INDC(NDS)-62/W + Spec.

International Atomic Energy Agency

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INTERNATIONAL NUCLEAR DATA COMMITTEE

Survey of current and future needs for charged particle and photonuclear reaction data*

by

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July 1974

IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

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* Paper submitted to the IAEA Consultants Meeting on Charged Particle and Photonuclear Reaction Data, Vienna, 24-26 April 1974

(revised version July 1974)

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Introduction

Interaction of particles with matter induces radioactivity. Whether this activity is produced intentionally or not, nuclear data are essential for its determination and are of fundamental importance to basic research as well as to applied uses in science and technology.

This survey attempts to identify and summarize specific needs for charged particle and photonuclear reaction data. Reaction data characterize quantities which are dependent on the nature and energy of the impinging particle and of the target nucleus, such as excitation function, nature and number of secondary particles, their angular and energy distributions, etc.

In the neutron field, data needs for reactor design and development have induced the generation of numerous compilation and evaluation activities which now benefit the whole community of neutron data users. On the other hand, there exists at the present time no single application of charged particle and photonuclear reaction data which covers as broad a scope, extends over as long a period, and concerns as crucial an issue as that of fission reactor technology. In many cases, charged particle and photonuclear reaction data are currently used for the extension and/ or refinement of available techniques based on the use of neutrons such as activation analysis, isotope production, etc. Consequently the unavailability of a broad base of reaction data encourages reliance on already available methods and inhibits the development of new applications. The scope of data needs covered by this survey is therefore not representative of the true potential needs, it only reflects the present status of those needs for the present and future applications which have been documented.

The formulation of those needs is not always clearly expressed and depends on the various fields of application and sources of information available. In a few cases, the task to find out about the needs is made easier by international request lists compiled and published by the Nuclear Data Section which specify nuclear data requirements for nuclear energy applications.

It is not the purpose of this paper to assess the possible coverage of needs by already available data.

Data needs have been identified and categorized in six main fields of application, each one practically setting specific constraints upon the quantities, the target materials and the energy range required. In addition partial data needs have been included for selected applications in various areas of science and technology.

Data needs in various fields of application

1. Activation analysis

The activation analysis techniques using charged particles or photons are undergoing a fast development. The growing use of compact cheap accelerators, in particular cyclotrons for charged particles and microtrons for the production of very large fluxes of bremsstrahlung gamma-rays, contributes to this development. In many cases these new techniques are used to solve analytical problems extremely difficult or impossible to solve with more conventional techniques, e.g. the determination of C and O in very pure alkali metals - in particular in sodium where carbon and oxygen concentrations are below 1 $\mu g.\ g^{-1}$ - can be done only by photon activation analysis [1].

Charged particles and photons are now principally used to determine the concentration of light elements (Be, B, C, N, O, F), but extension of their use to heavier elements is beginning. An illustration is the following new method [2] in which sulfur - the determination of which is of great importance in metallurgy, petroleum products etc. - is analysed by means of the capture reaction $^{32}S(p,\gamma)^{33}Cl$. Other examples are the determinations of lead in biological materials [3] and of valuable trace elements in the copper ore [4] by bremsstrahlung activation analysis.

A given element can be determined using various projectiles and reactions; optimization of the analysis depends upon the knowledge of the excitation functions. Table 1 lists a number of radionuclides through which various light elements are determined. It must be emphasized that charged particle and photonuclear reaction data are also needed in neutron activation analysis to estimate the yields of secondary interference reactions [5].

A general survey of the nuclear data needs in activation analysis was performed by H. Muenzel and W. Michaelis [6] by means of a questionnaire disseminated in 30 countries. From a total of 156 requests expressing needs for reaction cross-sections, 38 applied to charged particles and 15 to photons as shown in Table 2. Requests for specific nuclides are given in Table 3.

The needed excitation functions for charged-particle and photon analysis cover energy ranges which according to [1] extend from threshold to the following maximum values:

photons	50 - 60 MeV
p	15 - 20 MeV
d	20 - 25 MeV
t	20 - 25 MeV
^{3}He	25 - 30 MeV
α	45 - 50 MeV

Table 1 – Radionuclides through which light elements are determined by means of charged particles or photons (from ref. [1]).

Radionuclide (Half-life)	Element to determine	activating projectile
^{6}He (0.802 s)	Li	γ
^{8}Li (0.884 s)	Be	γ
^{9}Li (0.176 s)	B	γ
^{7}Be (53.4 d)	Li B	p,d p,d
^{11}C (20.3 min)	Be B C N	^{3}He,α p,d γ,^{3}He,α p
^{13}N (1.96 min)	B C N O	^{3}He,α p,d γ,^{3}He,α p
^{17}N (4.25)	^{18}O F	γ γ
^{15}O (2.03 min)	C N O	α d γ
^{17}F (66 s)	N O	α d
^{18}F (109.7 min)	O F	p,t,^{3}He,α γ,p,d,α
^{34}Cl (32 min)	S	p,d

Not only excitation functions, but also angular distributions are required for the newly developing analytical applications of elastic scattering of charged particles, such as protons, α-particles and heavier ions [7].

Further data needs can be expected from the foreseeable development of machines producing intense beams of energetic tritons, the use of which appears to be very promising in activation analysis. Some potential needs are associated with the future use of heavy ions like ^{12}C and ^{16}O.

Table 2 - Number of requests for various cross-sections (from ref.[6]).

Cross section for	Accuracy requested (in %)						Total
	< 0.1	< 1	< 2	< 5	< 10	not stated	
thermal reactor neutrons		14	3	16	3	27	63
fast neutrons (mainly 14 MeV)		6	2	14	2	16	40
Charged particles (p,d,^{3}He, ^{4}He)		6	1	14	4	13	38
γ-rays, Bremsstrahlung		1	1	4	1	8	15
						Total	156

Table 3: Data requests for specified nuclides or groups of nuclides (reproduced from [6]).

Nuclides	Type and accuracy of data (accuracy in %; if not stated +)					
	Cross sections			Decay data		
	n_{therm} $+n_{react}$	n_{14}	charged p. projectiles	$T_{1/2}$	E	I
^{16}O,^{18}O,^{14}N,^{15}N,^{28}Si			1			
B,C,N,O,F,Na,Al, Si,S,Cl			5			
^{64}Cu, ^{76}As				+	γ+	
^{72}Se,^{121}Sb,^{122}Te (α,xn)			1			
^{81}Br (n,p)	0,1 mb					
As,Se,Ga,Ge			5			
^{87}Rb, ^{238}U (spont.fission)				1		
^{104}Rh,^{109m}Ag,^{192}Ir, ^{194}Ir,^{199}Au				5	γ 2	
^{109}Ag	5					
^{133}Ba				1		γ(abs)1
^{140}Ba,^{148}Pm				1	γ 0.1	γ(abs)1
Light elements*)			5 5	2	α2;ß2;γ2 γ 0,1 keV	α2;ß2;γ2 ß2;γ2
Rare earth elements	5					
Fission products	fission yields			+	γ+;ß**	γ+

additional data: *) yield of X-ray emission induced by charged particles

**) average ß-energy, accuracy 1 %.

2. Controlled Thermonuclear Research

Nuclear data needs for CTR are identified by the International Nuclear Data Request List [8] which includes only one request for a non-neutron induced reaction, namely for $^{6}Li + ^{6}Li \rightarrow ^{7}Be + \alpha + n$ in the keV to MeV range. This list refers implicitly to the deuterium - tritium fuel cycle and does not consider the following longer term needs.

Cross sections of (γ,n) reactions occurring in the blanket, particularly in beryllium, are needed.

A potential need for charged-particle nuclear data is connected with the investigations of "exotic" fuels and of charged-particle nuclear-fusion chain reactions. In response to inquiries from the IAEA about the relative priorities of charged-particle nuclear data in CTR, the Request List for Charged-Particle Nuclear Data (Table 4) was prepared by J.R. McNally, jr. of Oak Ridge National Laboratory, USA. The priority criteria which appear in Table 4 are defined in Appendix I.

2.1 Charged-Particle nuclear-fusion chain reactions

In these reactions, analogous to chemical chain reactions, fuels such as Li or Li-D might be burned by interacting with energetic "chain centers" such as p, d, t, ^{3}He. Table 5 illustrates several of these reactions. The individual reactions which are members of a chain reaction, could take place in more easily attainable plasma conditions than those required for the net reaction. An introduction and bibliography on the application of thermonuclear chain reactions in controlled fusion research has been prepared by McNally [9].

2.2 "Exotic" fuels

Net energy production can be obtained from the interaction of protons with light nuclei of mass number A = n-1 (^{7}Li, ^{11}B, ^{15}N, ^{19}F) which break into n alpha particles. The energy is entirely communicated to the alpha particles and could be recovered with high efficiency by magnetohydrodynamic techniques. The most promising reaction, $^{11}B(p,d)^{8}Be$, is being studied extensively [10], [11].

Table 4 – (reproduced from [8]).

PRIORITY	REACTION	ENERGY RANGE
1	$^{6}Li(d,\alpha)\alpha + 22.4$ MeV	100 keV - 5 MeV
1	$^{6}Li(d,p)^{7}Li + 5.0$ MeV	100 keV - 5 MeV
1	$^{6}Li(d,p)t + \alpha + 2.6$ MeV	100 keV - 5 MeV
1	$^{6}Li(d,n)^{7}Be + 3.4$ MeV	100 keV - 5 MeV
1	$^{6}Li(d,n)^{3}He + \alpha + 1.8$ MeV	100 keV - 5 MeV
1	$^{6}Li(d,d')^{6}Li^{*} \rightarrow d + \alpha - 1.5$ MeV	3 MeV - 6 MeV
1	$^{6}Li(\alpha,\alpha')^{6}Li^{*} \rightarrow d + \alpha - 1.5$ MeV	3 MeV - 12 MeV
1	$^{6}Li(p,p')^{6}Li^{*} \rightarrow d + \alpha - 1.5$ MeV	3 MeV - 15 MeV
1	$^{6}Li(p,^{3}He)\alpha + 4.0$ MeV	100 keV - 15 MeV
1	$^{9}Be(p,\alpha)^{6}Li + 2.1$ MeV	10 keV - 15 MeV
1	$^{9}Be(p,d)2\alpha + 0.7$ MeV	10 keV - 15 MeV
1	$^{11}B(p,\alpha)2\alpha + 8.7$ MeV	10 keV – 5 MeV
3	$^{6}Li(^{6}Li,x)v$ (8 reactions)	100 keV – 5 MeV
3	$^{6}Li(t,p)^{8}Li \xrightarrow{0.9s} \beta^{-} + 2\alpha + 14$ MeV	10 keV - 2 MeV
3	$^{6}Li(t,n)2\alpha + 16.1$ MeV	10 keV - 2 MeV
3	$^{6}Li(t,d)^{7}Li + 1.0$ MeV	10 keV - 2 MeV
3	$^{6}Li(^{3}He,n)^{8}B \xrightarrow{0.6S} e^{+} + 2\alpha + 12$ MeV	2 MeV - 8 MeV
3	$^{6}Li(^{3}He,d)^{7}Be + 0.1$ MeV	100 keV - 8 MeV
3	$^{6}Li(^{3}He,p)2\alpha + 16.9$ MeV	100 keV - 8 MeV
3	$^{6}Li(\alpha,p)^{9}Be - 2.1$ MeV	3 MeV - 12 MeV
3	$t(t,n)n + \alpha + 11.3$ MeV	10 keV - 10 MeV
3	$t(p,n)^{3}He - 0.8$ MeV	1.5 MeV - 15 MeV
3	$d(x,x')p + n - 2.2$ MeV	{ x = p,α 3 MeV - 15 MeV
3	$^{3}He(t,d)\alpha + 14.3$ MeV	100 keV - 10 MeV
4	All other light particle reactions $(p,d,t,^{3}He,\alpha)$ with elements through ^{18}O for CTR with special search for resonances	100 keV - 15 MeV

Table 5 - Several charged-particle fusion chain reactions involving ^{6}Li or ^{6}Li-D fuel

Charged-particle fusion chain reactions		Fuel	Chain Centers	Ashes
	$p + {}^6Li \longrightarrow {}^3He + \alpha + 4.0$ MeV	Li-D	p, ^{3}He	α
	${}^3He + d \longrightarrow p + \alpha + 18.4$ MeV			
net reaction	$d + {}^6Li \longrightarrow 2\,\alpha + 22.4$ MeV			
	$p + {}^6Li \longrightarrow {}^3He + \alpha + 4.0$ MeV	Li	p, ^{3}He	α
	${}^3He + {}^6Li \longrightarrow p + 2\alpha + 16.9$ MeV			
net reaction	${}^6Li + {}^6Li \longrightarrow 3\alpha + 20.9$ MeV			
	$p + {}^6Li \longrightarrow {}^3He + \alpha + 4.0$ MeV	Li	α,p	^{3}He, ^{9}Be
	$\alpha + {}^6Li \longrightarrow p + {}^9Be - 2.1$ MeV			
net reaction	${}^6Li + {}^6Li \longrightarrow {}^9Be + p + {}^3He + 1.9$ MeV			
	$d + {}^6Li \longrightarrow t + p + \alpha + 2.6$ MeV	Li	t,d	^{7}Li,p,α
	$t + {}^6Li \longrightarrow d + {}^7Li + 1.0$ MeV			
net reaction	${}^6Li + {}^6Li \longrightarrow {}^7Li + p + \alpha + 3.6$ MeV			
	$d + {}^6Li \longrightarrow {}^3He + n + \alpha + 1.8$ MeV	Li	d, ^{3}He	^{7}Be,α,n
	${}^3He + {}^6Li \longrightarrow d + {}^7Be + 0.1$ MeV			
net reaction	${}^6Li + {}^6Li \longrightarrow {}^7Be + \alpha + n + 1.9$ MeV			

3. Life Sciences

3.1 Nuclear Medicine

The use of radioactive tracers in medicine and biology is rapidly growing. Table 6 gives more than 100 radionuclides with a potential use in this field. The specific needs of nuclear medicine for charged particle and photonuclear reaction data are mostly related to the production of radionuclides which are used in diagnostic techniques for various diseases and metabolic misfunctions of the human body. Some of these radionuclides with very short half-lives, e.g. ^{15}O(2.05 min), ^{11}C(20.4 min), ^{13}N(10 min) have to be produced at medical institutes. This can best be done with cyclotrons or betatrons located at those institutes. Compact cyclotrons for medical use are becoming more widely available. In 1975, about 30 are expected to be used for radionuclide-production, activation analysis and radiobiological research in medical, biological and biophysical institutions [12].

3.1.1 Charged Particle Reaction Data

In order to develop and optimize production techniques, one has to know excitation functions for all nuclear reactions leading to useful radionuclides (see Table 6) and for all commonly accelerated particles, e.g. p, d, t, ^{3}He, ^{4}He and possibly ^{7}Li, ^{12}C, ^{16}O and other heavy ions at energies up to 15 MeV for deuterons, 27 MeV for protons, 30 MeV for alpha particles and 39 MeV for ^{3}He particles [13]. As illustrated in Table 7, a given radionuclide can be produced by various charged particle reactions, all the corresponding excitation functions are needed before a decision can be reached about which type of reaction should be used with a certain type of cyclotron or accelerator.

3.1.2 Photonuclear Reaction Data

Many hospitals have betatrons for radiotherapy. Bremsstrahlung photons are produced by electrons striking a platinum target. The photons are distributed in energy up to maximum electron energy, typically 40 MeV.

Biologically important positron emitters, such as ^{11}C, ^{13}N, ^{30}P, ^{31}S can be produced by photonuclear reactions. The production of labelled biopolymers with short-lived radioisotopes is also considered.

3.2 Personnel dosimetry

Evaluation of the dose induced in personnel by irradiation or contamination from radioisotopes requires knowledge of the excitation functions and angular distributions of the neutron producing reactions (α,n) and (γ,n) on light elements such as F, O, Al, Ca.

Excitation functions for spallation reactions are also needed for estimation of the dose absorbed in accidental exposure of human beings to high-energy proton beams.

Table 6 – (reproduced from Appendix E of [13]).

The medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine is publishing an enlarged and updated revision of MIRD Pamphlets 4 and 6. The following radionuclides will be tentatively included in the publication

Radionuclides to be included in revision of Dillman pamphlet

H-3
Be-7
C-11
C-14
N-13
O-15
F-18
Na-22
Na-24
Mg-28

Al-28
P-32
S-35
K-40
K-42
K-43
Ca-45
Ca-47
Ca-49
Sc-47

Sc-49
Cr-51
Mn-52
Mn-52m
Mn-54
Fe-52
Fe-55
Fe-59
Co-57
Co-58

Co-60
Cu-64
Cu-67
Zn-62
Zn-65
Ga-66
Ga-67
Ga-68
Ga-72
Ge-68

As-73
As-74
Se-73
Se-75
Se-77m
Br-77
Br-82
Kr-81
Kr-81m
Kr-85

Kr-85m
Rb-81
Rb-82
Rb-84
Rb-86
Sr-82
Sr-85
Sr-87m
Sr-90
Y-87

Y-90
Mo-99
Tc-99m
Ru-97
Pd-103
Ag-109m
Cd-109
In-111
In-113m
Sn-113

I-123
I-124
I-125
I-126
I-130
I-131
I-132
Xe-127
Xe-133
Cs-129

Cs-131
Cs-137
Ba-133
Ba-135m
Ba-137m
Ce-139

Dy-157
Er-171
Yb-169
W-188
Re-188
Os-190m

Ir-190m
Au-195
Au-195m
Au-198
Au-199

Hg-197
Hg-203
Bi-206
Ra-224
Am-241

Total number of radionuclides 102 8/28/72

A-37
In-115m
I-129
I-133
Cs-127
Tl-201

Total number of Radionuclides 108 10/2/72

Cs-134

Total number of Radionuclides 109 10/20/72

Table 7 - (reproduced from Appendix E of [13]).

Excitation Functions Needed

Fluorine-18

1. a. $^{16}\mathrm{O}(^{3}\mathrm{He},n)^{18}\mathrm{Ne} \xrightarrow{\beta^+} {}^{18}\mathrm{F}$
b. $^{16}\mathrm{O}(^{3}\mathrm{He},p)^{18}\mathrm{F}$
2. a. $^{16}\mathrm{O}(\alpha,2n)^{18}\mathrm{Ne} \xrightarrow{\beta^+} {}^{18}\mathrm{F}$
b. $^{16}\mathrm{O}(\alpha,pn)^{18}\mathrm{F}$
3. $^{20}\mathrm{Ne}(d,\alpha)\ {}^{18}\mathrm{F}$
4. $^{22}\mathrm{Ne}(p,\alpha n)^{18}\mathrm{F}$
5. $^{18}\mathrm{O}(p,n)^{18}\mathrm{F}$
6. a. $^{19}\mathrm{F}(p,2n)^{18}\mathrm{Ne} \xrightarrow{\beta^+} {}^{18}\mathrm{F}$
b. $^{19}\mathrm{F}(p,pn)^{18}\mathrm{F}$

Potassium-43

1. $^{40}\mathrm{Ar}(\alpha,p)^{43}\mathrm{K}$
2. a. $^{44}\mathrm{Ca}(d,^{3}\mathrm{He})^{43}\mathrm{K}$
b. $^{44}\mathrm{Ca}(d,\alpha)^{42}\mathrm{K}$

Gallium-67

1. $^{66}\mathrm{Zn}(d,n)^{67}\mathrm{Ga}$
2. $^{67}\mathrm{Zn}(d,2n)^{67}\mathrm{Ga}$
3. $^{65}\mathrm{Cu}(^{3}\mathrm{He},n)^{67}\mathrm{Ga}$
4. $^{65}\mathrm{Cu}(\alpha,2n)^{67}\mathrm{Ga}$
5. $^{67}\mathrm{Zn}(p,n)^{67}\mathrm{Ga}$
6. $^{67}\mathrm{Zn}(p,2n)^{67}\mathrm{Ga}$

Iodine-123

1. $^{122}\mathrm{Te}(d,n)^{123}\mathrm{I}$
2. $^{122}\mathrm{Te}(^{3}\mathrm{He},2n)^{123}\mathrm{Xe} \xrightarrow{\beta^+} {}^{123}\mathrm{I}$
3. $^{123}\mathrm{Te}(p,n)^{123}\mathrm{I}$
4. $^{123}\mathrm{Te}(d,2n)^{123}\mathrm{I}$
5. $^{123}\mathrm{Te}(^{3}\mathrm{He},3n)^{123}\mathrm{Xe} \xrightarrow{\beta^+} {}^{123}\mathrm{I}$
6. $^{124}\mathrm{Te}(p,2n)^{123}\mathrm{I}$

Cesium-129

1.a. $^{130}\mathrm{Ba}(p,2n)^{129}\mathrm{La} \xrightarrow{\beta^+} {}^{129}\mathrm{Cs}$
b. $^{130}\mathrm{Ba}(p,2p)^{129}\mathrm{Cs}$
2. $^{132}\mathrm{Ba}(p,\alpha)^{129}\mathrm{Cs}$
3. $^{127}\mathrm{I}(\alpha,2n)^{129}\mathrm{Cs}$
4. $^{127}\mathrm{I}(^{3}\mathrm{He},n)^{129}\mathrm{Cs}$

Strontium-82

1. $^{82}\mathrm{Kr}(^{3}\mathrm{He},3n)^{82}\mathrm{Sr}$
2. $^{80}\mathrm{Kr}(\alpha,2n)^{82}\mathrm{Sr}$
3. $^{84}\mathrm{Sr}(p,3n)^{82}\mathrm{Y} \xrightarrow{\beta^+} {}^{82}\mathrm{Sr}$

Iron-52

1. $^{50}\mathrm{Cr}(\alpha,2n)^{52}\mathrm{Fe}$
2. $^{52}\mathrm{Cr}(^{3}\mathrm{He},3n)^{52}\mathrm{Fe}$

Yttrium-87 $\xrightarrow{\beta^+}$ Strontium-87m

1. $^{87}\mathrm{Rb}(^{3}\mathrm{He},3n)^{87}\mathrm{Y}$
2. $^{87}\mathrm{Sr}(p,n)^{87}\mathrm{Y}$
3. $^{88}\mathrm{Sr}(p,2n)^{87}\mathrm{Y}$

Indium-111

1. $^{109}\mathrm{Ag}(\alpha,2n)^{111}\mathrm{In}$
2. $^{109}\mathrm{Ag}(^{3}\mathrm{He},n)^{111}\mathrm{In}$
3. $^{111}\mathrm{Cd}(p,n)^{111}\mathrm{In}$
4. $^{112}\mathrm{Cd}(p,2n)^{111}\mathrm{In}$
5. $^{110}\mathrm{Cd}(d,n)^{111}\mathrm{In}$
6. $^{111}\mathrm{Cd}(d,2n)^{111}\mathrm{In}$

Dysprosium-157

1. $^{159}\mathrm{Tb}(p,3n)^{157}\mathrm{Dy}$
2. $^{156}\mathrm{Gd}(^{3}\mathrm{He},2n)^{157}\mathrm{Dy}$
3. $^{155}\mathrm{Gd}(\alpha,2n)^{157}\mathrm{Dy}$

4. Safeguards

One of the essential objective of Safeguards is to be able to determine the quantity of fertile and fissile heavy isotopes at any position in the fuel cycle. Non-destructive assay methods are mostly based on two fundamental signatures. The first one consists of the decay properties of the nuclides of interest including fission products and is used in passive assay methods. The second one is due to the fission properties of these nuclides and is used in active assay methods.

In such methods, samples are "interrogated" by neutrons or photons which induce fission. The interrogating neutrons can be produced by a photoneutron source through (γ,n) reactions on deuterium or beryllium but the main need for photonuclear reaction data in safeguards is connected with interrogating gammas, mostly bremsstrahlung gammas [14]. The requests on bremsstrahlung-induced data can be divided into three classes: prompt-neutron yield, prompt-fission neutrons, and delayed neutrons and γ-rays from fission [15].

Detailed data needs are given in the Request List of Nuclear Data for Safeguards Development Purposes [16]. The priority criteria used in establishing this list are defined in Appendix II.

5. Shielding

5.1 Space shielding

The radiation environment in the interplanetary space essentially consists of charged particles and is devided in three categories: intergalactic cosmic radiation, the solar wind and solar flares.

- Galactic cosmic radiation consists of charged particles having the following abundances [17].

Charged Particle	Relative Abundance in the Universe
Proton	100 000
Alpha	7 500
Lithium, Beryllium, Boron	3×10^{-3}
Carbon	10
Nitrogen	15
Oxygen	50
$10 \leqslant Z \leqslant 30$	30
$30 \leqslant Z$	8×10^{-4}
Electron	6 600

- The solar wind is an electrically neutral plasma of protons, electrons and other particles emitted by the sun.
- Solar flares consist of protons, alpha particles and electrons emitted by the sun during solar storms. The energies of these particles may range from 1 MeV to several GeV and the duration of the event as it passes a given location in space may be from hours to weeks.

Designing space experiments requires, among other nuclear data, the knowledge of spallation and activation cross-sections of charged-particle induced reactions.

5.2 Accelerator shielding

Shielding calculations for high energy accelerators such as TRIUMF, LAMPF etc.... fall into the same category of data needs. The accurate computation of shielding requires detailed knowledge of the process of nuclear interaction of fast particles (protons, neutrons, alpha-particles, etc.) especially such as the cross-sections of "inelastic" interaction of such particles with nuclei and the number, type and angular and energy distributions of secondary (cascade and evaporated) particles [18].

Extensive neutron yield, angular and energy distributions data are also required for Monte Carlo calculations of the neutrons resulting from the bombardment of thick heavy targets by electrons.

5.3 Reactor shielding

High energy gammas in reactors (5-15 MeV) can induce photoneutrons through (γ,n) reactions which have a not too large negative Q-value such as (γ,n) reactions on deuterium, beryllium and heavy nuclides.

Another basis for the shielder's concern is the fact that fuel with high burn-up has a build-up of alpha-active transuranium isotopes (e.g. ^{244}Cm, ^{238}Pu, etc.). The fuel may contain light elements some of which have appreciable (α,n) cross sections.

The yield assessment of neutrons originated in (γ,n) and (α,n) reactions goes through the knowledge of the excitation function of the relevant reactions.

6. Astrophysics

The nuclear fusion chain reaction concept can also be applied to model calculations describing rapid nuclear processes in astrophysical explosions [9]. The nuclear fuels considered for these chain reactions are ^{12}C, ^{14}N, ^{16}O, ^{20}Ne which involve many charged-particle and neutron induced reactions on light elements up to Si, as illustrated in fig. 1.

$^{20}Ne(\alpha,p)^{23}Na - 2.38$ MeV

$^{23}Na(\alpha,p)^{26}Mg + 1.84$ MeV

$^{26}Mg(\alpha,n)^{29}Si + 0.02$ MeV

$^{29}Si(\alpha,n)^{32}S - 1.53$ MeV

$^{16}O(n,\alpha)^{13}C - 2.20$ MeV

$^{13}C(p,\alpha)^{10}B - 4.08$ MeV

$^{10}B(p,\alpha)^{7}Be + 1.15$ MeV

$^{7}Be(n,\alpha)\alpha + 18.99$ MeV

$^{20}Ne + {}^{16}O + 4\,\alpha \rightarrow {}^{32}S + 5\,\alpha + 11.81$ MeV

Delayed Reaction (^{7}Be Residue)

$^{7}Be \xrightarrow{\beta+} {}^{7}Li + 0.86$ MeV (53.6 days)

$^{7}Li(p,\gamma)^{8}Be$ — $2\,\alpha + 17.34$ MeV

Fig. 1 Nuclear fusion chain-reaction burning of oxygen and neon nuclei [from ref. 9].

Excitation functions for charged particle induced reactions on light elements are needed for these calculations.

In the same way, a need for photonuclear reaction data is connected with the calculation of the effectiveness of the universal radiation field in disintegrating ultrahigh-energy cosmic-ray nuclei ($\sim 10^{11}$GeV). Very low energy photons of the black body universal radiation field at 2.7°K, when transformed in the rest frame of the ultrahigh-energy cosmic-ray nuclei, can disintegrate these nuclei [19].

7. Selected applications of charged particle and photonuclear reaction data

7.1 Fission reactors

Charged particles from ternary fission and from secondary reactions may induce nuclear reactions in structure materials. High energy gammas contribute a small amount to the reactivity through photofission. Excitation functions for (γ,n) reactions on deuterium and beryllium are also needed.

7.2 Neutron sources

Neutrons can be obtained from the following sources: nuclear reactors, nuclear explosions, accelerators, isotope sources, spontaneous and induced fission sources. Acceleratoors and isotope sources pertain to the scope of this survey.

7.2.1 Accelerator neutron sources

Accelerators may be divided into three broad classes: potential drop machines, linear accelerators and cyclotrons. The most currently used charged-particle induced reactions for producing neutrons with potential drop machines and cyclotrons are the following:

D(d,n)^{3}He	Q = 3.2 MeV	^{7}Li(d,n)^{8}Be	Q = 15.0 MeV
T(d,n)^{4}He	Q = 17,6 MeV	^{9}Be(d,n)^{10}B	Q = 4.4 MeV
T(p,n)^{3}He	Q = -0.8 MeV	^{9}Be(^{3}He,n)^{11}C	Q = 7.6 MeV
^{12}C(^{3}He,n)^{14}O	Q = -1.1 MeV		

The energy of incoming particles extends from threshold up to about 30 MeV.

On the other hand, proton-induced spallations on heavy nuclei and bremsstrahlung-induced (γ,n) reactions on light and heavy targets are used for neutron production in high energy proton and electron linear accelerators respectively.

7.2.2 Isotope sources

In isotope sources, the neutrons are produced through (α,n) or (γ,n) reactions by an alpha or gamma emitter thoroughly mixed with a stable target isotope whose cross-section is high enough to yield an adequate source of neutrons.

Deuterium and beryllium are so far the only target materials used for (γ,n) sources.

In (α,n) sources the target material is taken among the following elements: Li, Be, B, C, ^{18}O, O, F, Na, Al. [20].

7.3 Neutron flux measurements

In some methods of absolute neutron flux measurements, neutrons are produced in charged-particle induced reactions such as D(d,n)^{3}He, T(p,n)^{3}He, T(d,n)^{4}He for the associated particle method and ^{7}Li(p,n)^{7}Be, ^{51}V(p,n)^{51}Cr, ^{65}Cu(p,n)^{65}Zn and ^{57}Fe(p,n)^{57}Co for the associated activity method.

7.4 Cardiac pacemaker

A specific need for photonuclear reaction data arises in the fabrication of ^{238}Pu for cardiac pacemaker [21]. The biomedical quality of ^{238}Pu requires the lowest possible ^{236}Pu concentration. A good knowledge of the (γ,n) and (n,2n) cross-sections of ^{237}Np is necessary for calculating the ^{236}Pu concentration and for optimizing the irradiation conditions. Also important is the evaluation of neutron and gamma-ray yields from (α,$\alpha'\gamma$), (α, pγ) and (α,nγ) reactions on light elements contaminants in ^{238}Pu such as F, O, Al, Ca.

Table of the data needs

Field of application	Quantities needed	Target material	Energy range
1. Activation Analysis	-Excitation functions for charged particle and photonuclear reactions such as:	Mostly light elements (Be, B, C, N, O, F, etc) + all possible components of the matrix	From threshold up to 100 MeV
1.1 Conventional Activation Analysis			
- with bremsstrahlung	(γ,n), (γ,p), (γ,t), $(\gamma,\alpha n)$, etc.		
- with charged particles	(p,n), (d,n), $(^3\mathrm{He},\alpha)$, $(\alpha,2n)$, etc.		
1.2 Prompt-radiation Activation Analysis - with charged-particles	(p,α), (α,p), etc.		
1.3 Analysis by elastic scattering	-Excitation function + angular distribution for (p,p), (α,α), etc.		
2. Controlled Thermonuclear Research	-Excitation functions for charged-particle induced reactions such as: (d,α),(d,p), (t,d), (p,α), $(^3\mathrm{He},n)$, etc.	T,D, ^{3}He, ^{6}Li, ^{9}Be, ^{11}B, ^{15}N, ^{18}O, ^{19}F	10 keV to 15 MeV
	-Excitation functions for (γ,n) reactions	Blanket materials (particularly Be)	threshold - 10 MeV

Field of application	Quantities needed	Target material	Energy range
3. <u>Life sciences</u>			
3.1 Isotope production for Nuclear medicine	– Excitation functions for charged-particle and photonuclear reactions such as: (p,n), (p,pn), (d,α), (^{3}He,p), (α,pn), etc. (γ,p), (γ,n), (γ,2p), etc.	All material which produce, after interaction with charged particles or photons, medically interesting nuclides such as: ^{11}C, ^{18}F, ^{123}I, etc. (more than 100, see table 6)	From threshold up to 100 MeV
3.2 Dosimetry	– Excitation functions and angular distribution for (α,n) and (γ,n) reactions.	Tissue components	From threshold up to 15 MeV
	– Excitation functions of high-energy protons induced spallations.		up to 1 GeV
4. <u>Safeguards</u>	– Bremsstrahlung induced reaction data such as: total neutron-yield, delayed neutron- and gamma ray yield, delayed-gamma ray spectra	D, ^{6}Li, ^{9}Be, ^{13}C, ^{17}O, ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu	$E_{electron}$ = threshold – 10 MeV
	– Photoneutron spectra.	^{235}U, ^{238}U, ^{239}Pu	5–8 MeV
	– Energy dependence of the fission fragment yield, of the neutron yield and of the fission cross-section in (γ,f) reactions	^{238}Pu, ^{241}Pu, ^{241}Am	Threshold – 10 MeV

Field of application	Quantities needed	Target material	Energy range
5. Shielding			
5.1 Space shielding	-Spallation and activation cross sections for charged particle induced reactions.		
5.2 Accelerator shielding	-Excitation functions for "inelastic" interactions of charged particles.		
	-Yield, type, angular and energy distributions of secondary (cascade and evaporated) particles.	structure materials	1 MeV to several GeV
	-Yield, angular and energy distributions of neutrons from (e,γ,n) reactions.	heavy elements	up to 1 GeV
5.3 Fission reactor shielding	-Excitation functions for (γ,n) reactions	Be, D, heavy elements	threshold up to 15 MeV
	-Excitation functions for (α,n) reactions	light elements	up to 6 MeV
6. Astrophysics	-Excitation functions for charged-particle induced reactions such as:		
	(p,α), (p,n), (d,α), (t,n), (α,p), etc.	light elements up to sulphur	10 keV to 20 MeV
	-Excitation functions for photonuclear reactions	^{4}He, Fe and other ultrahigh-energy cosmic-rays nuclei	threshold up to 100 MeV

Field of application	Quantities needed	Target material	Energy range
7. Selected applications of charged particles and photonuclear reaction data			
7.1 Fission reactors	Excitation functions for charged particle and photonuclear reactions such as: (α,n), (p,n), $p,\gamma)$, (γ,n), (γ,f), etc.	D, Be, structure materials, fissile nuclides	threshold up to 15 MeV
7.2 Neutron sources			
7.2.1 Accelerator neutron sources	Excitation functions for charged particle reactions such as: (p,n), (d,n), $(^{3}He,n)$, etc.	D, T, ^{7}Li, ^{9}Be, ^{12}C	threshold up to 30 MeV
7.2 Isotope neutron sources	Excitation functions for (γ,n) reactions	D, Be	threshold up to the maximum gamma energy from radionuclides
	Excitation functions for (α,n) reactions	Li, Be, B, C, O, ^{18}O, F, Na, Al	threshold up to the maximum alpha energy from radionuclides
7.3 Neutron flux measurement	Excitation functions and angular distributions for (d,n) and (p,n) reactions.	D, T, ^{7}Li, ^{51}V, ^{57}Fe, ^{65}Cu	threshold up to 15 MeV
7.4 Cardiac pacemaker	(γ,n) cross-section	^{237}Np	thermal capture γ-rays
	Excitation functions for $(\alpha,\alpha'\gamma)$, $(\alpha,p\gamma)$ and $(\alpha,n\gamma)$	O, F, Al, Ca	up to 6 MeV

Appendix I

Priority Criteria*for Nuclear Data Requests in Controlled Fusion Research (CFR)

Priority 1

In general highest (first) priority shall be assigned to those nuclear data upon which some important aspect of CFR is immediately contingent. Specifically Priority 1 shall be assigned to requests for nuclear data which

1.) are required for evaluation of the feasibility of a proposed CF reactor concept or

2.) are required for immediate application of plasma phenomena in a fusion reactor context, or

3.) are essential for application of a material which is of conceptual importance in CFR, or

4.) are required for an important decision involving allocation of resources or redirection of research effort in CFR programmes, or

5.) are necessary to develop some important aspect of current CFR programmes to a level consistent with progress in other aspects of these programmes.

Priority 2

Priority 2 shall be assigned to nuclear data which

1.) are required for evaluation of materials of high potential utility in current CF reactor designs, or

2.) are expected to contribute to significant progress in CFR or reactor design studies in the near future.

Priority 3

Priority 3 shall be assigned to nuclear data which

1.) are of use in current design studies but are not of crucial importance, or

2.) are not of immediate importance for CFR but which have probability of becoming important as CFR programmes develop.

Priority 4

Priority 4 shall be assigned to nuclear data which

1.) fill out the body of information needed for fusion reactor technology, or

2.) are of potential interest for CFR but which cannot be assigned more definite priority at present.

* reproduced from INDC(NDS)-57

Appendix II

Priority Criteria* for Requests for Nuclear Data for Safeguards Purposes.

First Priority

First priority shall be given to those requests for nuclear data that

(1) are necessary for the refinement of an existing technique in order to bring its accuracy to within acceptable limits for safeguards purposes, or

(2) are essential for the development of a new and promising technique for the nondestructive assay and control of Special Nuclear Material in amounts that are significant to the safeguards system.

Second Priority

Second priority shall be given to those requests for nuclear data that

(1) are essential for the use or interpretation of an existing or proposed technique for nondestructive assay and that are now obtained either by extrapolation or by an empirical method but for which experimental confirmation is desirable, or

(2) are necessary for the development of a technique for nondestructive assay that may reasonably be expected to be useful for safeguards purposes.

Third Priority

Third priority shall be given to those requests for nuclear data that

(1) may be needed for the nondestructive assay of materials not now included in the safeguards system but that are likely to be in the future, or

(2) are necessary for the assessment or elimination of minor sources of error in the assay of Special Nuclear Material, or

(3) are needed for the exploration of new techniques for nondestructive assay for future applications, or

(4) may be needed for the development of new techniques for nondestructive assay for which the required technology does not now exist but which may reasonably be expected to in the future.

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* Criteria recommended for use in the U.S.A. and reproduced from Appendix A-2 of Report INDC(USA)-33/G

LIST OF REFERENCES

[1] Ch. ENGELMANN
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)2, IAEA, Vienna (1973) 459.

[2] M.A. ESWARAN, N.L. RAGOOWANSI, M. ISMAIL
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)2, IAEA, Vienna (1973) 489

[3] J.S. HISLOP, D.R. WILLIAMS
Analyst; 97: No. 1150, 78 (Jan.72)

[4] W. RATYNSKI, A. STEGNER, Z. SUJKOWSKI
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)2, IAEA, Vienna (1973) 411.

[5] V. KRIVÁŇ
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)2 IAEA, Vienna (1973) 193.

[6] H. MUENZEL, W. MICHAELIS
Rep. KFK 1812 June 1973

[7] V. KRIVÁŇ
Z. Anal. Chem. 262 (1972)1.

[8] Request lists of nuclear data for controlled fusion research as submitted to the International Atomic Energy Agency by member states.
Rep. INDC(NDS)-57, December 1973.

[9] J.R. MCNALLY, Jr.
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)2, IAEA, Vienna (1973) 41.

[10] G. HALE, D.R. HARRIS, P.G. YOUNG
LASL, T-2 Quarterly Progress Report for Period Ending 30 September 1973, p. 19

[11] I.D. PROCTOR, H.F. LUTZ, W. BARTOLINI
Rep. INDC(USA)-62, p. 87

[12] R.B.R. PERSSON
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)1,
IAEA, Vienna (1973) 359

[13] Technical minutes of the USNDC meeting 24-26 October 1972 (Appendix E).

[14] Report of the NCSAC AD-HOC Subcommittee on Safeguards
Rep. INDC(USA)-33.

[15] T. GOZANI, D.E. RUNDQUIST, R.O. GINAVEN, R.L. BRAMBLETT
Safeguards Techniques (Proc.Symp. Karlsruhe, 1970)2,
IAEA, Vienna (1970) 143.

[16] Request List of Nuclear Data for Safeguards Development
Purposes as submitted to the IAEA by Member States.
Rep. INDC(NDS)-44 June 1972.

[17] B.C. CLARK, P.G. KASE, J.P. MARTIN, J.G. MORSE
Nuclear Data in Sciences and Technology (Proc.Symp. Paris, 1973)1,
IAEA, Vienna (1973) 577.

[18] V.A. KONSHIN, E.S. MATUSEVICH
Atomic Energy Review vol. 6, no. 4, (1968) 3

[19] F.W. STECKER
Phys. Rev. 180 (1969) 1264

[20] A. LORENZ
Rep. UCRL-51298 (June 1972)

[21] C. BERGERS, C. DEVILLERS, F. GERVAISE
Nuclear Data in Sciences and Technology (Proc.Symp.Paris, 1973)1,
IAEA, Vienna (1973) 329.