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CALCULATED α-INDUCED THICK TARGET NEUTRON YIELDS AND SPECTRA, WITH COMPARISON TO MEASURED DATA

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Abstract: One component of the neutron source associated with the decay of actinide nuclides in many environments is due to the interaction of decay α particles in (α,n) reactions on low Z nuclides. Measurements of (α,n) thick target neutron yields and associated neutron spectra have been made for only a few combinations of α energy and target nuclide or mixtures of actinide and target nuclides. Calculations of thick target neutron yields and spectra with the SOURCES code require α-energy-dependent cross sections for (α,n) reactions, as well as branching fractions leading to the energetically possible levels of the product nuclides. A library of these data has been accumulated for target nuclides of Z $\leq$ 15 using that available from measurements and from recent GNASH code calculations. SOURCES, assuming neutrons to be emitted isotropically in the center-of-mass system, uses libraries of α stopping cross sections, (α,n) reaction cross sections, product nuclide level branching fractions, and actinide decay α spectra to calculate thick target (α,n) yields and neutron spectra for homogeneous combinations of nuclides. The code also calculates the thick target yield and angle integrated neutron spectrum produced by α-particle beams on targets of homogeneous mixtures of nuclides. Illustrative calculated results are given and comparisons are made with measured thick target yields and spectra.

[(α,n) neutron sources, thick target neutron yields, neutron spectra]

Introduction

The accurate calculation of the magnitude and spectrum of neutrons emitted from (α,n) reactions in thick targets is required for the description of source/target combinations for which there are no experimentally measured thick target neutron yield data. We have accumulated measured data describing (α,n) reaction cross sections and partial cross sections leading to the various product-nuclide energy levels, α-particle stopping cross sections, α decay spectra, (α,n) thick-target yields, and thick-target neutron yield spectra. These data have been supplemented with the results of nuclear reaction physics model code calculations to complete all data requirements for light (α,n) targets with Z $\leq$ 15 and α-particle energies $E_\alpha \leq$ 6.5 MeV. The description of these data, the thick-target (α,n) neutron yields and neutron spectra calculated with the data and the SOURCES code, and comparisons to measured yields and spectra are described in the sections that follow.

Theory

The loss of energy by αs slowing within a material m is described by the stopping power of the material,

$$SP_m^\alpha(E) = -\frac{dE}{dx}(E). \tag{1}$$

A variety of quantities are elsewhere found to be defined as "stopping powers", or often "stopping cross sections", including (typically without regard to sign) $\frac{dE}{d\chi} = \frac{dE}{d\rho x} = \frac{dE}{\rho dx}$; $\frac{dE}{Z^2dx}$, $\rho\frac{dE}{dx}$, and $\frac{dE}{N_m dx}$. Here χ is material thickness (mg/cm^2), Z is atomic number, ρ is material density (g/cm^3), and N_m is the total atom density of the material (atoms/cm^3). This last quantity we define as the stopping cross section,

$$\epsilon_m^\alpha(E) = -\frac{dE}{N_m dx}(E). \tag{2}$$

The probability of an α of energy E_α having an (α,n) reaction with nuclide target i having (α,n) cross section $\sigma_i(E)$ while traveling some distance dx (or changing energy by some dE) is simply

$$p_i(E) = N_i\sigma_i(E)dx = \frac{N_i\sigma_i(E)}{dE/dx}dE = -\frac{N_i\sigma_i(E)}{N_m\epsilon_m^\alpha(E)}dE, \tag{3}$$

where ϵ_m^α is formed from the atom-density-weighted contributions ϵ_z^α of the elemental constituents. The probability of such an event while slowing from E_0 to E_1 is then

$$p_i(E_0,E_1) = -\frac{N_i}{N_m}\int_{E_0}^{E_1}\frac{\sigma_i(E)}{\epsilon_m^\alpha(E)}dE = \frac{N_i}{N_m}\int_{E_1}^{E_0}\frac{\sigma_i(E)}{\epsilon_m^\alpha(E)}dE. \tag{4}$$

The material's (α,n) thick-target neutron yield for α's incident at E_0 is this probability with the terminal energy taken as the reaction threshold or, in general, zero:

$$P_i(E_0) = \frac{N_i}{N_m}\int_0^{E_0}\frac{\sigma_i(E)}{\epsilon_m^\alpha(E)}dE. \tag{5}$$

The SOURCES code assumes all (α,n) neutrons to be emitted isotropically in the center of mass system, resulting in neutrons uniformly distributed in laboratory system energy [1] between the limits E_{min}^n and E_{max}^n defined by the conservation of energy and momentum.[2] These limits are unique for each combination of incident α energy and product nuclide energy level produced. The contribution to the neutron energy spectrum contained in group g, with upper energy limit E_g and lower energy limit E_{g+1}, from an α at E_α slowing some dE in material m via target nuclide i and subsequent product nuclide level l is given by

$$s_{i,l,g}(E_\alpha) = p_i(E_\alpha)f_{i,l}(E_\alpha)\frac{E_g - E_{g+1}}{E_{max}^n(E_\alpha) - E_{min}^n(E_\alpha)}G_{i,l,g}(E_\alpha), \tag{6}$$

where $f_{i,l}(E_\alpha)$ is the fraction of (α,n) reactions at E_α on target i that result in the direct production of product nuclide level l, $G_{i,l,g}(E_\alpha)$ is the fraction of group g contained within the energy range E_{min}^n to E_{max}^n associated with (α,n) reactions at E_α on target nuclide i via product nuclide level l, and $p_i(E_\alpha)$ is defined by Eq. 3. The total multigroup neutron spectrum is formed by summing all contributions for all targets and product nuclide levels, each integrated over the α energy range from threshold to incident energy. SOURCES calculates all quantities on a grid of several thousand α energy values and performs trapezoidal integration to obtain the (α,n) spectrum contributions and total spectrum.

Nuclear Data

The data quantities required for (α,n) source magnitude and spectrum calculations are those used in the theoretical development above. These are:

- Q values for the production of all possible product nuclide energy levels for all targets and α energies of interest;
- stopping cross sections for all elements and α energies of interest;
- (α,n) reaction data, including
  1. (α,n) cross sections for all targets and α energies of interest; and
  2. product nuclide level branching fractions for all targets, product levels, and α energies of interest;

- α decay spectra for all α-emitting radionuclides of interest.

The amount of data required increases greatly with the the maximum α energy of interest, due to the greater number of product nuclide levels that can be produced. In this work we limit data to that required to describe targets of Z $\leq$ 15 and α energies $E_\alpha \leq 6.5$ MeV. These targets and product nuclide energy levels are listed in Table 1, along with the α threshold energies required for their excitation.

Q Values

The Q values for the production of the ground state of the product nuclide for these targets have been calculated from the masses of Gove and Wapstra.[3] Q values for the direct production of higher states were calculated using level excitation energies given by Lederer and Shirley.[4] These Q values were used to obtain the laboratory system α threshold energies given in Table 1.

Stopping Cross Sections

The stopping cross sections of ions in materials are described in great detail in the series edited by J. F. Ziegler;[5] volume 4 of the series gives stopping cross sections for αs in the range 1 keV $\leq E_\alpha \leq$ 100 MeV slowing in all elements $Z \leq 92$. These data are tabulated at six energies per decade over the five decades of energy in units of eV/(10^{15} atoms/cm^2); parametric fits are given for each element. This extensive set of data has been extended to elements of higher Z using the data of Northcliffe and Schilling,[6] which lists *stopping powers* $\frac{dE}{dX}$ in units of MeV/(mg/cm^2) for a wide range of ions and materials; plots given of ratios to $\frac{dE}{dX}$ for αs in $_{13}$Al of $\frac{dE}{dX}$ for αs in materials of $Z \leq 100$ were extrapolated and used with estimated atomic masses A to extend the ϵ_z^α data of Ziegler[5] for the description of materials extending to $Z \leq 105$. These extended data were fit with equations of the same form given by Ziegler[5] for materials of $Z \leq 92$, using the STEPIT code.[7]

(α,n) Reaction Data

The reaction data required includes cross sections $\sigma_i(E)$ and product nuclide level branching fractions $f_{i,l}(E)$ for the the production of each energy level. These latter data are equal to ratios of partial cross sections $\sigma_i^l(E)$ to the total $\sigma_i(E)$. The sources of these data include the following:

- experimentally measured data,
- cross sections stripped from measured energy-dependent (α,n) thick-target neutron yields,
- reciprocal reaction data, and
- nuclear reaction physics model code calculations.

We have used data from all sources, generally ordered in preference as given above, to complete reaction data requirements for the range of targets and energies desired. Utility codes STRIP and RECIPROCAL were written to perform their obvious tasks, and the GNASH nuclear reaction physics model code[8] was used to calculate cross sections and partial cross sections for targets of Z $\geq$ 5. These nuclear model code calculations reveal the general characteristics of the reactions, such as the smooth energy dependence of the cross sections and partial cross sections; however, the resonance structure found in many cross section measurements cannot be reproduced by either model code calculations or the stripping of cross sections from measured thick target yields. Each of the target nuclides listed in Table 1 has presented a unique situation and is described separately below:

Lithium. The ^{7}Li (α,n) cross section has a threshold at 4.384 MeV. Differential cross section measurement results are given by Bichsel and Bonner[9] for $E_\alpha \leq 5.7$ MeV at only a few angles, and measured total values are given by Olson and Kavanagh[10] for $E_\alpha < 5.67$ MeV. Measured total (α,n) cross sections shown by Gibbons and Macklin[11] for $E_\alpha \leq 8.2$ MeV have been used to calculate thick target yields, which are greater by 19-50% than measured values given by Bair and del Campo[12] over this energy range and 11% lower than that measured at $E_\alpha = 5.3$ MeV by Roberts.[13] The cross sections of Ref.12 are used in SOURCES without adjustment. No data have been found for the excitation of the 1st excited state of ^{10}B, which is produced by αs above 5.51 MeV. This target is below the range of validity of GNASH. In the absence of data we have assumed the branching to this level to be zero.

Table 1. Properties of (α,n) Targets and Product Nuclide Energy Levels for Z $\leq$ 15 and $E_\alpha \leq$ 6.5 MeV

Target, Reaction	level, MeV	E_{th}, MeV	Target, Reaction	level, MeV	E_{th}, MeV
			${}^{22}_{10}\mathrm{Ne}(\alpha,n){}^{25}_{12}\mathrm{Mg}$	0.	0.570
${}^{7}_{3}\mathrm{Li}(\alpha,n){}^{10}_{5}\mathrm{B}$	0.	4.384		0.585	1.261
	0.718	5.513		0.975	1.722
${}^{9}_{4}\mathrm{Be}(\alpha,n){}^{12}_{6}\mathrm{C}$	0.	0.		1.612	2.474
	4.439	0.		1.965	2.891
	7.654	2.820		2.564	3.600
	9.641	5.690		2.736	3.806
${}^{9}_{4}\mathrm{Be}(\alpha,\alpha'n){}^{8}_{4}\mathrm{Be}$	0.	4.3		2.801	3.880
${}^{10}_{5}\mathrm{B}(\alpha,n){}^{13}_{7}\mathrm{N}$	0.	0.		3.405	4.594
	2.365	1.827		3.414	4.604
	3.511	3.432		3.971	5.262
	3.547	3.482		4.060	5.368
${}^{11}_{5}\mathrm{B}(\alpha,n){}^{14}_{7}\mathrm{N}$	0.	0.		4.277	5.624
	2.313	2.939		4.359	5.721
	3.948	5.168		4.712	6.138
	4.915	6.487		4.721	6.149
${}^{13}_{6}\mathrm{C}(\alpha,n){}^{16}_{8}\mathrm{O}$	0.	0.		5.012	6.493
	6.049	5.013	${}^{23}_{11}\mathrm{Na}(\alpha,n){}^{26}_{13}\mathrm{Al}$	0.	3.485
	6.130	5.119		0.228	3.753
	6.919	6.151		0.417	3.974
	7.117	6.410		1.058	4.727
${}^{14}_{7}\mathrm{N}(\alpha,n){}^{17}_{9}\mathrm{F}$	0.	6.090		1.759	5.550
${}^{17}_{8}\mathrm{O}(\alpha,n){}^{20}_{10}\mathrm{Ne}$	0.	0.		1.851	5.658
	1.634	1.294		2.069	5.913
	4.247	4.522		2.072	5.917
	4.968	5.412		2.365	6.261
	5.622	6.220		2.545	6.473
	5.785	6.422	${}^{25}_{12}\mathrm{Mg}(\alpha,n){}^{28}_{14}\mathrm{Si}$	0.	0.
${}^{18}_{8}\mathrm{O}(\alpha,n){}^{21}_{10}\mathrm{Ne}$	0.	0.851		1.779	0.
	0.351	1.280		4.618	2.278
	1.746	2.985		4.979	2.697
	2.789	4.259		6.277	4.202
	2.796	4.269		6.691	4.683
	2.866	4.354		6.879	4.901
	3.662	5.327		6.889	4.912
	3.734	5.415		7.381	5.483
	3.883	5.597		7.417	5.526
	4.432	6.268		7.799	5.968
	4.524	6.381		7.933	6.124
${}^{19}_{9}\mathrm{F}(\alpha,n){}^{22}_{11}\mathrm{Na}$	0.	2.360	${}^{26}_{12}\mathrm{Mg}(\alpha,n){}^{29}_{14}\mathrm{Si}$	0.	0.
	0.583	3.066		1.273	1.429
	0.657	3.156		2.028	2.300
	0.891	3.439		2.426	2.759
	1.528	4.210		3.067	3.499
	1.937	4.705		3.624	4.141
	1.952	4.723		4.080	4.668
	1.984	4.762		4.741	5.430
	2.212	5.037		4.840	5.544
	2.572	5.473		4.895	5.608
	2.696	5.624		4.934	5.733
	3.060	6.065		5.255	6.020
${}^{21}_{10}\mathrm{Ne}(\alpha,n){}^{24}_{12}\mathrm{Mg}$	0.	0.		5.286	6.056
	1.369	0.		5.652	6.479
	4.123	1.872	${}^{27}_{13}\mathrm{Al}(\alpha,n){}^{30}_{15}\mathrm{P}$	0.	3.027
	4.239	2.010		0.677	3.804
	5.236	3.200		0.709	3.841
	6.010	4.119		1.454	4.696
	6.432	4.621		1.973	5.292
	7.348	5.712		2.538	5.941
	7.553	5.955		2.723	6.154
	7.616	6.030		2.839	6.287
	7.748	6.187		2.938	6.400
	7.812	6.263		3.019	6.493
			${}^{29}_{14}\mathrm{Si}(\alpha,n){}^{32}_{16}\mathrm{S}$	0.	1.739
				2.230	4.273
				3.779	6.036
			${}^{30}_{14}\mathrm{Si}(\alpha,n){}^{33}_{16}\mathrm{S}$	0.	3.958
				0.840	4.910
				1.966	6.187
			${}^{31}_{15}\mathrm{P}(\alpha,n){}^{34}_{17}\mathrm{Cl}$	0.	6.378

Beryllium. The most productive source of (α,n) neutrons is Be, which is 100% ^{9}Be. This cross section has been well investigated by Geiger and Van der Zwan[14], from whom we have taken this cross section and level branching fractions. A variety of other cross section measurements have been made for this popular target.[11,15-18] Thick target yields calculated with this cross section are consistently higher than measured data: 12-13% above those of West and Sherwood,[19] 8-9% above those of Geiger,[20] 22-28% above those of Smith,[21] and 9-42% above those of Bair and del Campo.[12] We have reduced the data of ref.14 to 88.5% to better agree with the body of measured thick target yield data. The branching data of ref.14 also includes the fraction of neutrons produced via the ^{9}Be(α,α'n)^{8}Be$\Rightarrow 2\alpha$ path, for which SOURCES is yet unable to describe associated neutron spectra.

Boron. The cross section for ^{nat}B was measured by Walker[22] below 5 MeV, but thick-target yields calculated with this cross section are about 40% greater than yields measured for 3.5-4.5 MeV αs on B by Bair and del Campo,[12] and for 5.3 MeV αs on B by Roberts[13] and by Gorshkov et al.[23] Also, the use of a cross section for a mixture a nuclides precludes the calculation of neutron spectra. We have used ^{10,11}B cross sections from GNASH calculations, the reciprocal from the ENDF/B-V ^{14}N(n,α_0)^{11}B evaluation, and ^{10,11}B(α,n) cross sections stripped from the respective thick target yields of Bair and del Campo[12] to examine these reactions in Ref.24. SOURCES uses these stripped cross sections without adjustment. Level branchings were taken from GNASH calculations.

Carbon. The ^{13}C(α,n) cross section has been measured below 5.4 MeV by Bair and Haas[25], as later described in Ref. 12. Additional measurements have been made by Ramstrom[26], by Sekharan et al.[27], and by Walton[28]. We have used the data from Refs. 12 and 25 in thick target calculations, producing results that are consistently greater than measured yields — 33-46% above the results of Jacobs and Liskien[29], 30-32% above the results of West and Sherwood[19], and 21-38% above the results of Bair and del Campo[9]. We have decreased this cross section in SOURCES to 72.5% of the reported magnitude to provide calculated thick target yields more in agreement with measurements. Level branchings were taken from GNASH calculations.

Nitrogen With a threshold at 6.09 MeV, the ^{14}N cross section from GNASH calculations are included only for completeness. No measured thick target yields for ^{nat}N or for Nitrogen compounds are available for which N is the predominant (α,n) target. No product nuclide levels other than the ground state are produced.

Oxygen Cross section measurements of Bair and Willard[30], Bair and Haas [25], Bair and del Campo[12], and Hansen et al.[31] were combined by us in determining these cross sections over the desired domain, as described in Ref. 32. We are using level branchings from GNASH calculations.

Fluorine The ^{19}F(α,n) cross section has been measured by Balakrishnan, Kailas and Mehta[33] below 5.3 MeV, and we have extended this data with GNASH calculated results. The resulting cross section, when used in thick target yield calculations, gives results lower than measured yields — 18-33% below the results of Jacobs and Liskien[29] and 3-15% below the results of Bair and del Campo[12]. No adjustment has been made to the cross section. Level branchings for this reaction have been measured by Van der Zwan and Geiger[34] for some but not all levels produced; we have used level branchings from GNASH calculations.

Neon Other than the detailed low energy measurements by Hammer et al.[35] presented at this conference, no known measurements are available for ^{21,22}Ne(α,n) cross sections or thick target yields. We have calculated both cross sections and level branchings for these targets with GNASH for use in SOURCES, although the accuracy of these is not established.

Sodium No cross section measurements for the ^{23}Na(α,n) reaction are known to us, although Roberts[13] has deduced a thick target yield at 5.3 MeV. We have taken the cross section and level branching data for this reaction from GNASH calculations. The yield calculated at 5.3 MeV is 95% greater than that given by Roberts, but no adjustment of the cross section has been made.

Magnesium The ^{nat}Mg cross section was measured by Halpern[15] below 5.05 MeV, and Bair and Willard[30] measured the ^{26}Mg(α,n) cross section below 5.4 MeV. We have used the results of GNASH calculations for these cross sections and level branching fractions. Use of these data in thick target calculations produce yields that are consistently greater than measured data — 40-72% greater than the results of West and Sherwood[19], 51-90% greater than the results of Bair and del Campo[12], and 13-25% greater than other measured yields. We have decreased the GNASH cross sections to 2/3 of the calculated values to better represent the measured thick target yield data.

Aluminum The cross section for the ^{27}Al(α,n) reaction has been measured over various energy domains by Bowman and Blann[36], Flynn et al.[37], Halpern[15], Howard et al.[38], Sahakundu, Qaim and Stocklin[39] and by Stelson and McGowan[40]. Calculations of thick target yields using the cross section data of Howard et al. produce results that are in excellent agreement with the measured values of Bair and del Campo[12] and good agreement with the values measured by Jacobs and Liskien[29]. Level branching data have been taken from GNASH calculations.

Silicon The ^{29,30}Si(α,n) cross sections have been measured by Flynn et al.[37], Gabbard, Flynn and Hershberger[41], Gibbons and Macklin[11], Sekharan[42], and by Okon et al.[43]. We have used GNASH calculated cross sections to calculate thick target yields that are in poor agreement with measured values — 50-450% greater than measured values. Thick target calculations with the data of Flynn produce yields that range from 30% below to 175% greater than measured values; this range decreases to -30% to +38% for α energies above 4.5 MeV. SOURCES presently uses the Flynn data without adjustment. Level branching data has been taken from GNASH results.

Phosphorus The ^{31}P(α,n) reaction, with threshold of 6.38 MeV, is described with GNASH calculated cross sections. There exist no thick target yield measured values with which to evaluate the cross section data. No levels other than the ^{34}Cl ground state are produced.

α Decay Spectra

The spectra of αs emitted in the decay of all significant fission products and actinides have been accumulated from ENDF/B-V files[44] and from Ref. 4. These decay spectra have been included in a decay data file used by SOURCES. Most of these α sources lie below our 6.5 MeV energy limit, although these α energies extend as high as the 10.549 MeV α infrequently emitted in the decay ^{212}Bi $\Rightarrow ^{212}$Po* $\Rightarrow ^{208}$Pb.

Thick-Target (α,n) Neutron Yields

The resolved cross section and stopping cross section data described above have been used in calculations of thick target neutron yields and compared to available measured yield data for elemental targets in Table 2. Comparisons of thick target neutron yields for targets of mixtures of elements and isotopically enriched targets are not compared because of space limitations. Measured values are listed in Table 2 for Jacobs and Liskien[29] (Ja83),West and Sherwood[19] (We82), Geiger[20] (Ge80), Smith[45] (Sm80), Bair and del Campo[12] (Ba79), Bulanenko[46] (Bu79), Geiger and Van der Zwan[47] (Ge75), Anderson and Hertz[48] (An71), Gorshkov[23] (Go62), Runnalls and Boucher[49] (Ru56), and Roberts[13] (Ro44).

Thick-Target (α,n) Neutron Yield Spectra

The cross section, level branching, and stopping cross section data of the SOURCES code package have been developed for the calculation of thick target neutron yield spectra for the stated α energy and target range. The code's ability to describe the contributions from the ground state and the 1^{st} and 2^{nd} levels of ^{12}C to the ^{241}Am-Be neutron source — excluding the breakup reaction contribution — is demonstrated in figure 1 with comparison to the total neutron spectrum shape measured by Lorch.[50]

Conclusions

The SOURCES code and data library is a useful tool for the calculation of thick-target neutron yields and neutron spectra. The code is useful for the description of mixtures of α sources and target nuclides and for beam-on-target problems. Less than one second of CRAY-1 time is required for each yield calculation, and about one minute is required for a 100-group spectrum calculation. The code and data libraries will be released through the Radiation Shielding Information Center at Oak Ridge National laboratory.

Table 2. Comparison of Measured and SOURCES-Calculated Thick-Target (α,n) Yields for Z $\leq$ 15 and $E_\alpha \leq$ 6.5 MeV

		Thick-Target (α,n) Neutron Yields, neutrons/10^6 αs											
	E_α	SOURCES	Measured Values										
Target	MeV	Calculation	Ja83	We82	Ge80	Sm80	Ba79	Bu79	Ge75	An71	G062	Ru56	Ro44
^{nat}Li	4.5	.032					.028						
	5.0	.867					.629						
	5.3	2.041											2.4
	5.5	2.792					2.15						
	6.0	5.806					4.873						
	6.5	11.98					10.41						
^{nat}Be	2.0	3.16											
	2.5	7.73											
	3.0	12.30					9.79			10.05			
	3.5	15.40					12.79			14.4			
	4.0	22.86		22.86			19.88			21.1			
	4.5	39.35					33.27			34.8			
	5.0	56.89		56.78			49.43			35.5			
	5.3	70.35			73.		63.		64.	69.	84.4		80.
	5.48	79.28			82.	70.						74.	
	5.5	80.31					71.81		80.				
	5.79	96.56			100.								
	6.0	108.5		109.5		99.16							
	6.1	113.9			118.							112.	
	6.5	136.0				126.2							
^{nat}B	3.5	2.86					3.15						
	4.0	6.00	5.6				6.24						
	4.5	10.26	10.5				10.63						
	5.0	15.22					15.64						
	5.3	18.2									19.6		21.
	5.5	20.14	20.6				20.59						
	6.0	24.88					25.35						
	6.5	29.36					29.85						
^{nat}C	3.0	..029					.024						
	3.5	.051					.040						
	4.0	.057	.039	.043			.042						
	4.5	.065	.046				.047						
	5.0	.081	.061	.065			.063						
	5.3	.114									.113		.09
	5.5	.142	.101				.11						
	6.0	.224		.172			.170						
	6.5	.325					.252						
^{nat}N	6.5	.484											
^{nat}O	3.0	.003											
	3.5	.006					.006						
	4.0	.017	.016				.014						
	4.5	.032	.029				.026						
	5.0	.050	.052				.045						
	5.3	.061						.07			.068		.061
	5.5	.070	.065				.068						
	6.0	.096					.092						
	6.5	.125					.132						
^{nat}F	3.5	.216					.031						
	4.0	.856	1.28				.879						
	4.5	2.03	2.76				2.159						
	5.0	4.18	5.09				4.394						
	5.3	5.75									11.6		10.4
	5.5	6.98	9.50				7.746						
	6.0	10.66					12.26						
	6.5	15.17					17.95						
^{nat}Ne	3.0	**.255**											
	3.5	**.520**											
	4.0	**.907**											
	4.5	**1 42**											
	5.0	**2.03**											
	5.3	**2.44**											
	5.5	**2.74**											
	6.0	**3.58**											
	6.5	**4.55**											
^{nat}Na	4.0	**.043**											
	4.5	**.434**											
	5.0	**1.46**											
	5.3	**2.53**											1.3
	5.5	**3.44**											
	6.0	**6.53**											
	6.5	**11.1**											

Table 2. (Continued)

Target	E_α MeV	SOURCES Calculation	Thick-Target (α,n) Neutron Yields, neutrons/10^6 αs — Measured Values: Ja83	We82	Ge80	Sm80	Ba79	Bu79	Ge75	An71	G062	Ru56	Ro44
^{nat}Mg	.024	.035											
	4.0	.097		.085			.077						
	4.5	.292					.263						
	5.0	.661		.709			.644						
	5.3	.999									1.33		1.2
	5.5	1.28					1.262						
	6.0	2.16		2.27			2.141						
	6.5	3.29					3.250						
^{nat}Al	3.5	.0008					.0012						
	4.0	.0158	.019				.0169						
	4.5	.0828	.087				.0802						
	5.0	.281	.260				.2643						
	5.3	.495									.76		.64
	5.5	.697	.747				.6967						
	6.0	1.468					1.438						
	6.5	2.855					2.780						
^{nat}Si	4.0	.011	.004	.004									
	4.5	..032	.014				.016						
	5.0	.080	.058	.067			.052						
	5.3	.118									.168		.15
	5.5	.146	.113				.114						
	6.0	.277		.249			.231						
	6.5	.411					.385						
^{nat}P	6.5	.0036											

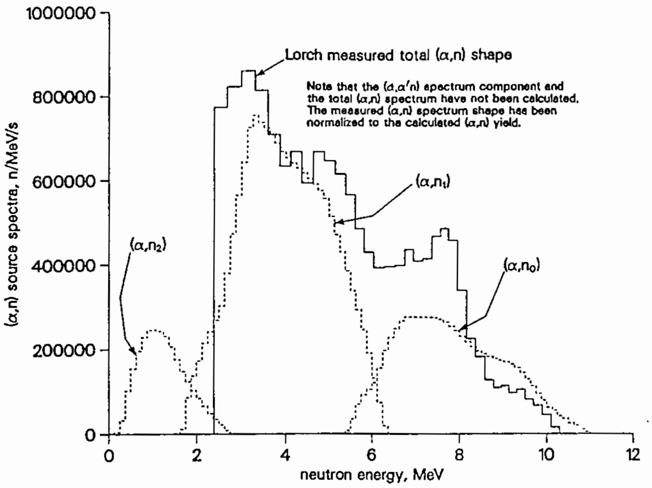

Fig. 1 Comparison of SOURCES calculated neutron spectra with that measured by E. A. Lorch for ^{241}Am/Be.

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