LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

·LA-UR -88-2380

LA-UR--88-2380

DE88 014336

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: CALCULATED NEUTRON-ACTIVATION CROSS SECTIONS FOR $E_n \leq$ 100 MEV FOR A RANGE OF ACCELERATOR MATERIALS

AUTHOR(S): M. Bozoian, T-2
E. D. Arthur, T-2
R. T. Perry, T-2
W. B. Wilson, T-2
P. G. Young, T-2

SUBMITTED TO: International Conference of Nuclear Data for Science and Technology, May 30-June 3, 1988, Mito, Japan

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

CALCULATED NEUTRON-ACTIVATION CROSS SECTIONS FOR $E_n \leq 100$ MeV FOR A RANGE OF ACCELERATOR MATERIALS

M. Bozoian, E. D. Arthur, R. T. Perry, W. B. Wilson and P. G. Young
Los Alamos National Laboratory, Los Alamos, New Mexico, USA 87545

Abstract: Activation problems associated with particle accelerators are commonly dominated by reactions of secondary neutrons produced in reactions of beam particles with accelerator or beam stop materials. Measured values of neutron-activation cross sections above a few Mev are sparse. Calculations with the GNASH code have been made for neutrons incident on all stable nuclides of a range of elements common to accelerator materials. These elements include B, C, N, O, Ne, Mg, Al, Si, P, S, Ar, K, Ca, Cr, Mn, Fe, Co, Ni, Cu, Zn, Zr, Mo, Nd and Sm. Calculations were made for a grid of incident neutron energies extending to 100 MeV. Cross sections leading to the direct production of as many as 87 activation products for each of 84 target nuclide were tabulated on this grid of neutron energies, each beginning with the threshold for the product nuclide's formation. Multigrouped values of these cross sections have been calculated and are being integrated into the cross-section library of the REAC-2 neutron activation code. Illustrative cross sections are presented.

(medium-energy neutrons, neutron activation, accelerators)

Introduction

Neutron activation rates are calculated as the integral over neutron energy of the product of the neutron flux and activation cross sections. These radionuclide production rates can be used in a radionuclide inventory code to calculate the temporal inventory of coupled radionuclides following a specific irradiation history. Versions of the CINDER[1] and ORIGEN[2] codes are typically used for such calculations in nuclear reactor applications. The REAC code[3-5], developed by Fred Mann at HEDL, has been used for the past eight years for medium-energy neutron activation calculations for a variety of magnetic fusion energy (MFE) studies and the Fusion Materials Irradiation Test Facility (FMIT) design study. The code's multigroup cross-section library extends to 50 MeV and consists mainly of data calculated with the nuclear systematics code THRESH-II,[6] with data processed from ENDF/B-V[7] and other evaluations used where available. ENDF/B-V contains evaluated neutron reaction cross sections for neutron energies $E_n \leq 20$ MeV.

The design study for the 100-MeV H^- Ground Test Accelerator facility (GTA) has required the development of a library of cross sections for REAC extending to a neutron energy of 100 MeV and consisting of processed ENDF/B-V data extended or supplemented with reaction data obtained from nuclear reaction physics model code calculations. These calculations and their results, as well as comparisons to available data, are described in the sections that follow.

GNASH Calculations

GNASH Input Parameters and Data

The streamlined version of GNASH,[8] including evaporation and preequilibrium models, was used for producing the composite spectra and individual reaction data for the neutron activation of eighty-four target nuclides in the range $5 \leq Z \leq 62$ and incident neutron energies $E_n \leq 100$ MeV. The following were the common GNASH modeling features of the cases executed:

- preequilibrium model included a nuclear surface model guishability memory factor implemented in the emission rate formula;
- preequilibrium model augmented with multistage preequilibrium modeling[9] which follows as a logical extension of the master equation basis of the GNASH exciton model;
- Ignaytuk level density was selected;
- each neutron activation target was described by two separate calculations based on energy range;
  - for the eleven incident neutron energies E_n = 0.5, 1., 2., 3., 5., 7.5, 10., 12.5, 15. and 17.5 MeV an emitted-particle energy grid ΔE of 0.25 MeV was used; a maximum of 15 compound nuclides ($\Delta Z=3$, $\Delta N=5$) were allowed to be formed.
  - for the seventeen incident neutron energies E_n = 20., 25., 30.,..., 100 MeV an emitted-particle energy grid ΔE of 1.0 MeV was selected; a maximum of 54 compound nuclides ($\Delta Z=6$, $\Delta N=9$) were allowed to be formed.
- compound systems formed were allowed to decay by gamma, neutron, proton, deuteron, triton and α-particle emission;
- additional data describing
  - ground-state masses,
  - separation energies,
  - spins and parities,
  - transmission coefficients and inverse cross sections based on various optical model calculations,
  - gamma decay level information extracted from the CDRL82 file,[10] and
  - optional direct reaction cross sections were used.

GNASH Results

Table 1 lists the target nuclides for which GNASH calculations were made. Identified for each target in Table 1 are the particles and nuclides formed for which production cross seccombined GNASH output files for each target were interrogated with a utility code READGN to accumulate cross sections for the production of each product from all reaction paths generated in the calculation, resulting in a machine-readable file of cross-section values beginning at the threshold value and a plotting file for the local MAPPER 4 0 computer graphics software.

Comparisons with Measured Data

GNASH calculations have been made for this set of nuclides because of a general absence or sparsity of measured cross section data. The recently published 1987 IAEA Handbook on Nuclear Activation Data[11] identifies ten standard monitor reactions for neutrons, of which three are reactions calculated in this study; also listed are cross sections below 20 MeV for some 206 reactions, including some common to the data set described here. Additional data are accumulated in the earlier 1973 IAEA Handbook[12], and a variety of neutron-reaction data sources are identified in the IAEA CINDA compilation.[13] The EXFOR computer data library of experimentally measured neutron induced reaction data, available from international nuclear data centers, also list cross-section and other data extending beyond the typical 20-MeV limitation. To illustrate the validity of the magnitude and energy-dependent shapes of calculated reaction cross sections, we compare calculated results of reactions for which there exist appreciable measured data and results of other calculations.

Figure 1 compares the $^{12}C(n,p)^{12}B$ cross section calculated with GNASH and the measured data of Kreger and Kern[14] and Rimmer and Fisher[15]. Figures 2-6 compare GNASH calculated (n,2n) cross sections for ^{12}C, ^{14}N, ^{16}O, ^{63}Cu and ^{92}Mo, respectively, with the data of Brill et al.,[16], Brolley et al.,[17], McMillan and York,[18], and Furguson and Thompson.[19] Figure 7 shows the GNASH results for the $^{27}Al(n,x)^{24}Na$ cross section, accumulated from $^{27}Al(n,\alpha)$, $^{27}Al(n,n\ ^{3}He)$ and $^{27}Al(n,d\ d)$ contributions. This calculated cross section is compared with the data of Bayhurst et al.[20] and with ENDF/B-V. Also shown is the REAC data for this reaction, consisting of multigrouped ENDF/B-V data extended with the shape of THRESH-II results. We have extended ENDF/B-V with the shape of GNASH results, resulting in a much better agreement with the Bayhurst data over it's limited range.

Conclusions

GNASH has been used to calculate cross sections for about 6000 neutron-induced nuclide production cross sections for the eighty-four stable target nuclides of 24 elements common to an accelerator environment. Simplifications to the GNASH code have been employed to permit the calculation of data for this range of nuclides. Comparisons with limited measured data indicate uncertainties of about a factor of 2. These data are currently being used at HEDL to extend the REAC-2 cross-section library.

References

1. T.R. England: WAPD-334 [Rev] (1964).
2. M.J. Bell: ORNL-4628 (1973).
3. F.M. Mann: HEDL-TME 81-37(1982)
4. F.M. Mann et al.: *Radiation Effects* 92,207(1986)
5. F.M. Mann, this conference.

7. Evaluated [illegible] and maintained by the National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY.
8. P.G. Young and E.D. Arthur: LA-6947(1977)
9. E.D. Arthur and C. Kalbach, in LA-10915-PR(1987),pp 6-8.
10. D. George, private communication to M. Bozoian (May, 1988).
11. International Atomic Energy Agency Technical Reports Series No. 273(1987).
12. International Atomic Energy Agency Technical Reports Series No. 156(1973).
13. International Atomic Energy Agency CINDA84 Supplement(1984).
14. W.E. Kreger and B.D. Kern: *Phys. Rev.* 113,890(1959).
15. E.M. Rimmer and P.S. Fisher: *Nuclear Physics* A108,567 (1958).
16. O.D. Brill et al., *Doklady* 6,24(1961).
17. J E. Brolley et al., *Phys. Rev.* 88,618(1952).
18. E.M. McMillan and H.F. York, *Phys. Rev.* 73,262(1948).
19. J.M. Furguson and W.E. Thompson, *Phys. Rev.* 118,228 (1960).
20. B.P. Bayhurst et al.: *Phys. Rev.* C12,451(1975).

Table 1. GNASH Neutron Activation Results

Target	Products Formed	
	#	Product Nuclides
^{10}B	23	^{1-4}H, ^{3-7}He, ^{4-9}Li, ^{6-10}Be, ^{7-9}B
^{11}B	25	^{1-4}H, ^{3-7}He, ^{4-8}Li, ^{6-11}Be, ^{7-10}B
^{12}C	30	^{1-4}H, ^{3-7}He, ^{4-9}Li, ^{6-11}Be, ^{7-12}B, ^{9-11}C
^{13}C	31	^{1-4}H, ^{4-7}He, ^{6-8}Li, ^{6-12}Be, ^{7-13}B, ^{9-12}C
^{14}N	35	^{1-3}H, ^{4-7}He, ^{5-9}Li, ^{6-12}Be, ^{7-13}B, ^{9-14}C, $^{11-13}N$
^{15}N	35	^{1-3}H, ^{4-7}He, ^{6-9}Li, ^{7-12}Be, ^{8-14}B, ^{9-15}C, $^{11-14}N$
^{16}O	46	^{1-4}H, ^{3-7}He, ^{4-9}Li, ^{6-12}Be, ^{7-14}B, ^{9-16}C, $^{11-16}N$, $^{13-15}O$
^{17}O	48	^{1-4}H, ^{4-7}He, ^{6-9}Li, ^{6-12}Be, ^{7-15}B, ^{9-16}C, $^{11-17}N$, $^{13-16}O$
^{18}O	48	^{1-4}H, ^{4-7}He, ^{6-9}Li, ^{7-12}Be, ^{8-15}B, ^{9-17}C, $^{11-18}N$, $^{13-17}O$
^{20}Ne	45	^{1-3}H, ^{4}He, ^{9-12}Be, $^{10-15}B$, $^{11-17}C$, $^{12-18}N$, $^{13-19}O$, $^{15-20}F$, $^{16-19}Ne$
^{21}Ne	44	^{1-3}H, ^{4}He, $^{10-12}Be$, $^{11-15}B$, $^{12-16}C$, $^{13-19}N$, $^{14-20}O$, $^{15-21}F$, $^{17-20}Ne$
^{22}Ne	41	^{1-3}H, ^{4}He, $^{11,12}Be$, $^{12-18}B$, $^{13-18}C$, $^{14-20}N$, $^{15-21}O$, $^{16-22}F$, $^{18-21}Ne$
^{24}Mg	72	^{1-3}H, ^{4}He, ^{8-16}B, ^{9-18}C, $^{10-20}N$, $^{12-21}O$, $^{14-22}F$, $^{15-23}Ne$, $^{16-24}Na$, $^{20-23}Mg$
^{25}Mg	74	^{1-3}H, ^{4}He, ^{9-18}B, $^{10-18}C$, $^{11-20}N$, $^{12-22}O$, $^{14-23}F$, $^{16-24}Ne$, $^{16-25}Na$, $^{20-24}Mg$
^{26}Mg	74	^{1-3}H, ^{4}He, $^{10-16}B$, $^{11-18}C$, $^{12-20}N$, $^{13-22}O$, $^{14-24}F$, $^{16-25}Ne$, $^{16-26}Na$, $^{20-25}Mg$
^{27}Al	74	^{1-3}H, ^{4}He, $^{11-18}C$, $^{12-20}N$, $^{13-22}O$, $^{14-24}F$, $^{16-25}Ne$, $^{16-26}Na$, $^{20-27}Mg$, $^{22-26}Al$
^{28}Si	72	^{1-3}H, ^{4}He, $^{12-20}N$, $^{13-22}O$, $^{14-24}F$, $^{16-25}Ne$, $^{16-26}Na$, $^{20-27}Mg$, $^{22-26}Al$, $^{24-27}Si$
^{29}Si	74	^{1-3}H, ^{4}He, $^{13-20}N$, $^{14-22}O$, $^{15-24}F$, $^{16-25}Ne$, $^{16-27}Na$, $^{20-28}Mg$, $^{22-29}Al$, $^{24-28}Si$
^{30}Si	74	^{1-3}H, ^{4}He, $^{14-20}N$, $^{15-22}O$, $^{16-24}F$, $^{17-26}Ne$, $^{16-26}Na$, $^{20-29}Mg$, $^{22-30}Al$, $^{24-29}Si$
^{31}P	74	^{1-3}H, ^{4}He, $^{15-22}O$, $^{16-24}F$, $^{17-26}Ne$, $^{18-28}Na$, $^{20-29}Mg$, $^{22-30}Al$, $^{24-31}Si$, $^{26-30}P$
^{32}S	72	^{1-3}H, ^{4}He, $^{16-24}F$, $^{17-26}Ne$, $^{18-28}Na$, $^{20-29}Mg$, $^{22-30}Al$, $^{24-31}Si$, $^{26-32}P$, $^{28-31}S$
^{33}S	74	^{1-3}H, ^{4}He, $^{17-24}F$, $^{18-26}Ne$, $^{19-28}Na$, $^{20-30}Mg$, $^{22-31}Al$, $^{24-32}Si$, $^{26-33}P$, $^{28-32}S$
^{34}S	74	^{1-3}H, ^{4}He, $^{18-24}F$, $^{19-26}Ne$, $^{20-28}Na$, $^{21-30}Mg$, $^{22-32}Al$, $^{24-33}Si$, $^{26-34}P$, $^{28-33}S$
^{36}S	88	^{1-3}H, ^{4}He, $^{20-24}F$, $^{21-28}Ne$, $^{22-28}Na$, $^{23-30}Mg$, $^{24-32}Al$, [illegible]

Table 1 (Continued)

Target	#	Products Formed: Product Nuclides
^{36}Ar	71	$^{1-3}$H,^{4}He,$^{20-23}$Na,$^{21-30}$Mg,$^{22-32}$Al,$^{24-33}$Si,$^{26-34}$P,$^{28-35}$S,$^{30-36}$Cl,$^{33-35}$Ar
^{38}Ar	73	$^{1-3}$H,^{4}He,$^{22-28}$Na,$^{23-30}$Mg,$^{24-32}$Al,$^{25-34}$Si,$^{26-36}$P,$^{28-37}$S,$^{30-38}$Cl,$^{33-37}$Ar
^{40}Ar	67	$^{1-3}$H,^{4}He,$^{24-28}$Na,$^{25-30}$Mg,$^{26-32}$Al,$^{27-34}$Si,$^{28-36}$P,$^{29-38}$S,$^{30-40}$Cl,$^{33-39}$Ar
^{39}K	72	$^{1-3}$H,^{4}He,$^{23-30}$Mg,$^{24-32}$Al,$^{25-34}$Si,$^{26-36}$P,$^{28-37}$S,$^{30-38}$Cl,$^{33-39}$Ar,$^{35-38}$K
^{40}K	72	$^{1-3}$H,^{4}He,$^{24-30}$Mg,$^{25-32}$Al,$^{26-34}$Si,$^{27-36}$P,$^{28-38}$S,$^{30-39}$Cl,$^{33-40}$Ar,$^{35-39}$K
^{41}K	70	$^{1-3}$H,^{4}He,$^{25-30}$Mg,$^{26-32}$Al,$^{27-34}$Si,$^{28-36}$P,$^{29-38}$S,$^{30-40}$Cl,$^{33-41}$Ar,$^{35-40}$K
^{40}Ca	64	$^{1-3}$H,^{4}He,$^{24,29-32}$Al,$^{25-27,29-34}$Si,$^{26-36}$P,$^{28-37}$S,$^{30-38}$Cl,$^{33-39}$Ar,$^{35-40}$K,$^{37-39}$Ca
^{42}Ca	69	$^{1-3}$H,^{4}He,$^{26,29-32}$Al,$^{27-34}$Si,$^{28-36}$P,$^{29-38}$S,$^{30-40}$Cl,$^{33-41}$Ar,$^{35-41}$K,$^{37-41}$Ca
^{43}Ca	68	$^{1-3}$H,^{4}He,$^{27,29-32}$Al,$^{28-34}$Si,$^{29-36}$P,$^{30-38}$S,$^{31-40}$Cl,$^{33-42}$Ar,$^{35-43}$K,$^{37-42}$Ca
^{44}Ca	67	$^{1-3}$H,^{4}He,$^{28-32}$Al,$^{29-34}$Si,$^{30-36}$P,$^{31-38}$S,$^{32-40}$Cl,$^{33-43}$Ar,$^{35-44}$K,$^{37-43}$Ca
^{46}Ca	59	$^{1-3}$H,^{4}He,$^{30-32}$Al,$^{31-34}$Si,$^{32-36}$P,$^{33-38}$S,$^{34-40}$Cl,$^{35-45}$Ar,$^{36-46}$K,$^{38-45}$Ca
^{48}Ca	48	$^{1-3}$H,^{4}He,^{32}Al,^{33,34}Si,$^{34-36}$P,$^{35-38}$S,$^{36-40}$Cl,$^{37-46}$Ar,$^{38-48}$K,$^{40-47}$Ca
^{50}Cr	76	$^{1-3}$H,^{4}He,$^{34-40}$Cl,$^{35-45}$Ar,$^{36-48}$K,$^{37-47}$Ca,$^{39-48}$Sc,$^{41-49}$Ti,$^{43-50}$V,$^{45-49}$Cr
^{52}Cr	80	$^{1-3}$H,^{4}He,$^{36-40}$Cl,$^{37-46}$Ar,$^{38-48}$K,$^{39-49}$Ca,$^{40-50}$Sc,$^{41-51}$Ti,$^{43-52}$V,$^{45-51}$Cr
^{53}Cr	79	$^{1-3}$H,^{4}He,$^{37-40}$Cl,$^{38-46}$Ar,$^{39-48}$K,$^{40-50}$Ca,$^{41-51}$Sc,$^{42-52}$Ti,$^{43-53}$V,$^{45-52}$Cr
^{54}Cr	75	$^{1-3}$H,^{4}He,$^{38-40}$Cl,$^{39-46}$Ar,$^{40-48}$K,$^{41-50}$Ca,$^{42-52}$Sc,$^{43-53}$Ti,$^{44-54}$V,$^{46-53}$Cr
^{55}Mn	83	$^{1-3}$H,^{4}He,$^{39-46}$Ar,$^{40-48}$K,$^{41-50}$Ca,$^{42-52}$Sc,$^{43-53}$Ti,$^{44-54}$V,$^{45-55}$Cr,$^{47-54}$Mn
^{54}Fe	78	$^{1-3}$H,^{4}He,$^{38-48}$K,$^{39-49}$Ca,$^{40-50}$Sc,$^{41-51}$Ti,$^{43-52}$V,$^{45-53}$Cr,$^{47-54}$Mn,$^{49-53}$Fe
^{56}Fe	84	$^{1-3}$H,^{4}He,$^{40-48}$K,$^{41-50}$Ca,$^{42-52}$Sc,$^{43-53}$Ti,$^{44-54}$V,$^{45-55}$Cr,$^{47-56}$Mn,$^{49-55}$Fe
^{57}Fe	83	$^{1-3}$H,^{4}He,$^{41-48}$K,$^{42-50}$Ca,$^{43-52}$Sc,$^{44-54}$Ti,$^{45-55}$V,$^{46-56}$Cr,$^{47-57}$Mn,$^{49-56}$Fe
^{58}Fe	79	$^{1-3}$H,^{4}He,$^{42-48}$K,$^{43-50}$Ca,$^{44-52}$Sc,$^{45-54}$Ti,$^{46-56}$V,$^{47-57}$Cr,$^{48-58}$Mn,$^{50-57}$Fe
^{59}Co	83	$^{1-3}$H,^{4}He,$^{43-50}$Ca,$^{44-52}$Sc,$^{45-54}$Ti,$^{46-56}$V,$^{47-57}$Cr,$^{48-58}$Mn,$^{49-59}$Fe,$^{51-58}$Co
^{58}Ni	81	$^{1-3}$H,^{4}He,$^{42-50}$Sc,$^{43-53}$Ti,$^{44-54}$V,$^{45-55}$Cr,$^{47-56}$Mn,$^{49-57}$Fe,$^{51-56}$Co,$^{50-57}$Ni
^{60}Ni	85	$^{1-3}$H,^{4}He,$^{44-52}$Sc,$^{45-54}$Ti,$^{46-56}$V,$^{47-57}$Cr,$^{48-58}$Mn,$^{49-59}$Fe,$^{51-60}$Co,$^{52-59}$Ni
^{61}Ni	83	$^{1-3}$H,^{4}He,$^{45-52}$Sc,$^{46-54}$Ti,$^{47-56}$V,$^{48-58}$Cr,$^{49-59}$Mn,$^{50-60}$Fe,$^{51-61}$Co,$^{53-60}$Ni
^{62}Ni	79	$^{1-3}$H,^{4}He,$^{46-52}$Sc,$^{47-54}$Ti,$^{48-56}$V,$^{49-58}$Cr,$^{50-60}$Mn,$^{51-61}$Fe,$^{52-62}$Co,$^{54-61}$Ni
^{64}Ni	68	$^{1-3}$H,^{4}He,$^{48-52}$Sc,$^{49-54}$Ti,$^{50-56}$V,$^{51-58}$Cr,$^{52-60}$Mn,$^{53-62}$Fe,$^{54-64}$Co,$^{56-63}$Ni
^{63}Cu	83	$^{1-3}$H,^{4}He,$^{47-54}$Ti,$^{48-56}$V,$^{49-58}$Cr,$^{50-60}$Mn,$^{51-61}$Fe,$^{52-62}$Co,$^{53-63}$Ni,$^{55-62}$Cu
^{65}Cu	74	$^{1-3}$H,^{4}He,$^{49-54}$Ti,$^{50-56}$V,$^{51-58}$Cr,$^{52-60}$Mn,$^{53-62}$Fe,$^{54-64}$Co,$^{55-65}$Ni,$^{57-64}$Cu
^{64}Zn	86	$^{1-3}$H,^{4}He,$^{48-56}$V,$^{49-58}$Cr,$^{50-60}$Mn,$^{51-61}$Fe,$^{52-62}$Co,$^{53-63}$Ni,$^{54-64}$Cu,$^{56-63}$Zn

Table 1 (Continued)

Target	#	Products Formed: Product Nuclides
^{66}Zn	79	$^{1-3}$H,^{4}He,$^{50-56}$V,$^{51-58}$Cr,$^{52-60}$Mn,$^{53-62}$Fe,$^{54-64}$Co,$^{55-65}$Ni,$^{56-66}$Cu,$^{58-65}$Zn
^{67}Zn	74	$^{1-3}$H,^{4}He,$^{51-56}$V,$^{52-58}$Cr,$^{53-60}$Mn,$^{54-62}$Fe,$^{55-64}$Co,$^{56-66}$Ni,$^{57-67}$Cu,$^{59-66}$Zn
^{68}Zn	69	$^{1-3}$H,^{4}He,$^{52-56}$V,$^{53-58}$Cr,$^{54-60}$Mn,$^{55-62}$Fe,$^{56-64}$Co,$^{57-67}$Ni,$^{58-68}$Cu,$^{60-67}$Zn
^{70}Zn	57	$^{1-3}$H,^{4}He,$^{54-56}$V,$^{55-58}$Cr,$^{56-60}$Mn,$^{57-62}$Fe,$^{58-64}$Co,$^{59-67}$Ni,$^{60-70}$Cu,$^{62-69}$Zn
^{90}Zr	82	$^{1-3}$H,^{4}He,$^{74-82}$As,$^{75-85}$Se,$^{76-86}$Br,$^{77-87}$Kr,$^{78-88}$Rb,$^{80-89}$Sr,$^{82-90}$Y,$^{84-89}$Zr
^{91}Zr	83	$^{1-3}$H,^{4}He,$^{75-82}$As,$^{76-85}$Se,$^{77-87}$Br,$^{78-88}$Kr,$^{79-89}$Rb,$^{80-90}$Sr,$^{82-91}$Y,$^{84-90}$Zr
^{92}Zr	83	$^{1-3}$H,^{4}He,$^{76-82}$As,$^{77-85}$Se,$^{78-88}$Br,$^{79-89}$Kr,$^{80-90}$Rb,$^{81-91}$Sr,$^{82-92}$Y,$^{84-91}$Zr
^{94}Zr	77	$^{1-3}$H,^{4}He,$^{78-82}$As,$^{79-85}$Se,$^{80-88}$Br,$^{81-91}$Kr,$^{82-92}$Rb,$^{83-93}$Sr,$^{84-94}$Y,$^{86-93}$Zr
^{96}Zr	69	$^{1-3}$H,^{4}He,$^{80-82}$As,$^{81-85}$Se,$^{82-88}$Br,$^{83-91}$Kr,$^{84-94}$Rb,$^{85-95}$Sr,$^{86-96}$Y,$^{88-95}$Zr
^{92}Mo	73	$^{1-3}$H,^{4}He,$^{76-84}$Br,$^{77-87}$Kr,$^{78-88}$Rb,$^{80-89}$Sr,$^{82-90}$Y,$^{84-91}$Zr,$^{86-92}$Nb,$^{88-91}$Mo
^{94}Mo	82	$^{1-3}$H,^{4}He,$^{78-86}$Br,$^{79-89}$Kr,$^{80-90}$Rb,$^{81-91}$Sr,$^{82-92}$Y,$^{84-93}$Zr,$^{86-94}$Nb,$^{88-93}$Mo
^{95}Mo	85	$^{1-3}$H,^{4}He,$^{79-87}$Br,$^{80-90}$Kr,$^{81-91}$Rb,$^{82-92}$Sr,$^{83-93}$Y,$^{84-9[illegible]}$Zr,$^{86-95}$Nb,$^{88-94}$Mo
^{96}Mo	87	$^{1-3}$H,^{4}He,$^{80-88}$Br,$^{81-91}$Kr,$^{82-92}$Rb,$^{83-93}$Sr,$^{84-94}$Y,$^{85-95}$Zr,$^{86-96}$Nb,$^{88-95}$Mo
^{97}Mo	85	$^{1-3}$H,^{4}He,$^{81-88}$Br,$^{82-91}$Kr,$^{83-93}$Rb,$^{84-94}$Sr,$^{85-95}$Y,$^{86-96}$Zr,$^{87-97}$Nb,$^{89-96}$Mo
^{98}Mo	83	$^{1-3}$H,^{4}He,$^{82-88}$Br,$^{83-91}$Kr,$^{84-94}$Rb,$^{85-95}$Sr,$^{86-96}$Y,$^{87-97}$Zr,$^{88-98}$Nb,$^{90-97}$Mo
^{100}Mo	79	$^{1-3}$H,^{4}He,$^{84-88}$Br,$^{85-91}$Kr,$^{86-96}$Rb,$^{87-97}$Sr,$^{88-98}$Y,$^{89-99}$Zr,$^{90-100}$Nb,$^{92-99}$Mo
^{142}Nd	87	$^{1-3}$H,^{4}He,$^{126-134}$I,$^{127-137}$Xe,$^{128-138}$Cs,$^{129-139}$Ba,$^{130-140}$La,$^{131-141}$Ce,$^{132-142}$Pr,$^{134-141}$Nd
^{143}Nd	87	$^{1-3}$H,^{4}He,$^{127-135}$I,$^{128-138}$Xe,$^{129-139}$Cs,$^{130-140}$Ba,$^{131-141}$La,$^{132-142}$Ce,$^{133-143}$Pr,$^{135-142}$Nd
^{144}Nd	87	$^{1-3}$H,^{4}He,$^{128-136}$I,$^{129-139}$Xe,$^{130-140}$Cs,$^{131-141}$Ba,$^{132-142}$La,$^{133-143}$Ce,$^{134-144}$Pr,$^{136-143}$Nd
^{145}Nd	87	$^{1-3}$H,^{4}He,$^{129-137}$I,$^{130-140}$Xe,$^{131-141}$Cs,$^{132-142}$Ba,$^{133-143}$La,$^{134-144}$Ce,$^{135-145}$Pr,$^{137-144}$Nd
^{146}Nd	86	$^{1-3}$H,^{4}He,$^{130-138}$I,$^{131-140}$Xe,$^{132-142}$Cs,$^{133-143}$Ba,$^{134-144}$La,$^{135-146}$Ce,$^{136-146}$Pr,$^{138-145}$Nd
^{148}Nd	79	$^{1-3}$H,^{4}He,$^{132-138}$I,$^{133-140}$Xe,$^{134-142}$Cs,$^{135-144}$Ba,$^{136-146}$La,$^{137-147}$Ce,$^{138-148}$Pr,$^{140-147}$Nd
^{150}Nd	68	$^{1-3}$H,^{4}He,$^{134-138}$I,$^{135-140}$Xe,$^{136-142}$Cs,$^{137-144}$Ba,$^{138-146}$La,$^{139-148}$Ce,$^{140-150}$Pr,$^{142-149}$Nd
^{144}Sm	85	$^{1-3}$H,^{4}He,$^{128-138}$Cs,$^{129-139}$Ba,$^{130-140}$La,$^{131-141}$Ce,$^{132-142}$Pr,$^{133-143}$Nd,$^{135-144}$Pm,$^{137-143}$Sm
^{147}Sm	87	$^{1-3}$H,^{4}He,$^{131-139}$Cs,$^{132-142}$Ba,$^{133-143}$La,$^{134-144}$Ce,$^{135-145}$Pr,$^{136-146}$Nd,$^{137-147}$Pm,$^{139-146}$Sm
^{148}Sm	87	$^{1-3}$H,^{4}He,$^{132-140}$Cs,$^{133-143}$Ba,$^{134-144}$La,$^{135-145}$Ce,$^{136-146}$Pr,$^{137-147}$Nd,$^{138-148}$Pm,$^{140-147}$Sm
^{149}Sm	87	$^{1-3}$H,^{4}He,$^{133-141}$Cs,$^{134-144}$Ba,$^{135-145}$La,$^{136-146}$Ce,$^{137-147}$Pr,$^{138-148}$Nd,$^{139-149}$Pm,$^{141-148}$Sm
^{150}Sm	86	$^{1-3}$H,^{4}He,$^{134-142}$Cs,$^{135-144}$Ba,$^{136-146}$La,$^{137-147}$Ce,$^{138-148}$Pr,$^{139-149}$Nd,$^{140-150}$Pm,$^{142-149}$Sm
^{152}Sm	79	$^{1-3}$H,^{4}He,$^{135-142}$Cs,$^{137-144}$Ba,$^{138-146}$La,$^{139-148}$Ce,$^{140-150}$Pr,$^{141-151}$Nd,$^{142-152}$Pm,$^{144-151}$Sm
^{154}Sm	68	$^{1-3}$H,^{4}He,$^{136-142}$Cs,$^{139-144}$Ba,$^{140-146}$La,$^{141-148}$Ce,$^{142-150}$Pr,$^{143-152}$Nd,$^{144-154}$Pm,$^{146-153}$Sm

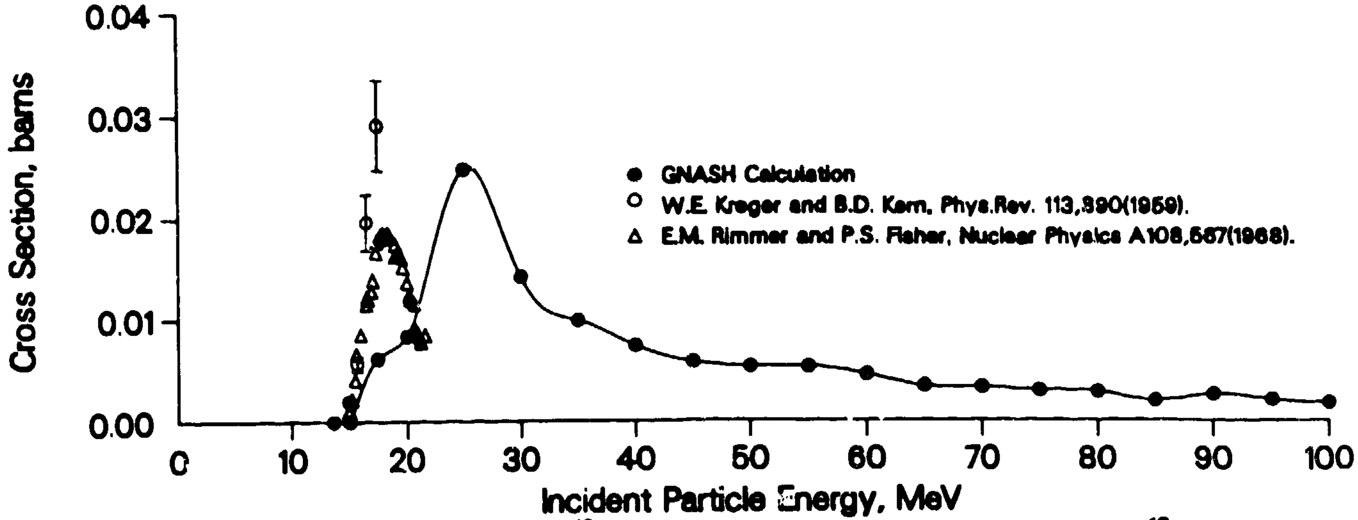

Fig. 1 GNASH results for ^{12}B production from neutrons on ^{12}C

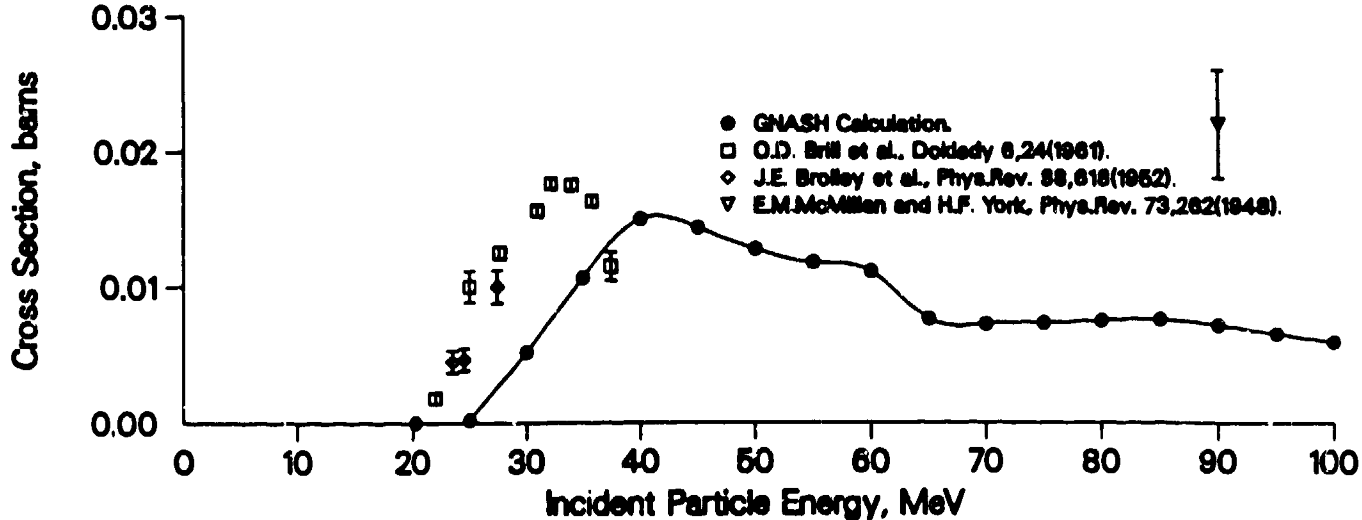

Fig. 2 GNASH results for ^{11}C production from neutrons on ^{12}C

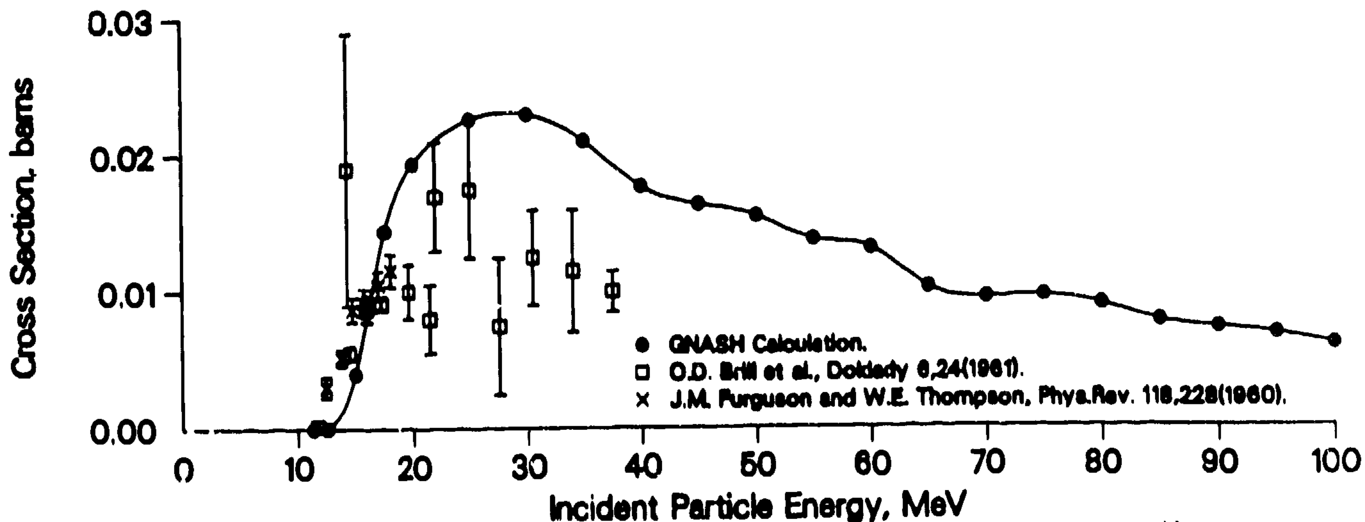

Fig. 3 GNASH results for ^{13}N production from neutrons on ^{14}N

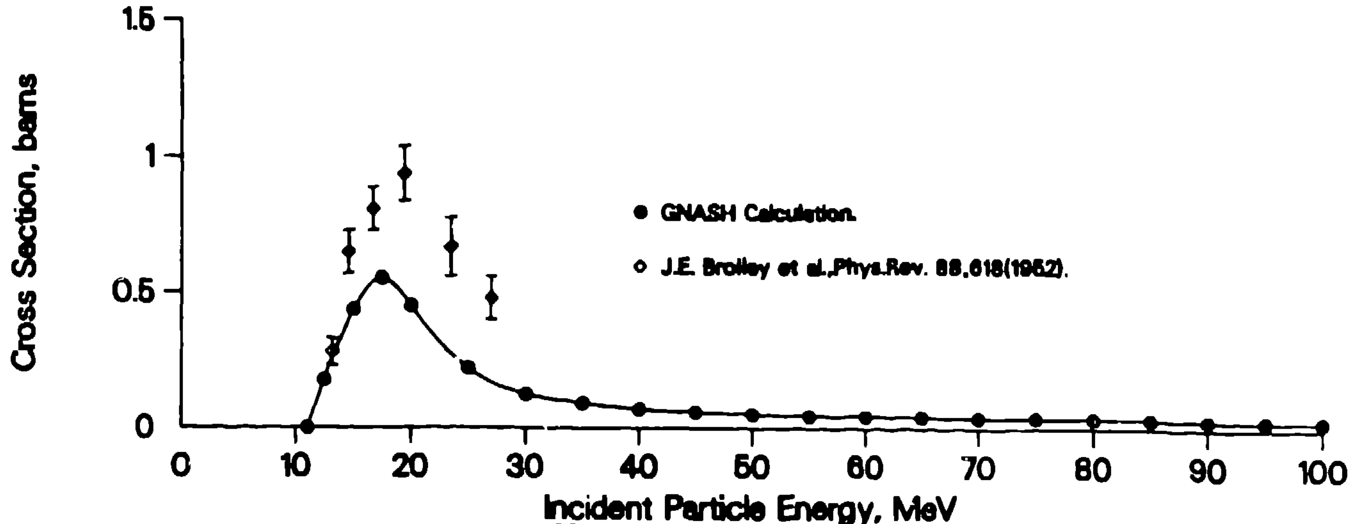

Fig. 4 GNASH results for ^{62}Cu production from neutrons on ^{63}Cu

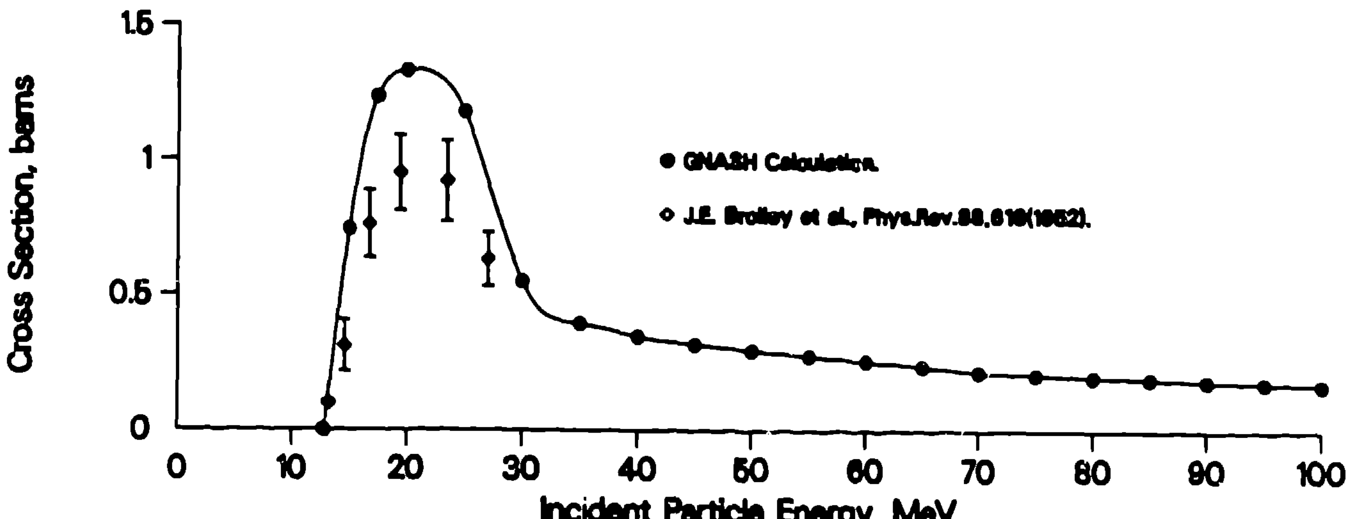

Fig. 5 GNASH results for ^{91}Mo production from neutrons on ^{92}Mo

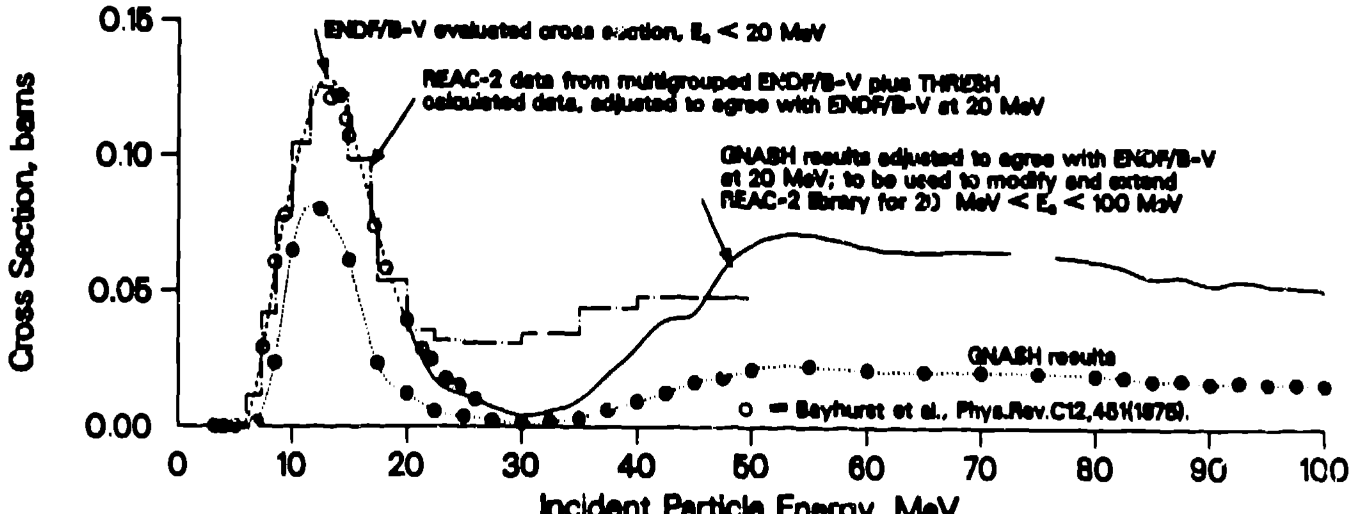

Fig. 6 GNASH results for ^{24}Na production from neutrons on ^{27}Al