REPORT TO THE
U. S. NUCLEAR DATA COMMITTEE

F. G. Perey

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Neutron Physics Division

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APRIL 1973

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ABSTRACT

This memo is a collection of brief reports on recent and not yet generally publicized work at ORNL which is of special interest to the USNDC. Included are abstracts of relevant ORNL reports and papers which have been only submitted for publication. The memo covers the period of time since the last USNDC meeting.

OAK RIDGE NATIONAL LABORATORY

A. NEUTRON PHYSICS1. Integral Neutron Scattering Measurements on Carbon From 1 to 20 MeV*,** (G. L. Morgan, T. A. Love and F. G. Perey)

The spectrum of neutrons above ~1 MeV scattered by a thick (3.81 cm) carbon ring has been measured as a function of the incident neutron energy over the range from 1 to 20 MeV. Data were taken for three angles: 60° , 90° , and 135° . A linac (ORELA) was used as a neutron source with a 47-m flight path. Incident energy was determined by time of flight while scattered spectra were determined by pulse-height unfolding techniques. The results of the measurement are presented in forms suitable for comparison to calculations based on the evaluated neutron data files.

* Abstract of ORNL-TM-4157.

** Relevant to Request Nos. 32 and 34.

2. Valency Model of Radiative Neutron Capture in $^{88}\text{Sr}(n,\gamma)^{89}\text{Sr}$
(R. R. Winters[†], O. A. Wasson^{††}, and R. L. Macklin)

The total capture cross section of the reaction $^{88}\text{Sr}(n,\gamma)^{89}\text{Sr}$ was measured from 2.5 to 400 keV neutron energies at the Oak Ridge Linear Electron Accelerator using a fluorocarbon liquid scintillator as a γ -ray detector. The capture events were weighted using the Total-Energy Weighting method of Macklin. The resonance energies, neutron widths, and total radiative widths were determined. The ground state partial radiative widths are also obtained from the relative size of the high energy part of the γ -ray spectrum. A comparison of these partial widths with the predictions of the valency model of neutron capture will be presented.

* To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

[†] Denison University

^{††} Brookhaven National Laboratory

3. Mass and Total Kinetic Energy Distributions from the Spontaneous Fission of ^{246}Cm * (Frances Pleasonton, Robert L. Ferguson, Franz Plasil and Curtis E. Bemis, Jr.)

Energies of coincident pairs of fission fragments from spontaneous fission of ^{246}Cm have been measured with silicon surface barrier detectors.

Fragment mass and total kinetic energy distributions have been deduced and compared to those obtained from a companion experiment, using the same apparatus, on ^{252}Cf (SF). For ^{246}Cm (SF) the first and second moments of the fragment distributions, in terms of "provisional" masses in amu and post-neutron-emission kinetic energies in MeV, are as follows: $\langle m_H \rangle = 139.5$; $\langle m_L \rangle = 106.5$, $\sigma_m = 6.6$; $\langle E_K \rangle = 181.3$; $\sigma_{EK} = 10.8$. Our results are compared with recent work¹ on other Cm isotopes and other trans-Pu elements.

* To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

¹See, for example, K. F. Flynn, B. Srinivasan, O. K. Manucl and L. E. Clendenin, Phys. Rev. C 6, 2211 (1972); D. C. Hoffman, G. P. Ford and J. P. Balagna, Phys. Rev. C 7, 276 (1973).

4. Half-Value Thickness Measurements of Ordinary Concrete for Neutrons from Cyclotron Targets* (H. M. Butler, K. M. Wallace and C. B. Fulmer)

Half-value thicknesses (or half-value layers) of ordinary concrete were determined for neutrons emitted from a variety of cyclotron beam-target combinations. Targets of carbon, aluminum, copper and tantalum were each bombarded with beams of protons, deuterons, alpha particles, and carbon ions at the Oak Ridge Isochronous Cyclotron. Measurements were made of neutron attenuation by an 80 cm thick wall for each target-beam combination. For protons, deuterons, and alpha particles a range of bombarding energies were used; maximum neutron energies were as high as 60 MeV. The half-value thicknesses for neutrons from all of these particle-target combinations are in the range of 9-10.5 centimeters.

* To be presented at the 1973 Annual AIHA Conference, Boston, Massachusetts, May 20-25, 1973.

5. Total Cross Section of Calcium* (J. L. Fowler, C. H. Johnson and N. W. Hill)

We have measured the total cross section of calcium (96.96% ^{40}Ca) from 60 keV to 1000 keV with energy resolution ranging from ~0.1 keV to ~1.0 keV. For the neutron detector at the 200-meter time-of-flight station of the Oak Ridge Electron Linear Accelerator, we used the plastic scintillator, NE-110. Delayed 0.5-MeV gamma rays from the source were removed by a 2-cm filter of ^{238}U . The delayed 2.2-MeV gamma-rays were removed by both the filter and by the use of a differential pulse height window for the detector. From the widths of narrow unresolved resonances, we determined the neutron energy resolution as a function of neutron energy as

follows: $\Delta E/E = 0.0004 [1 + 3.5 E(\text{MeV})]^{1/2}$. This empirical formula corresponds to an uncertainty in distance of 4 cm and a time spread to 5 nsec. In the range of our measurements up to 1000 keV we see ~100 resonances, about 1/6 of which we identify as s-wave resonances from their heights and shapes. Below 600 keV we see 2.5 times the number of resonances reported in the literature.

*To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

6. ^{241}Pu Neutron Total Cross-Section Measurements at ORELA* (F. B. Simpson†, J. A. Harvey and N. W. Hill)

Neutron total cross-section measurements for ^{241}Pu are in progress at ORELA in the energy range from 0.5 eV to ~8 MeV. An 80-meter flight path is used with accelerator pulse widths of 30 to 4 nsec, resulting in an energy resolution $\Delta E/E$ of $0.0007 \sqrt{1 + 4E(\text{in MeV})}$. Measurements are made with a ^6Li glass detector from 0.5 eV to 100 keV and with an NE-110 scintillation detector from 10 keV to 8 MeV. Backgrounds are $\leq 1\%$, with a major part of it being constant room background at low energies, 2.23-MeV gamma rays (with a 16-μsec decay period) from H-capture in the moderator at keV energies with the ^6Li glass detector, and a background in the keV measurements with the NE-110 detector due to neutrons being moderated (with a 5-μsec leakage period) by the detector and producing gamma rays from capture in the detector. Three different sample thicknesses are being measured and are cooled to liquid nitrogen temperature. The samples are 5/8 in. diameter metallic discs with thicknesses of 0.006 in., 0.026 in. and 0.126 in. The ^{241}Am was separated from the plutonium oxide sample just before converting the oxide to metal.

*Relevant to Request No. 474.

†Aerojet Nuclear.

7. Further Search for Intermediate Structure in the Re Isotopes* (A. Stolovy†, A. I. Namensont†, and J. A. Harvey)

As an extension of data taken previously¹, neutron resonances up to about 3 keV in the target nuclei ^{185}Re and ^{187}Re were observed at the 80-meter station of the ORELA facility. Data on several hundred resonances were obtained in each isotope. Four large NaI detectors were used to observe capture gamma rays as a function of time of flight. For each resonance, the intensity of the capture gamma rays above 4.0 MeV was divided by the intensity of capture gamma rays above 1.0 MeV. We then look for trends in this normalized primary transition intensity as a function of neutron energy. Our earlier data¹ appeared to show evidence for the

presence of an intermediate state in the compound nucleus ^{188}Re , similar to the structure reported by Coceva et al.² for ^{115}In . The data taken at ORELA comprise an order of magnitude more resonances than we had previously. We find no evidence for additional intermediate structure in either isotope. The data will be analyzed to obtain estimates of g_n^Γ , and various statistical tests will be applied.

* To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

† Naval Research Laboratory

¹ A. Stolovy, A. I. Namenson, and T. F. Godlove, Phys. Rev. C4, 1466 (1971).

² C. Coceva, F. Corvi, P. Giacobbe, and M. Stefanon, Phys. Rev. Letters 25, 1047 (1970).

8. Neutron Fission Cross Section of ^{249}Cf wrt ^{235}U , using 128 μg Sample* (J. W. T. Dabbs, C. E. Bemis, N. W. Hill, M. S. Moore† and A. N. Ellis†)

Time-of-flight measurements of the neutron-induced fission cross section of ^{249}Cf have been performed at ORELA, using an ultrapure 128 μg sample of ^{249}Cf and compared with that of a 458 μg sample of ^{235}U measured simultaneously in the same flight path. Identical diffused junction fission fragment detectors¹ were used. An α -particle count rate of $10^7/\text{sec}$ caused substantial deterioration of the ^{249}Cf detector during each overnight run. A total of $\sim 7 \times 10^5$ Cf events were recorded. Previous measurements² using an underground nuclear explosion gave results down to ~ 20 eV, with comparable resolution. Eleven new resonances were found between 0.3 eV and 20 eV, including a very large resonance at 0.71 eV of total width ~ 0.15 eV and $\sigma_0 \sim 4000$ b. This resonance accounted for $\sim 75\%$ of the total fissions recorded.

* To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

† Los Alamos Scientific Laboratory

¹ Solid State Radiations, Los Angeles, CA 90064, Model 600-PIN-125.

² M. G. Silbert, LASL Report LA-5042 MS; to be published.

9. Validity of the Valence Neutron Model for $^{98}\text{Mo}^*$,** (G. W. Cole†, R. E. Chrien†, R. C. Byrd†, S. F. Mughabghab†, G. G. Slaughter and J. A. Harvey)

Measurements of neutron capture gamma-ray spectra from ^{98}Mo taken at the HFBR chopper and later at the Oak Ridge Electron Linear Accelerator (ORELA) have indicated that for large neutron widths, the partial radiative

widths for ^{98}Mo are well predicted by a model which ascribes the radiative strengths to the motion of a valence p-neutron outside a ^{98}Mo core. The detailed extension of the model to higher neutron energies is made possible by additional total cross-section measurements at ORELA from which neutron widths and resonance parities may be derived. For these measurements a thick sample of 0.043 atoms/barn was used with a 78.2 meter flight path to give a nominal resolution of 0.06 ns/meter. Parameters were derived for resonances up to approximately 100 keV; detailed comparisons with the valence model, however, were restricted to energies below 10 keV. The validity of the model in this region is discussed.

* Presented at the New York APS Meeting, January 29 - February 1, 1973.

** Relevant to Requests 222 and 223.

† Brookhaven National Laboratory

10. The Neutron Total Cross Section of ^{248}Cm ,** (R. W. Benjamin†, C. E. Ahlfeld†, J. A. Harvey and N. W. Hill)

Neutron time-of-flight transmission measurements were made with 13.0 mg of 97% pure ^{248}Cm , using the Oak Ridge Electron Linear Accelerator. Data were collected from the cadmium cut-off to 3 keV. The small diameter (1.6 to 4 mm) cylindrical samples were cooled with liquid nitrogen to reduce Doppler broadening. The thickest sample had an inverse thickness of 637 barns/atom, which made possible the identification of forty resonances in ^{248}Cm below 3 keV. The average resonance spacing below 1 keV is about 50 eV. The first five resonances (7.25 eV, 26.9 eV, 35.0 eV, 76.1 eV, and 98.9 eV) are suitable for shape analyses to obtain Breit-Wigner, single-level resonance parameters. Results of the preliminary analyses will be presented.

* To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

** Relevant to Request No. 523.

† Savannah River Laboratory, Aiken, S.C.

11. Prompt Gamma Rays Emitted in the Thermal-Neutron Induced Fission of ^{233}U , ^{235}U , and ^{239}Pu and the Spontaneous Fission of ^{252}Cf ,** (Frances Pleasonton, Robert L. Ferguson, and H. W. Schmitt)

A series of four experiments, corresponding to four different fission reactions (see title), were performed to determine the average energy $\bar{E}_\gamma$ and average number $\bar{N}_\gamma$ of gamma rays emitted within ~5 nsec after fission as functions of fragment mass m and fragment total kinetic energy E_K . All

results for $\bar{E}_Y(m)$ and $\bar{N}_Y(m)$ exhibit a saw-tooth behavior. Further, the $\bar{E}_Y(m)$ results for all four cases are nearly congruent, as are the $\bar{N}_Y(m)$ results. The similarity of these functions to that describing the number of neutrons emitted in fission, $\nu(m)$, is shown. The average photon energy $\bar{E}$ has also been obtained as a function of m , and all quantities have been obtained as a function of E_K as well. Trends in all of these results are qualitatively understood in terms of fragment nuclear structures.

* To be presented at the Washington APS Meeting, April 23-26, 1973.

** Relevant to Request Nos. 358 and 449.

12. Fast Neutron Capture Cross Sections for Silicon* (B. J. Allen[†] and R. L. Macklin)

One of the continuing programs at the Oak Ridge Electron Linear Accelerator is the measurement of fast neutron capture by stable isotopes. A flight path of 40 meters and 3-5 ns pulses give an energy resolution of about 0.2% FWHM over an energy range 2.5 - 1000⁺ keV. Where there is a special interest in the inverse photonuclear reaction it is possible to study the partial radiative widths of capture resonances by simply recording the detector response above an appropriate high bias level separately. The high efficiency at good resolution and low neutron sensitivity of the detector system make this an attractive alternative to NaI(Tl) or Ge(Li) detector work when the excited states of the compound nucleus are an MeV or two above the ground state as in $^{207}\text{Pb}+n$ and $^{28}\text{Si}+n$.

Total neutron capture has been run with a 0.027 atom/barn sample of natural silicon. As expected, most of the resonances observed are from the 92.2% abundant ^{28}Si target. The average radiative width (for resonances of assigned spin) is 4.6 eV. The wide range (0.4 to 14.5) and suggestion of correlation with neutron width may favor nonstatistical capture mechanisms. An 808 keV resonance shape comparison with the photo-nuclear $^{29}\text{Si}+\gamma$ data of Jackson and Toohey¹ indicating a doorway state in the reaction will require better statistics, a thicker sample, and a high bias.

* Presented at the International Conference on Photo-Nuclear Reactions and Applications, March 26-30, 1973 at Pacific Grove, California.

[†] Present address: Australian Atomic Energy Commission, Lucas Heights, Australia.

¹ H. E. Jackson, R. E. Toohey, Phys. Rev. Letters 29, 379 (1972).

13. Neutron Total Cross Sections for Kilovolt Neutron Energies*
(W. M. Good, J. A. Harvey and N. W. Hill)

Neutron transmission studies have continued, of nuclides whose neutron resonant spacings are of the order of a kilovolt. The energy range of study generally is about 1 keV to 400 keV and separated isotopes are employed.

Continuing as of one year ago, $^{29,30}\text{Si}$, $^{40,42,43,44}\text{Ca}$, $^{47,49}\text{Ti}$, $^{54,57}\text{Fe}$, $^{204,206,207,208}\text{Pb}$ are in various stages of study and to these have been added $^{90,91,92,94,96}\text{Zr}$, $^{33,34}\text{S}$ and ^6Li .

Very little information is generally available on total cross sections $^{29,30}\text{Si}$, $^{33,34}\text{S}$ (Ref. 1). Hence the resonant energies observed for these nuclides in the present measurements are listed in Table I.

On account of ORELA's high resolution, many levels are expected to be observed in present transmission measurements which were unobservable before, excepting possibly for the earlier capture measurements (capture can be a bit more sensitive to narrow resonances than transmission). In Table I are listed the resonances observed in $^{54,57}\text{Fe}$ in the present measurements. The most recent data for comparison is Hockenbury *et al.*² and Rohr and Müller.³

No listing is provided of the resonance levels observed in $^{90,91}\text{Zr}$ (Ref. 4). However, a scan of the raw Zr transmission data indicates many small resonances not resolved in the previous measurements.⁵ In the energy interval from 3 keV to 70 keV on which only 13 resonances were then reported, there now appears at least 35.

* Relevant to Request Nos. 10, 165, 173, 182, 189 and 197.

¹ CINDA 72, Vol. 1, IAEA Vienna (1972).

² Hockenbury, Bartolome, Tatarczuk, Moyer, and Block, Phys. Rev. 178, 1746 (1969).

³ G. Rohr and K. N. Müller, Z. Phy. 227, 1 (1969).

⁴ Measurements on $^{90,91}\text{Zr}$ were made in collaboration with Mr. Richard E. Toohey, Physics Division, Argonne National Laboratory. Samples were courtesy of Dr. A. B. Smith, Argonne National Laboratory.

⁵ W. M. Good and H. Kim, Phys. Rev. 165, 1329 (1968).

Table I. Listing of Resonances Observed in the Target Nuclides
 $^{29,30}\text{Si}$, $^{33,34}\text{S}$, $^{54,57}\text{Fe}$. In $^{54,57}\text{Fe}$, * = new,

** = previously observed but different energy assignments.

^{29}Si keV	^{30}Si keV	^{33}S keV	^{34}S keV	^{54}Fe keV	^{57}Fe keV
15.29	2.235	13.44	30.37	7.813	1.628
38.79	4.98	17.63	118.5	9.476	3.973
159.6	63.43	23.93	231.3	11.169*	4.746
184.5	185.8	30.37	301.3	14.455	6.276
336.7	235.1	52.17	317.6	30.628*	7.215
385.4	302.7	53.54	357.2	39.053*	7.934
553.2	413.5	59.06	362.5	51.533*	12.847
650.3	644.4	77.84	396.6	52.1	13.286*
	747.6	81.46	435.7	55.341*	13.966
	849.9	87.50	464.0	72.089	18.224
		101.2	470.8	98.820	21.049*
		151.6	510.2		21.284
		168.7	642.5		28.624
		178.3	800.6		29.680
		197.3	814.5		37.078*
		221.7	839.5		39.361*
		228.8	851.0		41.643
		238.4	893.7		41.958*
			935.8		47.164
			1019		49.917*
			1089		52.644*
			1125		56.539
			1193		61.786
			1313		65.416*
			1352		74.331*
			1391		77.528
			1450		83.812*
					88.089*
					89.816*
					91.672*
					93.912*
					101.695**
					109.866**
					118.832**

14. Tungsten Neutron Elastic- and Inelastic-Scattering Cross Sections From 4.34 To 8.56 MeV* (W. E. Kinney and F. G. Perey)

Measured natural tungsten neutron elastic- and inelastic-scattering cross sections are presented and shown to be in good agreement with the results of others. An evaporation model of inelastic scattering was found to be applicable with nuclear temperatures in agreement with previous results but with total inelastic cross sections larger by as much as 20% than measured nonelastic cross sections. ENDF/B W (Mat 1060-63) elastic angular distributions agree with our data at angles less than 50° but do not at larger angles. The ENDF/B nuclear temperatures are 10-15% lower than experimental temperatures.

* Abstract of ORNL-4803.

15. Gamma-Ray Production Due to Neutron Interactions with Nitrogen for Incident Neutron Energies Between 2.0 and 20 MeV: Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with nitrogen have been obtained for neutron energies between 2.0 and 20 MeV for $\theta = 90$ and 125° using a NaI spectrometer. These data consist of neutron and gamma-ray production group cross-section values of $d^2\sigma/d\omega dE$ for $0.7 < E_\gamma < 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_\gamma < 1$ MeV to 250 keV for $E_\gamma \sim 9$ MeV. Neutron energy intervals varied from 1 MeV for $E_n = 2$ to 10 MeV to 3 MeV for $E_n = 14$ to 20 MeV.

* Abstract of ORNL-4864

** Relevant to Request No. 42.

16. Gamma-Ray Production Due to Neutron Interactions with Copper for Incident Neutron Energies Between 1.0 and 20 MeV: Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with copper have been obtained for neutron

energies between 1.0 and 20 MeV for $\theta_Y = 125$ deg. The $d^2\sigma/d\omega dE$ values were obtained using a NaI spectrometer. These data consist of neutron and gamma-ray production group cross-section values of $d^2\sigma/d\omega dE$ for $0.7 < E_Y < 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_Y < 1$ MeV to 160 keV for $E_Y \sim 9$ MeV. Neutron energy intervals varied from 0.5 MeV for $E_n = 1$ to 3 MeV to 3 MeV for $E_n = 14$ to 20 MeV.

* Abstract of ORNL-4846.

** Relevant to Request No. 127.

17. Gamma-Ray Production Due to Neutron Interactions with Tungsten for Incident Neutron Energies Between 1.0 and 20 MeV: Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with tungsten have been obtained for neutron energies between 1.0 and 20 MeV for $\theta_Y = 125$ deg. The $d^2\sigma/d\omega dE$ values were obtained using a NaI spectrometer. These data consist of neutron and gamma-ray production group cross-section values of $d^2\sigma/d\omega dE$ for $0.7 < E_Y < 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_Y < 1$ MeV to 160 keV for $E_Y \sim 9$ MeV. Neutron energy intervals varied from 0.5 MeV for $E_n = 1$ to 8 MeV to 3 MeV for $E_n = 14$ to 20 MeV.

* Abstract of ORNL-4847

** Relevant to Request Nos. 324 and 325.

18. Measurement of the ^{238}U Capture Cross Section for Incident Neutron Energies up to 100 keV*,** (G. de Saussure, E. G. Silver, R. B. Perez, R. Ingle and H. Weaver)

The neutron capture cross section of ^{238}U was measured for incident neutron energies between 5 eV and 100 keV using a pulsed electron linac neutron source and the time-of-flight technique. Capture gamma rays were detected by a large liquid scintillator located on a 40-m flight path. The incident neutron flux was monitored by a $^{10}\text{BF}_3$ ionization chamber. The cross section was normalized by the saturated resonance technique.

This memorandum contains a brief description of the experimental technique and a discussion of the results. A complete tabulation of one of the measurements is given in the appendix.

* Abstract of ORNL-TM-4059; also to be published in Nuclear Science and Engineering.

** Relevant to Request Nos. 421 and 422.

19. Simultaneous Measurements of the Neutron Fission and Capture Cross Sections for ^{235}U for Neutron Energies from 8 eV to 10 keV^{*,**} (R. B. Perez, G. de Saussure, E. G. Silver, R. W. Ingle, and H. Weaver)

Simultaneous measurements of the neutron fission and capture cross sections of ^{235}U have been performed at the Oak Ridge Electron Linear Accelerator (ORELA) for neutrons with energies between 8 eV and 10 keV. These cross sections were measured relative to the standard $^{10}\text{B}(n,\alpha)$ reaction cross section.

The comparison of the present ^{235}U capture cross section with the values from other available sources shows that below 200 eV there is general agreement within an error band of $\pm 5\%$. In the keV energy region, the average difference observed rises to $\pm 12\%$.

The fission cross section results presented here agree with a world-wide compilation of fission data typically within a 3% error in the entire range of neutron energies investigated in this work.

The values of alpha, capture-to-fission ratio, exhibit a remarkable amount of structure superimposed on the featureless behavior predicted by Bohr's fission channel theory.

* Abstract of ORNL-TM-3696; also to be published in Nucl. Sci. Eng.

** Relevant to Request Nos. 388, 389, 390, 393 and 394.

20. Multilevel Effects in the Unresolved Resonance Region of the Cross Sections of Fissile Nuclides* (G. de Saussure and R. B. Perez)

For the specification of the cross sections of the fissile isotopes in the neutron energy region of unresolved resonances, the single-level formalism is often used while an analysis of the cross sections in the resolved region indicates that a multilevel formula may be more appropriate. In this paper we compare the statistical properties of the cross sections generated using the single-level formalism with those obtained by a multilevel formulation. The multilevel parameters were chosen so as to give the same average cross sections as the single-level formalism. The comparison indicates that there are small but significant differences between the statistical properties of the cross sections obtained with the multilevel formalism and those obtained with the single-level formula. The differences are probably too small, particularly when Doppler broadening is considered, to affect reactor calculations.

* To be presented at the Chicago APS Meeting, June 1973; submitted to Nucl. Sci. Eng. for publication.

21. General Sensitivity Theory for Radiation Transport* (E. M. Oblow)

The theoretical framework of a general approach to sensitivity analysis using adjoint functions is introduced and developed for practical application. Sensitivity and the context in which it is used is defined quantitatively in terms of adjoint functionals. The physical meaning and applicability of such a definition are then discussed with reference to both analytic and predictive studies. Connections are made between the general approach and perturbation theory for predictive applications. Specific formulations useful in cross-section sensitivity work are described in detail.

* Abstract of ORNL-TM-4110.

22. Neutron Yield from a Small High Purity $^{238}\text{Pu O}_2$ Source*
(J. K. Bair and H. M. Butler)

The neutron yield from a small high purity $^{238}\text{Pu O}_2$ source has been measured to be 1.705×10^4 neutrons per second per gram of ^{238}Pu with an accuracy of better than 1%.

* Submitted for publication in Nuclear Tech., Technical Note.

23. Neutron Capture in Fluorine Below 1500 keV* (R. L. Macklin and R. R. Winters†)

Neutron time-of-flight radiative capture data taken at the Oak Ridge Electron Linear Accelerator have been analyzed for single level resonance parameters. Ten resonances were found, with parameters as indicated, listing E (keV), J value assumed, and Γ_n (eV) in order. 27.07(2)1.4 + .3, 48.7(1)1.7 + .4, 97.0(1) < 6.0 + 1.8, 269(1)3.5 + 0.8, 270(1) < 4.4, 386(1)7 + 2, 490.5(0) > 10 + 3, 595(1) > 12.6 + 2, 1460(1) > 11 + 3. Values of total width were also found for these resonances. Two resonances are very narrow and their capture areas yield estimates of $g\Gamma_n$. At 43.5 keV $g\Gamma_n = 0.86 + .02$ eV if $J \geq 1$ or $\Gamma_n = .42 + .1$ eV if $J = 0$, and at 173.5 keV $g\Gamma_n = .35 + .10$ eV. The increase of nearly an order of magnitude in radiative width with increasing energy up to 600 keV is notable. Twelve large resonances between 1600 and 5000 keV were not analyzed for capture because of detector sensitivity to the inelastic scattering channels which open in that energy region.

* Submitted to Phys. Rev. for publication.

† Denison University, Granville, Ohio.

24. Cross-Section Sensitivity of Breeding Ratio in a Fusion-Reactor Blanket* (D. E. Bartine, R. G. Alsmiller, Jr., E. Oblo and F. R. Mynatt)

In a reactor operating on deuterium-tritium fusion, it is necessary that the blanket surrounding the plasma have a tritium breeding ratio larger than unity,¹ (more than one tritium nucleus produced per incident neutron). In this paper, the sensitivity of this breeding ratio to changes in neutron cross sections in a model fusion-reactor blanket is studied using linear perturbation theory.² The blanket model used is the standard model that has been proposed for comparison of neutronics codes.³ All of the transport calculations were carried out with the one-dimensional discrete

ordinates code ANISN,⁴ using P_3S_{12} , while the code SWANLAKE⁵ was employed in the sensitivity studies. The cross-section data were taken from ENDF/B-III, MAT. 1164 for Nb, MAT. 1115 for ^6Li , MAT. 1116 for ^7Li , and MAT. 1165 for C.

The sensitivity which is numerically equal to the percent change in the breeding ratio due to a 1% increase in the indicated element's cross sections was -0.20% for Nb, +0.12% for ^6Li , +0.13% for ^7Li , and +0.06% for C. Sensitivities were also calculated for all partial cross sections (elastic, inelastic, etc.). All results are directly proportional to the assumed change in cross sections; i.e., to estimate the effect of a 2% increase in the cross sections, the values given should be multiplied by 2. However, if $\delta R/R$ becomes large, the analysis becomes invalid. In general, the total sensitivity of the breeding ratio to changes in the cross sections is quite low. The results indicate that the sensitivity is considerably influenced by the energy dependence of the tritium-production cross sections in ^6Li and ^7Li .

* To be presented at the Chicago ANS Meeting, June 10-15, 1973.

¹D. Steiner, Nucl. App. Tech. 9, 83 (1970).

²D. L. Prezbindowski and H. A. Sandmeier, Trans. Am. Nucl. Soc. 11, 193 (1968).

³D. Steiner, private communication (1972).

⁴W. W. Engle, Jr., "A Users Manual for ANISN, a One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering," K-1693, Computing Technology Center, Union Carbide Corporation (1967).

⁵D. E. Bartine, F. R. Mynatt and E. Oblow, ORNL-TM-3809 (to be issued).

25. Neutron Fission and Absorption Cross-Section Measurements for ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{241}Am * (L. W. Weston and J. H. Todd)

The neutron fission and absorption cross sections for ^{239}Pu , ^{240}Pu and ^{241}Pu were measured from thermal-neutron energies to 20 keV. In addition, the absorption cross sections of ^{240}Pu and ^{241}Am were measured from thermal-neutron energies to 200 keV. The ratio of the capture and fission cross sections, $(\sigma_c)/(\sigma_f)$, could be determined up to 200 keV for ^{239}Pu and ^{241}Pu .

The general trends of the ^{239}Pu and ^{241}Pu data have been reported previously.¹ The average absorption cross section of ^{240}Pu is in agreement with that reported by Hockenbury.² The shape of the two sets of data

is in good agreement over the range of overlap. The present data, which are normalized to the thermal cross section, are about 10% lower than that of Hockenbury at keV neutron energies. Both these normalizations are appreciably higher than ENDF III, however, all of the data on which ENDF-III was based have been renormalized upward. The average absorption cross section for ^{241}Am was in good agreement with ENDF-III up to 20 keV and is appreciably higher thereafter. There were little previous data on ^{241}Am available in the energy range from 20 to 200 keV.

These results, although not complete, have been reported to the ENDF-IV committee and will be considered in the revision of the ENDF data.

* Relevant to Request Nos. 449, 450, 455, 474 and 479.

¹ L. W. Weston and J. H. Todd, Trans. Am. Nucl. Soc. 15, 480 (1972).

² R. W. Hockenbury, W. R. Moyer and R. C. Block, Nucl. Sci. Eng. 49, 153-161 (1972).

B. CHARGED PARTICLE FISSION STUDIES

1. Photon Dose Rates from the Interactions of 200-GeV Protons in Iron and Iron-Lead Beam Stops* (T. A. Gabriel and R. T. Santoro)

The calculated photon dose rates from the long-lived ($\tau_{1/2} > 1$ min) beta- and gamma-active nuclides produced when 200-GeV protons are incident on a semi-infinite cylindrical iron beam stop having a radius of 40.64 cm (16 in.) are compared with the calculated photon dose rates from long-lived beta- and gamma-active nuclides produced by 200-GeV protons in semi-infinite beam stops having a 30.48-cm (12 in.) radius iron core but surrounded by either 5.08 cm (2 in.) or 10.16 cm (4 in.) of lead. Data are also presented comparing the calculated photon dose rates from the long-lived beta- and gamma-active nuclides produced when 200-GeV protons are incident on semi-infinite cylindrical iron beam stops having radii of 10.16 cm (4 in.), 20.32 cm (8 in.), 30.48 cm (12 in.), and 40.64 cm (16 in.).

* Abstract of Particle Journal Vol. 4, 169-186 (1973).

2. Calculations for Cancer Radiotherapy with Negatively Charged Pions* (Principal Investigator - R. G. Alsmiller, Jr.)

Very approximate estimates indicate that about 60,000 lives per year might be saved if new and improved radiotherapeutic techniques for cancer treatment were available. The use of negatively charged pions is one possible method of obtaining the needed improvement since these particles, because of their physical properties, make it possible, in principle, to deliver highly concentrated radiation doses to small localized regions. The calculational program described here is directed toward the following broad objectives: assessing the biological effect and radiotherapeutic value of negative-pion beams, ascertaining the influence of beam parameters on the dose, LET spectra, cell-survival probabilities, and oxygen-enhancement ratios, and providing quantitative data to aid in planning and understanding biological and therapeutic exposures.

* Part A Introduction of ORNL-TM-4159.

3. A Comparative Study of the Use of Photons, Neutrons, Protons, Negatively Charged Pions, and Heavy Ions in Cancer Radiotherapy* (Principal Investigator - R. G. Alsmiller, Jr.)

Radiotherapy, which is an important aid in the treatment of cancer, is used on about one-half of all cancer patients. Very approximate estimates

indicate that about 60,000 lives per year might be saved if new and improved radiotherapeutic techniques were available. To obtain these needed improvements, a variety of particle types - neutrons, protons, negatively charged pions, and heavy ions - has been proposed for use in radiotherapy. The purpose of the program discussed here is to carry out calculationally an objective comparative study of the therapeutic value of these various particles and the commonly used ^{60}Co gamma rays. The calculational techniques and cross-section data that are being utilized will be verified insofar as possible by comparisons with available experimental data.

* Part B Introduction of ORNL-TM-4159.

4. Fragment Kinetic Energies from ^{18}O -Induced Fission of ^{246}Cm *
(H. Freiesleben†, Franz Plasil, Robert L. Ferguson, Curtis E. Bemis, Jr. and H. W. Schmitt)

Recently it was predicted on the basis of a static scission model (SSM)¹ that total fragment kinetic energies $\langle E_K \rangle$ are larger than those predicted with the liquid drop model (LDM) when $250 \lesssim A < 290$. In a search for this effect, we measured $\langle E_K \rangle$ in bombardments of ^{232}Th and ^{246}Cm with 94-, 105- and 126-MeV $^{18}\text{O}^{5+}$ ions. Correlated energies of fission fragment pairs were measured with silicon surface barrier detectors; fragment mass and total kinetic energy distributions were deduced. The results for $\text{Th} + \text{O}$ are in good agreement with the LDM prediction. A preliminary analysis of the $\text{Cm} + \text{O}$ data shows a smaller $\langle E_K \rangle$ than the LDM predicts. This result, however, does not necessarily invalidate the SSM since the shell effects that lead to prediction of a large $\langle E_K \rangle$ may be washed out above the 50-MeV excitation energy of our $^{264}104$ compound nucleus. In addition, the possibility of fission following incomplete momentum transfer has not been ruled out.

* To be presented at the Washington, D. C. APS Meeting, April 23-26, 1973.

† University of Rochester.

¹H. W. Schmitt and U. Mosel, Nucl. Phys. A186, 1 (1972).

C. PROTON INDUCED REACTIONS1. Total Neutron Yields from the Proton Bombardment of $^{17,18}\text{O}$ ^{*}
(J. K. Bair)

The $^{17}\text{O}(p,n)^{17}\text{F}$ reaction has been observed for the first time in the energy region from threshold to 5 MeV. Total neutron production cross sections measured with good resolution are given. The reaction threshold is determined to be 3743 ± 6 keV. High resolution total neutron cross sections are also given for the reaction $^{18}\text{O}(p,n)^{18}\text{F}$ from threshold to 4 MeV.

^{*} Submitted to Phys. Rev. for publication.

2. Energy Levels of ^{94}Ru Observed with the $^{96}\text{Ru}(p,t)$ Reaction^{*}
(J. B. Ball, C. B. Fulmer, J. S. Larsen† and G. Sletten†)

The level structure of the neutron-magic nucleus ^{94}Ru , up to an excitation energy of 4 MeV, has been studied by means of the (p,t) reaction. Particular emphasis was placed on a search for excited 0^+ levels, none of which have been reported previously. Among new levels observed in this study are 0^+ levels at 2.995, 3.615 and 3.770 MeV, and the 3^- octupole vibration at 2.965 MeV.

^{*} Submitted to Nuclear Physics for publication.

[†] The Niels Bohr Institute, University of Copenhagen, Denmark.

3. The ^{110}Pd , $^{116}\text{Cd}(p,p'\gamma)$ Reactions^{*} (J. A. Deyet†, R. L. Robinson, and J. L. C. Ford, Jr.)

The possibility of extending our knowledge about higher-energy collective-type states among the vibrational nuclei by observing gamma rays from states excited by inelastically scattered protons has been examined. Gamma rays from ^{110}Pd and ^{116}Cd were detected in coincidence with inelastically scattered protons; the incident protons had energies of 12 and 13 MeV. Gamma rays, most of them previously unreported, were observed from 17 levels in ^{110}Pd and 14 levels in ^{116}Cd below ~ 2.5 MeV. The results are compared to predictions of a phonon-model interpretation of the levels. Evidence is shown for the existence of the three-quadrupole phonon quintet in ^{110}Pd .

^{*} Submitted to Nuclear Physics for publication.

[†] Radioisotope Lab., General Hospital, Cincinnati, Ohio.

4. Neutron Hole States in ^{138}La and ^{140}Pr * (V. D. Helton†, J. C. Hiebert† and J. B. Ball)

Protons accelerated to 30 MeV were used to investigate low-lying states in the odd-odd nuclei ^{138}La and ^{140}Pr with (p,d) reactions. The elastic scattering of 30 MeV protons and 23 MeV deuterons was also studied to determine optical potentials. Experimental angular distributions are compared with distorted-wave Born approximation calculations to extract spin, parity, and spectroscopic factors for levels up to 432 keV of excitation in ^{140}Pr and 530 keV in ^{138}La . Comparisons with the simple shell-model predictions and extended shell-model calculations are presented. The ^{140}Pr levels appear experimentally to have an almost pure particle-hole structure whereas the ^{138}La levels exhibit substantial mixing.

* Nuclear Physics A201, 225-246 (1973).

† Cyclotron Institute, Texas A&M University, College Station, Texas 77843.

5. Effective Interactions and the $^{40}\text{Ca}(p,p')$ Reaction* (G. R. Satchler)

The excitation of the lowest 3^- and 5^- levels in ^{40}Ca is studied using a microscopic description. The long-range part of the Hamada-Johnston potential is shown to be a good effective interaction especially when supplemented by a phenomenological imaginary term. Transition densities are constructed from hole-particle RPA wave functions normalized to give the correct electric transition rates. Various wave functions and other interactions are studied. Other features of the calculations are discussed.

* Submitted to Z. für Physik for publication.

6. Differential Cross Sections for the Production of Neutrons from the Bombardment of ^{12}C and ^{27}Al by 63-MeV Protons.* (J. W. Wachter, R. T. Santoro, T. A. Love and W. Zobel)

Differential cross sections in energy and angle have been obtained using time-of-flight spectroscopy for secondary neutrons produced in the reactions of 63-MeV protons with ^{12}C and ^{27}Al . Neutron energy spectra are given for laboratory angles of 20° , 45° , 60° , and 135° for energies > 10 MeV. The NE-213 efficiency was calculated using the 05S Monte Carlo code.¹ Comparisons between the Al cross sections and the predictions of the intra-nuclear cascade model of Bertini² show good agreement at medium angles.

The data do not show the predicted quasi-free scattering peak at 20° , although the energy-integrated cross sections agree. The calculated cross section at 135° is low by a factor of 3 to 4.

* Presented at the January APS Meeting, January 29 - February 1, 1973.

¹ R. E. Textor and V. V. Verbinski, ORNL-4160, 1968.

² H. W. Bertini, Phys. Rev. 131, 1801 (1963); with erratum Phys. Rev. 138, AB 2 (1965).

7. Systematics of Fragment Mass and Energy Distributions for Proton-Induced Fission of ^{233}U , ^{235}U , and $^{238}\text{U}^*$ (S. C. Burnett[†], H. W. Schmitt, R. L. Ferguson, F. Plasil and Frances Pleasonton)

Thin targets of ^{233}U , ^{235}U and ^{238}U were bombarded with protons of several energies between 7 and 13 MeV. Correlated energies of fission fragment pairs were measured with silicon surface barrier detectors. Fragment mass vs. total kinetic energy distributions were deduced, and their systematic variation with bombarding energy was studied. It was found that the yield in the valley of the mass distributions for symmetric divisions increases with increasing excitation energy, and that the peaks move slightly toward symmetry. The average total kinetic energy for mass divisions with one fragment mass ~ 132 amu was found to decrease with increasing excitation energy, while for other mass divisions little change was observed. The average overall total kinetic energy was found to decrease with increasing bombarding energy, and widths of both the kinetic energy distributions and the mass distributions were found to increase somewhat. The results are discussed in terms of fragment shell effects which appear to persist to our highest excitation energy (~ 18 MeV), and also in terms of the two-component fission hypothesis.

* Submitted to Phys. Rev. C for publication.

[†] U. S. Atomic Energy Commission, Washington, D. C. 20545.

8. Fission of ^{209}Bi by 36.1 MeV Protons: Search for an Asymmetric Component in the Mass Distribution, and Neutron Emission Results* (Franz Plasil, Robert L. Ferguson, Frances Pleasonton and H. W. Schmitt)

A thin deposit of ^{209}Bi was bombarded with 36.1 MeV protons from the Oak Ridge Isochronous Cyclotron and correlated energies of fission fragment pairs were measured with silicon surface barrier detectors. The

mass-yield distribution obtained from these energies was compared with the radiochemical results of Sugihara, Roesner and Meadows; we do not confirm the existence of the small asymmetric peak that appears in the wings of their distribution. Studies of statistical uncertainties and dispersion effects in our experiment indicate that they are not large enough to wash-out such peaks. The average number of neutrons emitted as a function of fragment mass was obtained from a cumulative yield calculation and is consistent with an earlier measurement for ^4He -induced fission of ^{209}Bi . Pre-neutron-emission mass and kinetic energy distributions are presented.

*Phys. Rev. C 7, 1186-1197 (1973).

D. ALPHA INDUCED REACTIONS

1. Neutron Shell Structure in ^{125}Sn by (d,p) and (α , ^3He) Reactions* (C. R. Bingham[†] and D. L. Hillis^{††})

Differential cross sections for $^{124}\text{Sn}(\text{d},\text{p})$ at 33.3 MeV were measured in 5° increments from 12.5° to 47.5° lab. The resolution was about 30 keV FWHM. The (α , ^3He) spectra with ~ 55 keV resolution were obtained at 15° and 20° lab. with 65.7 MeV α particles. Spectroscopic factors were obtained by comparison with distorted wave calculations. Consistent spectroscopic factors were obtained from the (d,p) and (α , ^3He) reactions. Spin assignments and spectroscopic factors were obtained for several levels which were not characterized in previous neutron-transfer studies. Sums of spectroscopic factors and centers of gravity are presented for the levels observed. Essentially all the neutron strength remaining in the neutron shell between $N = 50$ and $N = 82$ was located. Most of the strength in the $2f_{7/2}$, $3p_{3/2}$, and $1h_{9/2}$ levels of the next major shell was located. The spectroscopic factors sums and the centers-of-gravity are compared with the results of pairing theory.

* Submitted to Physical Review for publication.

[†] ORNL and the University of Tennessee.

^{††} University of Tennessee.

2. Absolute Neutron Yields from Thick Target $^{13}\text{C}(\alpha, n)^{16}\text{O}$ * (J. K. Bair)

Recent measurements of the neutron yield resulting from the α -particle bombardment of carbon have disclosed an error in the data reported in the literature. New values are given for the thick target yield of neutrons for α -particle energies between 2 and 9 MeV.

* Submitted to Nuclear Science and Engineering, Technical Note, for publication.

3. Total Neutron Yield from the (α, n) Reaction on $^{21,22}\text{Ne}$ * (F. X. Haas† and J. K. Bair)

Compound states of high excitation in $^{25,26}\text{Mg}$ have been observed, with good resolution, in the total neutron yield from α -particle bombardment of $^{21,22}\text{Ne}$. Bombarding energies were from 1 to 5 MeV. Analysis of the areas under the yield curves give α -particle strength functions of $S_{\alpha} = 0.031 \pm 0.021$ for $^{21}\text{Ne} + \alpha$ and $S_{\alpha} = 0.026 \pm 0.012$ for $^{22}\text{Ne} + \alpha$. For astrophysical purposes these strength functions are used to extrapolate the averaged cross sections to lower energies.

* Submitted to Physical Review for publication.

† Mound Laboratory, Miamisburg, Ohio.

4. Total Neutron Yield from the Reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{17,18}\text{O}(\alpha, n)^{20,21}\text{Ne}$ * (J. K. Bair and F. X. Haas†)

Compound states of high excitation in ^{17}O and $^{21,22}\text{Ne}$ have been observed, with good resolution, in the total neutron yield from the reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{17,18}\text{O}(\alpha, n)^{20,21}\text{Ne}$. Bombarding α -particle energies were approximately from 1 to 5 MeV. Analysis of the area under the excitation curves gives α -particle strength functions of $S_{\alpha} = 0.029 \pm 0.030$ for $^{13}\text{C} + \alpha$, 0.030 ± 0.023 for $^{17}\text{O} + \alpha$ and 0.022 ± 0.010 for $^{18}\text{O} + \alpha$. For astrophysical purposes these strength functions are used to extrapolate the average cross sections to lower energies.

* Submitted to Physical Review for publication.

† Mound Laboratory, Miamisburg, Ohio.

E. HEAVY ION INDUCED FISSION

1. Fission and Complete Fusion Measurements in ^{40}Ar Bombardments of ^{58}Ni and ^{109}Ag * (H. H. Gutbrod†, H. C. Britt††, B. H. Erkilat††, R. H. Stokes††, M. Blann†††, and F. Plasil)

Thin targets of ^{58}Ni and ^{109}Ag have been bombarded with 288 MeV ^{40}Ar ions from the Berkeley SUPER-HILAC. A particle telescope consisting of a gas proportional ΔE counter and a silicon surface barrier E detector was used to measure all reaction products ranging from elastically scattered argon ions to complete fusion products. Fission fragments and transfer products were also detected. A good separation between fission fragments and other reaction products was possible in the case of the $^{109}\text{Ag} + ^{40}\text{Ar}$ reaction. Angular distributions were obtained from 4° to 180° in the laboratory system. Elastic scattering was used to obtain energy and angular calibrations.

In the case of $^{109}\text{Ag} + ^{40}\text{Ar}$, the complete fusion cross section, σ_{CF} , was found to be 610 mb. The fission fragment angular distribution is characterized by a $1/\sin\theta$ function, and the integrated fission cross section was found to be 1160 mb. Thus essentially all of the estimated total reaction cross section σ_{R} of 1875 mb is accounted for. For $^{58}\text{Ni} + ^{40}\text{Ar}$, σ_{CF} was found to be ≈ 870 mb.

Results have been interpreted in terms of a model in which fission competes with other modes of de-excitation of the compound nucleus, and in which the effects of angular momentum on the fission barrier are taken into account. It was found that for $^{109}\text{Ag} + ^{40}\text{Ar}$, the calculated ratio $\sigma_{\text{CF}}/\sigma_{\text{R}}$ was 0.17 compared with the experimental result of 0.33 and for $^{58}\text{Ni} + ^{40}\text{Ar}$, the calculated ratio was 0.25 compared with a measured value of 0.47. The model seems to overestimate the fission contribution for the reactions investigated in this work. The implications of this conclusion are discussed.

* Submitted to the IAEA 3rd Symposium on the Physics and Chemistry of Fission, Rochester, New York, August 13-17, 1973.

† G.S.I. Darmstadt, Germany.

†† Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

††† University of Rochester, Rochester, New York.

2. Cross Sections for $^{61}\text{Ni}(^{16}\text{O},\text{X})$ Reactions* (J. C. Wells, Jr.[†]
Jung Lin[†], R. L. Robinson, H. J. Kim and J. L. C. Ford, Jr.

We have determined absolute cross sections for different exit channels for reactions induced by bombardment of ^{61}Ni with ^{16}O ions between 38 and 51 MeV. Targets were 1 mg/cm² enriched ^{61}Ni with Au backing. Cross sections were obtained from yields of gamma rays from residual radioisotopes, and from prompt gamma rays from the target. Identification of the products was based on gamma ray energies and intensities, and on the half-lives, in the case of the radioisotopes. Due to the proximity of the Coulomb barrier ($E \approx 42$ MeV), all of the cross sections increase rapidly with energy.

* To be presented at the Washington, D. C. APS Meeting, April 23 - 26, 1973.

[†] Tennessee Technological University, Cookeville, Tennessee.

3. In-Beam γ Rays from the $^{28}\text{Si}(^{16}\text{O},2\text{p})^{42}\text{Ca}$ Reaction* (H. J. Kim,
R. L. Robinson, W. T. Milner, J. C. Wells, Jr.[†] and J. Lin[†])

The yields and angular distributions of the prominent in-beam γ rays from the ^{16}O bombardment of ^{28}Si were investigated for bombarding energies of 24 to 42 MeV. To ascertain the origin of some of the γ rays, the in-beam γ rays from the 36- and 42-MeV ^{16}O bombardment of ^{29}Si and ^{30}Si were also studied. The γ rays from the stretched E2 transitions between the lowest-lying 6^+ , 4^+ , 2^+ and ground states of ^{42}Ca dominate the $^{16}\text{O} + ^{28}\text{Si}$ singles spectra. Above 36-MeV bombarding energy the side-feeding intensities for the 4^+ and 2^+ states are less than 25% and the production of ^{42}Ca proceeds mainly via the 6^+ state. The γ - γ coincident spectrum measured at 42 MeV with two large-volume Ge(Li) detectors shows that the 6^+ state is fed by many γ rays.

* To be presented at the Washington, D. C. APS Meeting, April 23 - 26, 1973.

[†] Tennessee Technological University, Cookeville, Tennessee.

4. Lifetime Measurements of 8^+ , 10^+ and 12^+ Rotational States in ^{164}Dy * (D. C. Hensley, N. R. Johnson, W. T. Milner, G. B. Hagemann[†] and L. L. Riedinger^{††})

Rotational states up to spin 12 in ^{164}Dy were populated by inelastic scattering of 153 keV ^{40}Ar from a thick target of ^{164}Dy . Gamma rays were detected in two Ge(Li) detectors at 0° and 90° to the beam and were recorded in coincidence with ^{40}Ar ions backscattered (160°) into an annular detector. Lifetimes were inferred from the Doppler broadened shapes of

the γ -transitions: $8^+ \rightarrow 6^+$, $10^+ \rightarrow 8^+$, and $12^+ \rightarrow 10^+$ by comparing the observed line shapes to those calculated taking into account the stopping power of projectiles and recoiling ions as well as the reaction kinematics and detector geometry. The results are presented as the ratio of the experimental $B(E2)$ to the $B(E2)$ predicted by the rigid rotor model, and, because of some uncertainty in the absolute value of the stopping power, the ratios have been scaled so that the ratio for the $(8^+ \rightarrow 6^+)$ transition is 1.0; $(10^+ \rightarrow 8^+) = 1.18 \pm 0.1$; and $(12^+ \rightarrow 10^+) = 1.35 \pm 0.2$. Measurements in ^{160}Dy are in progress.

* To be presented at the Washington, D. C. APS Meeting, April 23 - 26, 1973.

† Niels Bohr Institute.

†† University of Tennessee, Knoxville, Tennessee.

5. High Spin States in ^{164}Yb and ^{160}Er * (P. H. Stelson, G. B. Hagemann, D. C. Hensley, R. L. Robinson, L. L. Riedinger† and R. O. Sayer††)

The $^{156}\text{Gd}(^{12}\text{C}, 4n)^{164}\text{Yb}$ and $^{152}\text{Sm}(^{12}\text{C}, 4n)^{160}\text{Er}$ reactions at 74 MeV were used to excite high spin states in the residual nuclei. γ - γ coincidences with Ge(Li) detectors were used to relate γ -rays to the g.s. band. The systematic decrease of γ -ray intensity with increasing spin was helpful in placing observed γ -rays. In ^{164}Yb the $20 \rightarrow 18$ γ -ray intensity was about 10 percent of the $4 \rightarrow 2$ γ -ray intensity. For ^{164}Yb we confirm the previous results of the Jülich group (to 16^+). New γ -rays are found at 543.2 and 632.5 keV which are assigned to decay of the 18^+ and 20^+ states, respectively. Tentative evidence was obtained for a 713.0 keV γ -ray from decay of the 22^+ state. Several discrete γ -rays were observed which feed into the g.s. band at the spin 10-12 region. In ^{160}Er we observed γ -rays of 556.1 and 640.0 keV which are assigned to decay of the 18^+ and 20^+ states, respectively

* To be presented at the Washington, D. C. APS Meeting, April 23 - 26, 1973.

† University of Tennessee

†† Furman University

6. Heavy-Ion-Induced Fission of Nuclei in the Region of Silver*
(Franz Plasil, Robert L. Ferguson and Frances Pleasonton)

Studies of heavy-ion-induced fission of light nuclei have been initiated at the Oak Ridge Isochronous Cyclotron. Thin targets of ^{107}Ag were bombarded with 165 MeV ^{20}Ne ions. Surface barrier silicon detectors were used to detect coincident pairs of fission fragments and to measure fragment kinetic energies. Mass and total kinetic energy distributions were obtained from the correlated energy data by means of an iterative center-of-mass calculation. The fragment angular correlation was also measured, as was the fission cross section, σ_F , relative to Rutherford scattering. σ_F for ^{107}Ag and 165 MeV ^{20}Ne was found to be 172 mb. This value is about four times greater than that obtained from earlier track detector measurements. The angular correlation, which provides a measure of momentum transfer, was found to be slightly asymmetric, indicating a small contribution from three-body reactions.

The mass distribution was found to be symmetric, and the average total kinetic energy to be 90 MeV. Measured widths of the mass and total kinetic energy distributions were compared with the liquid drop model, which predicts the mass distribution to be broad (43 amu FWHM), and the total kinetic energy distribution to be narrow (17 MeV FWHM). The measured width of the mass distribution (36 amu FWHM) is, as expected, greater than the width of the kinetic energy distribution (27 MeV FWHM), but the measured values differ substantially from those predicted by the liquid drop theory.

Calculations of σ_F have been made on the basis of a model in which fission competes with other modes of de-excitation of the compound nucleus, and in which the variation of the fission barrier with angular momentum is taken into account. The calculated upper limit on σ_F was found to be 730 mb which is greater than the observed fission cross section of 172 mb. It is concluded that in addition to fission and to complete fusion of target and projectile, other reaction channels play an important role.

* Submitted to the IAEA 3rd Symposium on the Physics and Chemistry of Fission, Rochester, New York, August 13-17, 1973.

7. Single-Nucleon Transfer Reactions and Inelastic Scattering Induced by ^{11}B Ions Incident on ^{208}Pb * (J. L. C. Ford, Jr., K. S. Toth, D. C. Hensley, R. M. Gaedket, P. J. Riley††, and S. T. Thornton†††)

^{208}Pb was bombarded with 72-MeV ^{11}B ions accelerated in the Oak Ridge Isochronous Cyclotron. With the use of a 60-cm long, 3-wire, position sensitive proportional detector placed in the focal plane of a broad-range magnetic spectrograph all four single-nucleon transfer reaction products

were identified. Angular distribution measurements have been completed for five final states in ^{209}Bi populated in the reaction $^{208}\text{Pb}(^{11}\text{B}, ^{10}\text{Be})$ and for three states in ^{207}Pb populated in the reaction $^{208}\text{Pb}(^{11}\text{B}, ^{12}\text{B})$. The differential cross sections are single peaked and smooth. Once again, as reported earlier¹ for the analogous reaction $^{208}\text{Pb}(^{12}\text{C}, ^{11}\text{B})^{209}\text{Bi}$, the indication is that for the proton stripping reaction the peak angles remain constant with increasing excitation energy in ^{209}Bi . Angular distributions for inelastic scattering to the 3^- , 5^- and 2^+ states at 2.62, 3.20, and 4.10 MeV in ^{208}Pb were also measured.

* Presented at the Symposium on Heavy-Ion Transfer Reactions, Argonne, Illinois, March 15-17, 1973.

† Trinity University, San Antonio, Texas.

†† University of Texas, Austin, Texas.

††† University of Virginia, Charlottesville, Virginia.

¹ J. S. Larsen et al., Phys. Letters 42B, 205 (1972).

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