Title
NUCLEAR REACTION Q-VALUES

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Publication Date
1966-07-01

UCRL-16964 errata

University of California

Ernest O. Lawrence Radiation Laboratory

NUCLEAR REACTION Q-VALUES

Berkeley, California

Research and Development

UCRL-16964 / errata
UC-34 Physics
TID-4500 (48th Ed.)

see errata at back of report

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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Printed in USA. Price $7.00. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia.

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ABSTRACT

Tables of Q-values for nuclear reactions have been calculated from the currently available mass data on the nuclides. The calculations were carried out on all stable and naturally occurring radioactive isotopes from a Z of 2 to 92, as well as on a few common long-lived isotopes. The tabulated reactions involve the following:

Isotope	Incoming Particles	Outgoing Particles
$5 \leq Z \leq 22$	γ, n, p, d, t, He^3, He^4, Li^6, Li^7 and C^{12}	γ, n, p, d, t, He^3, He^4, He^6, Li^6, Li^7, Li^8, Li^9, Be^7, Be^9, Be^{10}, B^8, B^{10} and B^{11}
$2 \leq Z \leq 4$ and $23 \leq Z \leq 92$	γ, n, p, d, t, He^3, He^4, Li^6, Li^7 and C^{12}	γ, n, p, d, t, He^3, He^4, He^6 and Li^6

The computations were carried out using the FORTRAN IV program SHADRACH on an IBM-7094 computer. This program, which will be made available on request, contains all the stored mass information and permits the calculation of Q-value matrices for any set of incident and exit particles.

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I. INTRODUCTION

With the current advances in particle detection equipment and the advent of modern accelerators, some experimental nuclear physicists are expanding their research to include more complex nuclear reactions. The purpose of this report is to provide nuclear reaction Q-value information that includes some of these complex multi-nucleon transfer reactions and which utilizes the improved atomic mass information that has become available in the past few years.

In compiling the mass data for this report we relied largely on recent compilations by other authors [1,2,3], although eighty-six of these mass assignments have been revised in accordance with new experimental measurements and twenty-three new isotopes have been added. These additions and revisions are listed in Table I and discussed in Section II.

The choice of targets and the size of the Q-value matrices have been somewhat limited by space considerations. Matrices have therefore been calculated for all stable and naturally occurring radioactive isotopes (according to the Chart of the Nuclides, General Electric, 1966) and for a few common long-lived isotopes of $Z \leq 20$; the Table of Contents gives a full list of the target nuclides. The two-body reactions chosen and their inherent Q-values and errors are given in Table II. A more detailed description of the Q-value tables on pages 1 to 344 is given in Section III.

It was realized that our selection of both targets and reactions would be inadequate to cover the needs of many experimenters. For this reason the FORTRAN IV program SHADRACH will be made available on request. With this code it is possible to calculate any desired set of nuclear reactions on any series of targets. Furthermore the program includes a convenient means of maintaining an up-to-date mass table. A more complete discussion is given in Section IV.

II. ATOMIC MASSES

Three compilations formed the basis for the atomic mass data used in this report. That of Lauritsen and Ajzenberg-Selove [1)] was used from mass 5 to 10. The 1964 Atomic Mass Table of Mattauch, Thiele and Wapstra [2)] was used for masses 1 through 4 and 11 through 205. For the masses over 205 we used a recent revision of the 1964 Mass Table [3)]. This revision includes the recent experimental data in that mass region and corrects the masses of all the nuclides decaying by an α-β decay chain into Bi^{213}. The previously reported mass excesses of these nuclides have been found to be in error [3)]. This new information from Wapstra is derived in the same manner as in the earlier mass table [2)].

An attempt was made in the mass 1 to 205 region to include more recent experimental information than was available in the above compilations. Table I gives a list of changes or additions to references 1 and 2. Those mass excesses listed as estimates are based on indirect experimental measurements. With these exceptions only direct experimental determinations of masses were used. It should be noted that while Table I includes no mass predictions, references 2 and 3 do include mass values derived from estimated α- or β-decay energies, and these values are contained in the following tables. Token errors of 1 MeV have been assigned to such values [2)]. Q-values listed in the matrices as having errors of 1 MeV or

Table I. Additions and revisions to mass data.

Z	ISOTOPE	MASS EXCESS (MeV)	ERROR (MeV)	REF. NO.
2	He^{8}	31.650	0.120	4
4	* Be^{12}	25.100	1.000	5
6	C^{9}	28.990	0.070	6
7	N^{12}	17.349	0.009	7
	N^{18}	13.100	0.400	8
8	O^{13}	23.110	0.070	6
9	F^{16}	10.686	0.040	9
	F^{22}	4.500	0.060	10
10	Ne^{17}	16.510	0.200	11
11	Na^{20}	6.980	0.080	12
12	* Mg^{20}	16.400	1.500	13, (Na^{20})
	* Mg^{21}	10.900	0.200	14
	Mg^{22}	- 0.380	0.050	4
13	Al^{24}	- 0.070	0.060	79
14	* Si^{25}	4.000	0.200	14
	Si^{32}	-24.090	0.007	15
15	P^{28}	- 7.120	0.060	79
16	* S^{29}	- 2.900	0.200	16
	S^{30}	-13.957	0.025	17
18	Ar^{33}	- 9.600	0.200	27,18
19	K^{37}	-24.7996	0.0031	19
	K^{42}	-35.016	0.012	20
	K^{44}	-36.210	0.200	21
20	Ca^{37}	-13.240	0.050	22
	Ca^{41}	-35.125	0.004	23
	* Ca^{50}	-41.100	1.000	24
21	Sc^{40}	-20.380	0.060	25
	Sc^{41}	-28.630	0.011	(Ca^{41})
	Sc^{42}	-32.109	0.004	26
22	* Ti^{41}	-15.830	0.100	27, (Ca^{41})
23	V^{46}	-37.069	0.003	26
	V^{49}	-47.9565	0.0022	23
	V^{53}	-51.780	0.050	28
25	Mn^{50}	-42.618	0.005	26
	Mn^{53}	-54.6828	0.0034	23
26	Fe^{55}	-57.4728	0.0034	23
27	Co^{57}	-59.3389	0.0046	23
28	Ni^{59}	-61.1599	0.0039	23
	Ni^{67}	-63.200	0.300	29
30	Zn^{72}	-68.144	0.009	30
31	Ga^{67}	-66.862	0.010	23
	Ga^{75}	-68.530	0.200	31
32	Ge^{71}	-69.8992	0.0046	23
	Ge^{78}	-71.760	0.200	32
33	As^{81}	-72.600	0.200	31
34	Se^{75}	-72.1664	0.0037	23
	Se^{83}	-75.440	0.200	33
35	Br^{75}	-69.159	0.020	34
	Br^{86}	-75.660	0.300	35
	Br^{87}	-74.600	0.500	35
36	Kr^{74}	-61.310	1.000	36
	Kr^{75}	-64.060	1.000	(Br^{75})
	Kr^{90}	-74.806	0.100	(Sr^{90})
37	Rb^{83}	-79.160	1.000	37
	Rb^{86}	-82.725	0.007	20
	Rb^{90}	-79.366	0.100	(Sr^{90})
38	Sr^{83}	-76.950	1.000	38, (Rb^{83})
	Sr^{90}	-85.956	0.005	20, (Y^{90})
	Sr^{91}	-83.678	0.012	(Y^{91})
	Sr^{93}	-79.420	0.100	(Zr^{93})
39	Y^{90}	-86.502	0.004	39,40,20
	Y^{91}	-86.348	0.007	40
	Y^{93}	-84.223	0.021	(Zr^{93})
40	Zr^{93}	-87.113	0.006	41
	Zr^{98}	-82.010	1.000	(Nb^{98})
41	Nb^{92}	-86.455	0.010	42
	Nb^{98}	-83.510	0.200	43
42	Mo^{90}	-80.173	0.013	44
46	Pd^{101}	-85.404	0.023	45
48	Cd^{109}	-88.549	0.008	46
49	In^{108}	-84.730	0.050	47
	In^{109}	-86.530	0.013	(Cd^{109})
	In^{114}	-88.585	0.008	39,20
	In^{120}	-85.500	0.600	48
52	Te^{115}	-82.500	0.700	49
53	I^{118}	-80.700	1.100	50
	I^{130}	-86.890	0.011	51
54	Xe^{127}	-88.441	0.023	52
55	Cs^{127}	-86.341	0.060	(Xe^{127})
	Cs^{138}	-83.660	0.077	53
57	La^{135}	-86.820	0.220	54

* Estimated value

Table I. (cont.)

Z	ISOTOPE	MASS EXCESS (MeV)	ERROR (MeV)	REF. NO.	Z	ISOTOPE	MASS EXCESS (MeV)	ERROR (MeV)	REF. NO.
59	Pr^{138}	-82.930	0.054	55	71	Lu^{170}	-57.120	0.060	68
	Pr^{139}	-85.048	0.054	56		Lu^{179}	-48.920	0.090	53
	Pr^{140}	-84.785	0.025	57	72	Hf^{175}	-54.700	0.060	69
	Pr^{147}	-75.480	0.200	58	73	Ta^{177}	-51.562	0.070	53
	Pr^{148}	-72.930	0.400	58		Ta^{182}	-46.344	0.038	70
60	Nd^{140}	-84.485	1.000	(Pr^{140})	75	Re^{189}	-37.825	0.080	71
	Nd^{147}	-78.178	0.017	78	76	Os^{194}	-32.375	0.023	72
61	Pm^{144}	-81.335	0.056	60	77	Ir^{192}	-34.733	0.060	73
63	Eu^{144}	-75.660	0.030	59		Ir^{194}	-32.472	0.023	74
	Eu^{157}	-69.419	0.035	61		Ir^{196}	-29.233	0.024	75
	Eu^{159}	-66.016	0.050	62	79	Au^{195}	-32.548	0.017	76
65	Tb^{160}	-67.846	0.019	63,64		Au^{198}	-29.594	0.006	77
69	Tm^{165}	-62.870	0.035	65		Au^{199}	-29.085	0.007	77
	Tm^{166}	-61.876	0.034	66					
	Tm^{167}	-62.121	0.030	67					

greater have in general relied on at least one of these estimates. All values are atomic mass excesses in MeV on the C^{12} scale.

In compiling Table I we have chosen to use the experimental data of the reference cited. Where there are multiple references to an isotope, the first is to be considered the prime reference used in determining the listed mass excess. No attempt was made to average experimental measurements. In cases where an isotope is listed as a reference, a change in the mass of the reference isotope has affected the mass of the reported nuclide. This occurs when masses are related through β-decay chains. The error on the mass excesses shown in Table I is either the experimental error or - primarily for β-decay chain data - the rms value obtained using the experimental error of the decay energy and the error in the mass of the daughter nuclide. Often the β-decay energy between nuclides is known more accurately than the mass of the daughter; this is indicated by reporting the mass excess of the parent to more significant figures than the error placed on it would warrant.

III. DESCRIPTION AND USE OF TABLES

A matrix of the tabulated reactions is shown in Table II together with the inherent mass difference and error for each. The (X,γ) row of this Table provides the mass excess and error of the incident particles while the (γ,X) column (with a sign change) gives the mass excess and error of the outgoing particles.

On pages 1 through 344 the Q-values for the various reactions on 293 isotopes are tabulated in matrix form. The general notation for the reaction is:

Target (incoming, outgoing) Product.

The ten incoming particles are the same on all targets:

γ, n, p, d, t, He^3, He^4, Li^6, Li^7 and C^{12}.

Nine outgoing particles are also common to all targets:

γ, n, p, d, t, He^3, He^4, He^6 and Li^6.

In addition for targets of $5 \leq Z \leq 22$, reactions involving the following outgoing particles are also tabulated:

Li^7, Li^8, Li^9, Be^7, Be^9, Be^{10}, B^8, B^{10} and B^{11}.

Across the top of each matrix is written the symbol and mass number of the target nucleus, its mass excess and error. Beneath the target information is a list of the incoming particles. The outgoing particles are listed along the left hand margin. In the box corresponding to the intersection of the "incoming" column and the "outgoing" row there are, in general, four pieces of information pertaining to that reaction as follows:

Q-value of the reaction (MeV)
Error in Q-value (MeV)
Symbol and mass number of product nucleus
Mass excess of product nucleus (MeV).

The following special cases are, however, somewhat different:

(1) In elastic scattering reactions only the symbol and mass number of the target appears.

(2) Some capture reactions in the light elements are redundant when the composite nucleus is also a tabulated "outgoing" particle (e.g. $He^3(n,\alpha)\gamma$). In this case the word GAMMA appears in place of the product nucleus and no mass excess is given.

(3) In a reaction which does not conserve nucleons or when the product nucleus consists solely of multiple protons or neutrons, the words NO REACTION appear.

(4) In reactions where the mass of the product nucleus is not known, the words MASS XX UNKNOWN are written, where XX stands for the symbol and mass number of the nuclide in question.

In the very light elements we also suppress entirely those rows of the matrix in which the exit particle corresponds identically with the target nucleus, a case which reduces to simple elastic scattering.

Table II. Atomic mass differences and uncertainties (all in MeV).

OUT \ IN	GAMMA	N	P	D	T	He^3	He^4	Li^6	Li^7	C^{12}
GAMMA	———	8.0714 ±.0001	7.2890 ±.0001	13.1359 ±.0001	14.9499 ±.0002	14.9313 ±.0002	2.4248 ±.0004	14.0884 ±.0011	14.9073 ±.0011	0.0000 ±.0000
N	-8.0714 ±.0001	———	-0.7824 ±.0001	5.0645 ±.0001	6.8785 ±.0002	6.8599 ±.0002	-5.6467 ±.0004	6.0170 ±.0011	6.8359 ±.0011	-8.0714 ±.0001
P	-7.2890 ±.0001	0.7824 ±.0001	———	5.8469 ±.0001	7.6610 ±.0002	7.6423 ±.0002	-4.8642 ±.0004	6.7994 ±.0011	7.6183 ±.0011	-7.2890 ±.0001
D	-13.1359 ±.0001	-5.0645 ±.0001	-5.8469 ±.0001	———	1.8140 ±.0002	1.7954 ±.0002	-10.7112 ±.0004	0.9525 ±.0011	1.7714 ±.0011	-13.1359 ±.0001
T	-14.9499 ±.0002	-6.8785 ±.0002	-7.6610 ±.0002	-1.8140 ±.0002	———	-0.0186 ±.0003	-12.5252 ±.0004	-0.8615 ±.0011	-0.0426 ±.0011	-14.9499 ±.0002
He^3	-14.9313 ±.0002	-6.8599 ±.0002	-7.6423 ±.0002	-1.7954 ±.0002	0.0186 ±.0003	———	-12.5066 ±.0004	-0.8429 ±.0011	-0.0240 ±.0011	-14.9313 ±.0002
He^4	-2.4248 ±.0004	5.6467 ±.0004	4.8642 ±.0004	10.7112 ±.0004	12.5252 ±.0004	12.5066 ±.0004	———	11.6636 ±.0012	12.4825 ±.0012	-2.4248 ±.0004
He^6	-17.5982 ±.0040	-9.5268 ±.0040	-10.3092 ±.0040	-4.4623 ±.0040	-2.6483 ±.0040	-2.6669 ±.0040	-15.1734 ±.0040	-3.5098 ±.0041	-2.6909 ±.0041	-17.5982 ±.0040
Li^6	-14.0884 ±.0011	-6.0170 ±.0011	-6.7994 ±.0011	-0.9525 ±.0011	0.8615 ±.0011	0.8429 ±.0011	-11.6636 ±.0012	———	0.8189 ±.0016	-14.0884 ±.0011
Li^7	-14.9073 ±.0011	-6.8359 ±.0011	-7.6183 ±.0011	-1.7714 ±.0011	0.0426 ±.0011	0.0240 ±.0011	-12.4825 ±.0012	-0.8189 ±.0016	———	-14.9073 ±.0011
Li^8	-20.9462 ±.0015	-12.8748 ±.0015	-13.6572 ±.0015	-7.8103 ±.0015	-5.9962 ±.0015	-6.0149 ±.0015	-18.5214 ±.0016	-6.8578 ±.0019	-6.0389 ±.0019	-20.9462 ±.0015
Li^9	-24.9650 ±.0200	-16.8936 ±.0200	-17.6760 ±.0200	-11.8291 ±.0200	-10.0150 ±.0200	-10.0337 ±.0200	-22.5402 ±.0200	-10.8766 ±.0200	-10.0577 ±.0200	-24.9650 ±.0200
Be^7	-15.7689 ±.0011	-7.6975 ±.0011	-8.4799 ±.0011	-2.6330 ±.0011	-0.8190 ±.0011	-0.8376 ±.0011	-13.3441 ±.0012	-1.6805 ±.0016	-0.8616 ±.0016	-15.7689 ±.0011
Be^9	-11.3505 ±.0009	-3.2791 ±.0009	-4.0615 ±.0009	1.7854 ±.0009	3.5994 ±.0009	3.5808 ±.0009	-8.9257 ±.0010	2.7379 ±.0014	3.5568 ±.0014	-11.3505 ±.0009
Be^{10}	-12.6070 ±.0022	-4.5356 ±.0022	-5.3180 ±.0022	0.5289 ±.0022	2.3429 ±.0022	2.3243 ±.0022	-10.1822 ±.0022	1.4814 ±.0025	2.3003 ±.0025	-12.6070 ±.0022
B^8	-22.9231 ±.0015	-14.8517 ±.0015	-15.6341 ±.0015	-9.7872 ±.0015	-7.9732 ±.0015	-7.9918 ±.0015	-20.4983 ±.0016	-8.8347 ±.0019	-8.0158 ±.0019	-22.9231 ±.0015
B^{10}	-12.0522 ±.0005	-3.9808 ±.0005	-4.7632 ±.0005	1.0837 ±.0005	2.8978 ±.0005	2.8791 ±.0005	-9.6274 ±.0006	2.0362 ±.0012	2.8551 ±.0012	-12.0522 ±.0005
B^{11}	-8.6677 ±.0003	-0.5962 ±.0003	-1.3787 ±.0003	4.4682 ±.0003	6.2823 ±.0004	6.2637 ±.0004	-6.2429 ±.0005	5.4207 ±.0011	6.2396 ±.0011	-8.6677 ±.0003

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TABLE OF CONTENTS

* Naturally occurring or otherwise available radioactive isotope.

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Tables of Nuclear Reaction Q-Values