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AN EXAMPLE OF NUCLEAR DATA CENTER SERVICES FOR GEOPHYSICS APPLICATIONS

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Abstract

A bibliographic survey of the available experimental data on neutron induced gamma-ray production has been made. Use was made of Data Center on-line search and retrieval capabilities. CINDA was searched for prompt gamma-ray production data covering a large incident neutron energy range, and where possible, EXFOR was used to scan the data and select representative works. From the survey it appears that many measurements will have to be supplemented by theoretical calculations.

INTRODUCTION

Applications of nuclear techniques in the earth sciences are becoming increasingly more important. These applications require more and more accurate nuclear data. Nuclear data centers can play an active and vital role in supplying these needs. Data centers collate and evaluate nuclear data of interest to both the basic and applied researcher. Virtually the entire range of low-energy nuclear physics is addressed, including nuclear structure and decay data and nuclear reaction data. The files maintained by the various centers include bibliographies, compilations of experimental data, and evaluations. Data centers maintain evaluated data files such as ENDF/B[1] which contain neutron induced γ -ray production in a format that is application oriented. From these files, the centers provide specialized retrievals on request, on-line access, and timely publications. As a specific example, a survey of neutron-induced prompt gamma ray production has been made and the results are discussed.

BIBLIOGRAPHIC SEARCH

A bibliographic survey of the available experimental data on neutron induced prompt gamma-ray production was carried out. The experimental instead of evaluated data were studied since (1) the range of elements covered is probably more complete; (2) the data may be more current; and (3) the experimental data probably reflect the limits and accuracies of the evaluated data. We relied primarily on data center on-line search and retrieval capabilities which allowed us easy access to CINDA and EXFOR.

CINDA, a Computer Index of Neutron Data, contains bibliographic reference to measurements, calculations reviews, and evaluations of neutron cross sections and other microscopic neutron data; it also includes index references to computer libraries of numerical neutron data (EXFOR) exchanged between the four world-wide regional data centers. The contents of CINDA are periodically published in book form by the International Atomic Energy Agency (IAEA).

CINDA was searched for gamma-ray production data covering a large incident neutron energy range (at least 10 MeV) and at about 14 MeV. Where possible, EXFOR was then used to scan the data and select representative works.

1. 0.2- to 20-MeV Neutron Induced Prompt Gamma-Ray Production Measurements

Table 1 summarizes the data available. This table is not inclusive in that only one or two representative measurements are given for each element or isotope. Contained in this table are the element studied, neutron energy range, detector, gamma energy range, angles, reference, indication of use in ENDF/B-V, and explanatory comments. The EXFOR accession number has also been given when the data have been compiled. The data are dominated by work from the Oak Ridge Electron Linear Accelerator (ORELA) and this work spanning better than a decade has been reviewed by Larson[2], among others.

Most of the work has used sodium iodide detectors (NaI) which have poorer energy resolution than lithium-drifted germanium detectors Ge(Li). However, many of the measurements have an energy resolution or bin size of 10 to 20 keV for the lower-energy gammas. This may be adequate for nuclear geophysics since Clayton, et al.[3] note that a bin size of 50 keV was adequate for silicon. Sodium iodide measurements have the advantage of including many weak transitions as a continuum.[2] New measurements planned or under way at ORELA for structural and other materials using Ge(Li)'s,[4,5] at the Los Alamos White Neutron Source using bismuth germanate (BGO),[5] and by a collaboration providing data for the Mars Geoscience Climatology Observer[7], should improve the situtation over the next few years.

There seems to be a practical lower limit of 200-keV neutron energy for these experiments. Therefore, data below this limit will have to come from other experiments or calculations. Also note that there appear to be two large areas where no measurements have been made. These are from Ga through Sr and Sb through Hf.

Cross section uncertainties have not been included in Table 1 but are roughly comparable to those given in Table 2.

2. ∿ 14-MeV Neutron Induced Gamma-Ray Production Measurements

Table 2 summarizes the data available. Only one or two representative measurements are given for each element or isotope. Contained in this table are the element studied, detector, angles, cross section uncertainties, reference, and explanatory comments.

While there are more Ge(Li) data available at this energy, NaI measurements still dominate. The resolution of these NaI data also seem poorer than above, typically 100-500 KeV. The large gaps of no data, Ga through Sr, and Sb through Hf, are also evident here.

CONCLUSIONS

Evaluated γ-production files can readily be used by geophysicists in Monte Carlo calculations of neutron induced prompt γ spectra[8]. From the survey above, it appears that measurements will have to be supplemented by theoretical calculations. Nuclear model codes are becoming increasingly sophisticated and appear capable for reproducing the experimental data well within the experimental uncertainties.[9,10,11] Another approach is to employ semiempirical formalisms. One of these formalisms, relevant to gamma ray production, is the R-parameter formalism developed by Howerton and Plechaty.[12,13] Although this technique is limited in scope, it has the great advantage of simplicity.

Table 1. 0.2- to 20-MeV Prompt Gamma Production Measurements*

Element Isotope	En(MeV) Emin	En(MeV) Emax	En(MeV) ΔE	Detector	Eγ(MeV) Emin	Eγ(MeV) Emax	Eγ(MeV) ΔE	Angles	Ref	ENDF B-V	Comments
H											
He											
Li	0.5	20.6	0.01-1.1	NaI	0.48			125	1	Y	
7	0.2	40.		Ge(Li)	0.2	10			2		92.5%. In progress.
	0.5	19.8	0.007-0.2	NE213	0.48			125	3		
Be 9	2	25		BGO	1	20		45-140	4		5 angles. No data.
B 10	0.2	40.		Ge(Li)					5		19.9%. Planned.
11	0.2	40.		Ge(Li)					5		80.1%. Planned.
C 12	4.8	20.7	0.25-3.5	Ge(Li)	4.43			4π	6		98.90%.
N	6.2	15.9	1.0-2.5	Ge(Li)	0.73	7.03		4π	7		Discrete γ's.
	2.0	20.0	1.0-3.0	NaI	1.85	10.8	0.06-0.3	90,125	8	Y	
14	6.0	20.0	1.0-3.0	Ge(Li)	0.57	10.2	0.3-0.5	4π	6		99.634%.
O	6.5	20.0	0.5-3.0	NaI	1.6	10.6	0.03-0.15	125	9	Y	
F 19	1.3	20.0	0.23-3.0	NaI	0.91	10.6	0.02-0.3	125	1	Y	
Ne											
Na 23	0.2	20.1	0.2-3.0	NaI	0.35	10.6	0.02-0.25	125	10	Y	
Mg	1.0	19.9	0.25-0.5	NaI	0.69	10.3	≈0.1	90,125	11	Y	
Al 27	0.9	16.7	0.4-4.2	Ge(Li)	0.47	7.6	0.25	125	12		Also discrete γ's.
	0.85	20.0	0.2-3.0	NaI	0.69	10.6	0.02-0.2	90,125	13	Y	
Si	1.0	20.0	0.24-3.0	NaI	0.69	10.4	≈0.1	90,125	14		
P 31											
S											
Cl											
Ar											
K											
Ca	0.7	20.1	0.5-3.0	NaI	0.69	10.6	0.02-0.2	125	15	Y	
Sc 45											
Ti	0.4	19.9	0.3-3.0	NaI	0.31	20.5	0.02-1.0	125	16		
V 51	0.2	20.1	0.27-10.6	NaI	0.27	10.6	0.02-0.2	125	17	Y	99.750%.
Cr	0.2	20.0	0.4-3.0	NaI	0.30	10.3	0.01-0.1	125	18	Y	
	0.2	40.		Ge(Li)	0.2	10			19		Some data.
53	0.2	40.		Ge(Li)	0.2	10			19		9.501%. Some data.
Mn 55	0.2	20.0	0.4-3.0	NaI	0.22	10.6	0.01-0.2	125	20	Y	
Fe	0.9	16.7	0.4-4.0	Ge(Li)	0.41	7.88	0.25	125	12		Also discrete γ's.
	0.9	20.1	0.15-2.5	NaI	0.69	10.6	0.02-0.2	125	21	Y	
56	0.2	40.		Ge(Li)	0.2	10			19		91.72%. Some data.
57	0.16	21.5	0.01-5.0	Ge(Li)	0.12	2.8		4π	4		2.2%. Discrete γ's.
Co 59	0.2	40.		Ge(Li)					5		Planned.
Ni	1.0	20.0	0.5-3.0	NaI	0.69	20.6	0.02-0.3	125	22	Y	
	0.2	40.		Ge(Li)	0.2	10			19		Some data.
58	0.2	40.		Ge(Li)	0.2	10			19		68.27%. Some data.
Cu	0.2	20.1	0.4-3.0	NaI	0.30	10.6	0.02-0.2	125	23		
	1.0	20.0	0.25-2.5	NE213	0.76	20.5	0.04-1.0	130	24		
Zn	0.8	19.9	0.15-2.9	NaI	0.69	10.6	0.02-0.2	125	25		
Ga											
Ge											
As 75											
Se											
Br											
Kr											
Rb											
Sr											
Y 89											
Zr											
Nb 93	0.75	20.1	0.25-3.0	NaI	0.75	10.6	0.02-0.2	90	26		
Mo	0.20	20.0	0.4-3.0	NaI	0.30	10.6	0.02-0.2	125	27		
Ru											
Rh103											
Pd											
Ag	0.30	19.9	0.1-2.9	NaI	0.30	10.6	0.02-0.2	125	28		
Cd											
In											
Sn	0.75	19.9	0.24-3.0	NaI	0.69	10.6	0.02-0.2	125	29		
Sb											
Te											
I 127											
Xe											
Cs133											
Ba											

Table 1. 0.2- to 20-MeV Prompt Gamma Production Measurements (continued)*

Element Isotope	En(MeV) Emin	Emax	ΔE	Detector	Eγ(MeV) Emin	Emax	ΔE	Angles	Ref	ENDF B-V	Comments
La											
Ce											
Pr141											
Nd											
Sm											
Eu											
Gd											
Tb159											
Dy											
Ho165											
Er											
Tm169											
Yb											
Lu											
Hf											
Ta	0.4	20.2	0.1-5.0	NaI	1.0	10.4	0.04-0.2	90	30	Y	
181	2	25		BGO	1	20		45-140	31		99.988%. 5 angles. Some data.
W	1.0	20.0	0.5-3.0	NaI	0.69	10.6	0.02-0.2	125	32	Y	
Re	1.2	10.8	0.15-1.2	Scin	1.0	5.0	0.25	4π	33		
Os											
Ir											
Pt											
Au197	0.2	20.1	0.4-3.0	NaI	0.30	10.6	0.02-0.2	125	34		
Hg											
Tl											
Pb	0.6	20.0	0.4-2.5	???	0.3	10.6	0.02-0.2	125	35	Y	
Bi209											
Th232	0.3	20.0	0.2-3.0	NaI	0.31	10.6	0.02-0.2	125	36	Y	
U											

* Excluding Tc and Pm and the daughters of actinide decay, Po, At, Rn, Fr, Ra, Ac, and Pa which do not occur naturally. *No data were found for these nuclides.*

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Table 2. ≈14-MeV Prompt Gamma Production Measurements*

Element Isotope	Detector	Angles	ΔIγ(%)	Ref	Comments (Eγ in MeV)
H					
He					
Li 6	NaI	4π	36	1	7.5%. 3.56 γ.
7	NaI	4π	15	1	92.5%. 0.48 γ.
Be 9	NaI	4π	20-42	1	0.48, 2.45 γ's.
B 10	NaI	4π	12-50	1	19.9%. 12 γ's (0.46-6.1).
11	NaI	4π	10-33	1	80.1%. 10 γ's (1.1-9.3).
C	NaI	45-130	14	2	4.4 γ. 6 angles.
N 14	NaI	4π	10-50	1	99.634%. 13 γ's (0.73-7.0).
O 16	NaI	4π	10-50	1	99.762%. 13 γ's (0.74-7.1).
F 19	NaI	4π	11-25	3	5 γ's (1.39-5.20).
Ne					
Na23	Ge(Li)	4π	11-14	4	7 γ's (0.440-2.641).
Mg	NaI	4π	10-20	3	4 γ's. (1.37-4.00).
Al27	NaI	90,110,130	6-15	2	6 γ's (0.84-3.0).
	Ge(Li)	125	11-68	5	18 γ's (0.631-3.203).
Si	NaI	4π	14-50	1	Binned. 0.5-12.0; 0.5.
	NaI	90,110,130	12	2	1.78 γ.
28	NaI	4π	10-32	3	92.23%. 4 γ's (1.02-2.76).
P 31	NaI	4π	14-25	3	1.26, 2.23, 2.96 γ's.
S	NaI	4π	16-200	1	Binned. 0.5-12.0; 0.5.
32	NaI	4π	11-20	3	95.02%. 5 γ's (1.27-3.95).
Cl	NaI	4π	15-32	3	1.30, 2.19, 2.99 γ's.
35	Ge(Li)	125	24-27	5	75.77%. 1.769, 2.132 γ's.
37	Ge(Li)	125	31	5	24.23%. 1.730 γ.
Ar					
K					
Ca	NaI	90,110,130	10-36	2	Binned. 0.4-8.5; 0.1 to 0.5.
40	NaI	4π	35	3	96.941%. 3.9 γ.
Sc45					
Ti	NaI	90,110,130	10-24	2	Binned. 0.2-8.5; 0.1 to 0.5.
48	NaI	4π	9-18	6	73.8%. 0.99, 1.31 γ's.
V	NaI	90,110,130	10-23	2	Binned. 0.2-8.5; 0.1 to 0.5.
Cr	Ge(Li)	125	17-28	5	1.811, 1.946 γ's.
52	Ge(Li)	125	7-33	5	83.789%. 7 γ's (0.744-1.783).
Mn55					
Fe	Ge(Li)	90	10-50	4	30 γ's (0.412-3.602).
	Ge(Li)		0.8-57	7	43 γ's (0.438-8.80). Relative
Co59					
Ni	Ge(Li)	90	7-10	8	37 γ's (0.230-1.319).
Cu	Ge(Li)	80	9-43	9	13 γ's (0.365-1.853).
	Ge(Li)	55	8-50	10	29 γ's (0.344-1.861).
63	Ge(Li)	125	9-154	5	69.17%. 10 γ's (0.670-1.886).
65	Ge(Li)	125	11-48	5	30.83%. 6 γ's (0.470-1.482).
Zn	NaI	4π	16-100	1	Binned. 0.5-12.0; 0.5.
Ga					
Ge					
As75					
Se					
Br					
Kr					
Rb					
Sr					
Y 89	Ge(Li)	90	11-30	11	19 γ's (0.1276-1.5064).
Zr	NaI	4π	19-140	1	Binned. 0.5-12.0; 0.5.
Nb93	NaI	90,110,130	10-100	2	Binned. 0.2-8.5; 0.1 to 0.5.
Mo	NaI	4π	2-100	1	Binned. 0.5-12.0; 0.5.
Ru					
Rh103					
Pd					
Ag					
Cd	NaI	4π	16-100	1	Binned. 0.5-12.0; 0.5.
In	NaI	4π	16-200	1	Binned. 0.5-12.0; 0.5.
Sn	NaI	4π	16-100	1	Binned. 0.5-12.0; 0.5.

Table 2. ≈14-MeV Prompt Gamma Production Measurements (continued)*

Element Isotope	Detector	Angles	ΔIγ(%)	Ref	Comments (Eγ in MeV)
Sb					
Te					
I 127					
Xe					
Cs133					
Ba					
La					
Ce					
Pr141					
Nd					
Sm					
Eu					
Gd					
Tb159					
Dy					
Ho165					
Er					
Tm169					
Yb					
Lu					
Hf					
Ta	NaI	120	10–80	2	Binned. 0.3–8.5; 0.1 to 0.5.
W	NaI	4π	20–100	1	Binned. 0.5–7.0. 0.5.
Re					
Os					
Ir					
Pt	NaI	90,130	10–88	2	Binned. 0.4–8.5; 0.1 to 0.5.
Au197					
Hg	NaI	4π	17–100	1	Binned. 0.5–12.0; 0.5.
Tl					
Pb	Ge(Li)	80	6–50	8	12 γ's (0.538–4.089).
206	Ge(Li)	125	11–20	5	24.1%. 4 γ's (0.537–0.987).
207	Ge(Li)	125	11–27	5	22.1%. 6 γ's (0.569–1.777).
208	Ge(Li)	125	13–22	5	52.4%. 1.042, 2.614 γ's.
Bi209	Ge(Li)	80	6–20	8	5 γ's (0.896–2.741).
	Ge(Li)	4π	≥15	11	30 γ's (0.2853–1.938). Energy resolution=30-80 keV.
Th232	NaI	90,130	10–270	2	Binned. 0.4–8.5; 0.1 to 0.5.
U 235	NaI	120	10–67	2	0.7200%. Binned. 0.4–8.5; 0.1 to 0.5.
238	NaI	90,130	10–67	2	99.2745%. Binned. 0.4–8.5; 0.1 to 0.5.

* Does not include Tc or Pm which are not naturally occurring or the daughters of actinide decay, Po, At, Rn, Fr, Ra, Ac, and Ac. No data were found for these nuclides.

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