\langle\sigma_\gamma(30\ \text{keV})\rangle$	$N_S{}^a(10^6\text{Si})$	$N_S\langle\sigma_\gamma\rangle$
148	277 ± 11 mb	0.0295	8.17 ± 0.32
150	465 ± 17	0.0193	8.97 ± 0.33

a) taken from reference 3.

Table II. Maxwellian 30 keV averaged capture cross sections and measured abundances (relative to silicone) for ^{148,150}Sm.

The ratio of s-process currents is less than unity,

$$R = 0.91 \pm 0.05.$$

This is interpreted to be a result of branching (primarily at ^{147}Pm) in the s-process path in the samarium mass region. Considering only a branch at ^{147}Pm, the ratio R can be written

$$R = \frac{\lambda_\beta(147)}{\lambda_\beta(147) + \lambda_n(147)} \left[1 + \frac{\lambda_\beta(148)}{\lambda_\beta(148) + \lambda_n(148)}\right] \qquad (2)$$

where λ_β are beta decay rates and $\lambda_n \equiv \langle n_n \rangle V_T \langle \sigma_\gamma \rangle$ and where $\langle n_n \rangle$ is the average neutron density during s-process nucleosynthesis and V_T is the mean speed of neutrons in thermal equilibrium at temperature T. The capture cross sections for the unstable nuclides ^{147}Pm and ^{148}Pm have not been measured. However, they have been calculated using the Hauser-Feshbach formalism by G. Reffo,

$$\langle \sigma_\gamma(^{147}Pm) \rangle \approx 1.17 \text{ b}$$
$$\langle \sigma_\gamma(^{148}Pm) \rangle \approx 1.55 \text{ b}.$$

With these estimates, the average s-process neutron density can be calculated using the measured value for R. We find for the mean neutron density during s-process nucleosynthesis in the vicinity of the solar system,

$$\langle n_n \rangle = (1.1 {}^{+0.7}_{-0.6}) \times 10^8 \ \frac{\text{neutrons}}{\text{cm}^3} .$$

Two papers discussing this work are in preparation.

IIB. Reactor Technology Data Needs

The results for the ^{149}Sm average capture cross section are in serious disagreement with two recent measurements by Mizumoto et al.[4] and by Kononov et al.[5] and with the results in an unpublished report by Hockenbury et al.[6]. Yet the present results are in good agreement with an older measurement by Macklin et al.[7] Comparison with two of these data sets are shown in Table III. The comparison with Macklin's result is compromised by Macklin's use of the Maxwellian 30 keV average. Since such an average weights the cross section near and below 30 keV relatively heavily, it is not unexpected that Macklin's result for the average cross section is slightly higher than the averaged results in Table III from the present work.

E_n(keV)	$\bar{\sigma}_\gamma$(149) b		
	this work	Mizumoto et al.[3]	Macklin[4]
14-16	2.40 ± 0.11	4.22 ± 0.32	
20-25	1.83 0.08	3.20 0.26	
25-30	1.51 0.07	2.71 0.24	1.6*
30-35	1.34 0.06	2.47 0.25	
100-120	0.69 0.03	1.16 0.12	
*Maxwellian average with T = 30 keV			

Table III. Comparison of the results from this work and earlier work for ^{149}Sm(n,γ).

The discrepancy becomes even more serious when one considers the excellent agreement among the results of Mizumoto et al., Kononov et al., and Hockenbury et al. (for which I have no tabular data) shown in figure 8 and taken from reference 3. The discrepancy is serious, since the reactor technology data request for the ^{149}Sm(n,γ) cross section requires a precision of 5%. The discrepancy remains unresolved.

III. ^{187}Os(n,n')

Collaborators: R.R. Winters (DU); R.L. Macklin, J.A. Harvey, and N.W. Hill (ORNL)

As discussed in the preprint submitted with this report, this measurement has been completed. The paper[1] is scheduled to appear in either the October or November 1983 issue of the Astrophysical Journal. The most interesting aspect of this difficult measurement is the anisotropic Fe-Aℓ filter used to remove from the scattered neutron beam most neutrons of energy not within ∿2 keV of 24 keV. The filter is shown in figure 9. That the filter works well is shown in figures 10-12, in which the scattering yield from $^{187}Os(n,n')$, $^{188}Os(n,n)$ and backgrounds are shown.

The 34 keV inelastic scattering yield is apparent in figure 10. After correcting for multiple scattering and sample self-screening effects and normalizing the observed inelastic yield to ^{188}Os (whose scattering cross section could be calculated from the measured total[8] and capture[1,9] cross sections), we find for $^{187}Os(n,n')$, a result in excellent agreement

$$\bar{\sigma}_{nn'} \text{ (30 keV)} \approx (1.5 \pm 0.2) \text{ b}$$

(taking into account the expected energy dependence) with the results of a nearly simultaneous measurement by Hershberger et al.[10] at neutron energy ≈63 keV,

$$\bar{\sigma}_{nn'} \text{ (63 keV)} \approx (1.1 \pm 0.2) \text{ b.}$$

This result allows an estimation by Hauser-Feshbach calculations of the effective enhancement of the ^{187}Os capture cross section due to stellar temperature effects except for the uncertainty in estimating the gamma ray transmission factor T_γ. Woosley and Fowler[11] find a relatively large range in the enhancement (from 80% of the observed cross section to 110%) depending on whether T_γ is assumed to be independent of the spin of the compound nucleus or not. This results in a range of the estimates for the duration of stellar nucleosynthesis of from 9.8×10^9 years to 11.3×10^9 years. Fowler has asked for a measurement of the $^{189}Os(n,\gamma)$ cross section to help resolve this problem. Even so, this estimate of the duration of nucleosynthesis yields a relatively precise value for the age of the universe $\approx(16 \pm 3) \times 10^9$ years.

The quoted uncertainty is comparable to that achieved by observational techniques. It is true, however, that problems remain with estimating the effect of stellar temperatures and pressures on half-life of the $^{187}Re \rightarrow ^{187}Os$ decay. For a discussion of the problem see reference 12.

IV. Optical Model Analysis of ORELA High Resolution Total Cross Sections

Collaborators: R.R. Winters (DU) and C.H. Johnson (ORNL)

A significant portion of the time covered by this report was given over to two aspects of the problem of averaging the results of high resolution ORELA total neutron cross section data in a way clearly comparable with the results derived from an optical model. It became clear that the scattering matrix S(E) provides such a possible comparison, and this idea was developed by Johnson and Winters in a paper[13] included with this report. The approach involved finding a satisfactory approximation to the form of the scattering matrix (function, if only elastic scattering and capture reactions are energetically possible). However, the same approximation used in reference 13 failed when applied to ^{40}Ca + n. The failure was exhibited by a relatively strong dependence in <S> (and related functions) on the width of the weighting function used in the averaging process. After a great deal of work and the help of N. M. Larson (ORNL), we have developed a technique for numerically averaging S over the region of analysis $[E_\ell, E_u]$, typically [$\sim$0, $\sim$1 MeV]. In a very detailed paper[14] (included with this report), we compared various analytic approximations for <S(E)> with the result obtained numerically. A good approximation was found and applied to the already published ^{32}S + n data, obtaining the same results as in reference 1. The crux of the idea is in writing the R-function in such a way as to average only over the more rapidly varying parts and then using contour integration and theorem of residues to approximate <S(E)>. It is unfortunate, but the working out of these details resulted in a serious disagreement with one of our collaborators, Dr. W. MacDonald, who withdrew from the collaboration early in this contract period. That disagreement has resulted in an exchange of papers, a preprint[15] of one is included with this report. It is clear that for the case of ^{40}Ca + n, an adequate analytic approximation to <S(E)> must (1) avoid averaging over the background part of S(E) and (2) account for the energy dependence observed for the s-wave strength function. We believe that we have found such an approximation and are in the midst of the preparation of a paper detailing these results. This approximation is discussed in a letter to C. Mahaux dated July 28, 1983, and attached notes included in this report as Appendix A.

A substantial amount of time during this contract period was spent modifying the computer codes which calculate <S(E)> to include the new approximation and to propagate uncertainty estimates associated with the neutron strength functions and external R-functions through the calculation of <S> and the search for the optical model potential well depths. The results of this work for s-wave neutrons on ^{32}S are shown in figures 13 and 14. Just as for the case of ^{32}S, ^{28}Si, and ^{34}S, we find that ℓ-dependent well depths are required to reproduce the shape elastic and compound nuclear cross sections derived from <S> for ^{40}Ca + n.

V. $^{60}Ni(n,\gamma)$

Collaborators: R.R. Winters (DU); R.L. Macklin and C. Perey (ORNL)

One perennial problem involved in any measurement of a capture cross section at ORELA is estimating the corrections to be made to the observed capture yield to account for those events which are due to capture of sample-scattered neutrons or due to sample-scattered gamma rays. These corrections for both transmission and capture measurements are discussed in the paper[16] included with this report. While I am pleased that these corrections are usually small, in some cases the large uncertainty which I quote for these corrections dominates the uncertainty associated with the estimate of the total radiation width. In a recent measurement of $^{208}Pb(n,\gamma)$, Macklin and I showed that the uncertainty in the estimates of the correction factor can be substantially reduced. During the next contract period, the capture analysis codes will be modified to include this recent measurement.

VI. Conclusion

I have enjoyed the work this last year and believe that my students and colleagues at Denison have benefited from the diversity of professional contacts and ideas the research brings to our campus. My thanks to Dr. Stan Whetstone (DOE) for his continuing interest in and support of this work. I would not be able to continue as a research physicist without that support.

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