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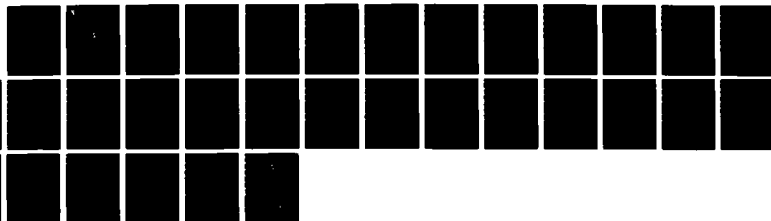
FUSION AND ADVANCED FUEL REACTION BIBLIOGRAPHY PARTICLE
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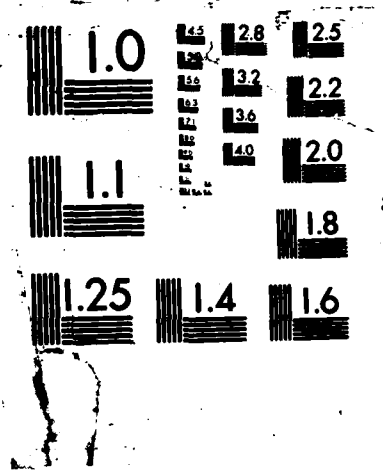
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Fusion, and Advanced Fuel, Reaction Bibliography

Particle Reactions from H1 to B11

August 1987

Author:
J. J. Pass, Jr.

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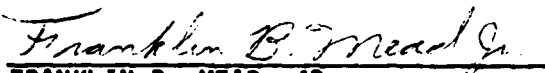
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FOREWORD

This document reports on the fusion, and advanced fuel, bibliography compiled as part of the on-going Air Force Astronautics Laboratory (AFAL) program of studying the feasibility of fusion-powered propulsion. AFAL Project Manager was Dr Frank Mead.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.


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Project Manager and Acting Chief,
Advanced Propulsion Branch

FOR THE COMMANDER


CLARK W. HAWK
Chief, Liquid Rocket Division

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The Air Force Astronautics Laboratory has on ongoing program of studying the feasibility of fusion-powered propulsion. This study will first examine nuclear fuels and their associated fuel cycles. The investigated fuels and fuel cycles will then be used to explore present and proposed fusion propulsion concepts. From this study, it will be determined which concepts, if any, will be able to produce fusion propulsion systems using present or near-term technology. The objective of the work reported herein was to compile a comprehensive list of the experimentally measured nuclear reactions involving the nuclides up to and including B11 (Boron-11). This compilation was performed in order to identify any new fuels and/or fuel cycles that would be potential candidates to replace the presently utilized fuels deuterium and tritium. Also, this project is intended to provide a readily accessible source of information for individuals who are studying fuels, reactions, and fuel cycles.					
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INTRODUCTION AND SUMMARY

The Air Force Astronautics Laboratory(AFAL) has an ongoing program that is studying the feasibility of fusion powered propulsion. This study will first examine nuclear fuels and their associated fuel cycles. The investigated fuels and fuel cycles will then be used to explore present and proposed fusion propulsion concepts. From this study, it will be determined which concepts, if any, will be able to produce reusable fusion propulsion systems using present or near-term technology.

The reason for the Air Force's interest in fusion propulsion systems is it's potential to achieve high specific impulse (> 1000 s), near zero neutron and gamma-ray production, and environmentally safe exhaust products.

The objective of the work reported in the following pages was to compile a comprehensive list of the experimentally measured nuclear reactions involving the nuclides up to and including B11 (Boron-11). This compilation was used to identify any new fuels and/or fuel cycles that would be potential candidates to replace the presently utilized fuels deuterium and tritium. This project is also intended to provide a readily accessible source of information to assist others who are studying fuels, reactions, and fuel cycles.

The search for reaction data involved the survey of books, technical journals, and national data bases; plus interfacing

with various experts in the field at universities and national laboratories.

A review of the reaction list revealed several nuclides that are likely candidates as fuels for use in fusion powered propulsion systems. These candidate fuels and their corresponding reactions are listed separately under the heading of "CANDIDATE REACTIONS FOR FUSION PROPULSION SYSTEMS".

FUSION, AND ADVANCED FUEL, REACTION BIBLIOGRAPHY

AFAL has an ongoing fusion propulsion study that partially involves a search to find a fuel cycle which produces very little, if any, neutrons and/or gamma-rays; with most of the energy being released in the form of charged particles. Many different nuclides can be used as a primary fuel, and each has its advantages and disadvantages. The present fuels that are being used, deuterium and tritium, produce copious amounts of high energy neutrons. Therefore, a fusion propulsion system based on deuterium and tritium is less attractive than other types of advanced propulsion concepts due to the extra weight required for shielding the payload and restricted operations. Thus, the consideration of other fuels to identify reactions that achieve or approach as close as possible the previously stated criteria of minimized neutron and/or gamma production is necessary in order to achieve a viable fusion propulsion system.

Before a propulsion system can be analyzed, the nuclides that will be used as the primary fuel must be chosen. After the primary fuel has been selected, the initial reactions and their products can be determined using this bibliography. Then, using these reaction products, the secondary reactions and their products can be established. This process can be carried out with the tertiary and higher order reactions until a complete fuel cycle is defined.

Once a complete fuel cycle has been defined, the next step

is to determine the cross sections and reactivities in order to choose an operating temperature that will maximize the desirable reactions and minimize the undesirable reactions. Also, using the energy or "Q" values of the reactions involved, an estimate of the energy release produced by the fuel cycle can be computed.

This bibliography is not to be considered a complete set of reactions for the nuclides existing between H1(Proton) and B11 (Boron-11); more nuclides and reactions could be verified in the future. Furthermore, neutron reactions have been considered and are included in this bibliography because they are necessary to completely analyze a fuel cycle.

BACKGROUND

Most of the work to discover nuclear reactions that occur in the isotopic range between H1 and B11 was done in the 1950's. A good reference for this early work is by S. Flugge [Ref. 1]. Since that time there has been no significant work done in this area. This is the first document that assembles all of the significant reactions.

LIST OF SYMBOLS

* = Q(MeV) was calculated using the mass defect formula--

$$Q = [(m_a + m_b) - (m_c + m_d + \dots)] * C$$

where:

$$a(b,c)d + \dots = a + b \rightarrow c + d + \dots$$

$$C = 931.481 \text{ MeV/amu}$$

m_a = mass of target particle

m_b = mass of incident particle

$m_c, m_d, \dots$ = masses of reaction products

' = isotope in an excited state

& = gamma-ray

e^- = electron

e^+ = positron

n = neutron

p = proton

d = deuteron

t = triton

He3,4,5,6 = Helium-3,4,5,6

Li6,7,8 = Lithium-6,7,8

Be7,8,9,10 = Beryllium-7,8,9,10

B9,10,11,12 = Boron-9,10,11,12

C10,11,12,13,14 = Carbon-10,11,12,13,14

N13,14 = Nitrogen-13,14

NEUTRON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.

$n + p \rightarrow d + 2.21^* \text{ MeV [Ref. 7]}$
 $n + d \rightarrow t + 6.24^* \text{ MeV [Ref. 7]}$
 $n + d \rightarrow p + 2n - 2.32^* \text{ MeV [Ref. 1]}$
 $n + t \rightarrow \alpha + H^4 + 1.88^* \text{ MeV [Ref. 7]}$
 $n + t \rightarrow 2n + d - 6.26^* \text{ MeV [Ref. 7]}$
 $n + t \rightarrow 3n + p - 8.48^* \text{ MeV [Ref. 7]}$
 $n + He^3 \rightarrow \alpha + He^4 - 1.25^* \text{ MeV [Ref. 7]}$
 $n + He^3 \rightarrow 2d - 3.27^* \text{ MeV [Ref. 7]}$
 $n + He^3 \rightarrow t + p + 0.764 \text{ MeV [Ref. 1]}$
 $n + He^4 \rightarrow d + t - 17.6^* \text{ MeV [Ref. 7]}$
 $n + Li^6 \rightarrow 2n + Li^5 \rightarrow p + He^4 - 25.5^* \text{ MeV [Ref. 7]}$
 $n + Li^6 \rightarrow n + d + He^4 - 1.48^* \text{ MeV [Ref. 7]}$
 $n + Li^6 \rightarrow t + He^4 + 4.6 \text{ MeV [Ref. 3]}$
 $n + Li^6 \rightarrow p + He^6 \rightarrow Li^6 + e^- + 0.222^* \text{ MeV [Ref. 1]}$
 $n + Li^6 \rightarrow t + He^4 + 4.797 \text{ MeV [Ref. 1]}$
 $t(2.7) + He^4(2.1) = 4.8 \text{ MeV [Ref. 4]}$
 $n + Li^6 \rightarrow d + He^5 \rightarrow n + He^4 - 1.38^* \text{ MeV [Ref. 1]}$
 $n + Li^6 \rightarrow t + He^4 + 4.78^* \text{ MeV [Ref. 1]}$
 $n + Li^7 \rightarrow 2n + Li^6 - 7.25^* \text{ MeV [Ref. 7]}$
 $n + Li^7 \rightarrow 3n + Li^5 \rightarrow p + He^4 - 11.0^* \text{ MeV [Ref. 7]}$
 $n + Li^7 \rightarrow n + t + He^4 - 2.47^* \text{ MeV [Ref. 7]}$

$n + \text{Li7} \rightarrow d + \text{He6} \rightarrow \text{Li6} + e^- - 4.66^* \text{ MeV [Ref. 1]}$
 $n + \text{Li7} \rightarrow t + \text{He5} \rightarrow n + \text{He4} - 2.47^* \text{ MeV [Ref. 1]}$
 $n + \text{Li7} \rightarrow \alpha + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4} + 17.6^* \text{ MeV [Ref. 1]}$
 $n + \text{Li7} \rightarrow \text{He4} + \text{H4} - 5.25^* \text{ MeV [Ref. 7]}$
 $n + \text{Be7} \rightarrow p + \text{Li7} + 1.62^* \text{ MeV [Ref. 1]}$
 $n + \text{Be7} \rightarrow 2\text{He4} + 18.97^* \text{ MeV [Ref. 1]}$
 $n + \text{Be9} \rightarrow \alpha + \text{Be10} + 6.84^* \text{ MeV [Ref. 1]}$
 $n + \text{Be9} \rightarrow 2n + \text{Be8} \rightarrow 2\text{He4} - 1.57^* \text{ MeV [Ref. 1]}$
 $n + \text{Be9} \rightarrow p + \text{Li9} \rightarrow n + 2\text{He4} - 0.791^* \text{ MeV [Ref. 7]}$
 $n + \text{Be9} \rightarrow p + \text{Li9} \rightarrow e^- + \text{Be9} + 0.271^* \text{ MeV [Ref. 7]}$
 $n + \text{Be9} \rightarrow d + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4} + 0.922^* \text{ MeV [Ref. 7]}$
 $n + \text{Be9} \rightarrow d + \text{Li8} \rightarrow 2\text{He4} + 1.43^* \text{ MeV [Ref. 7]}$
 $n + \text{Be9} \rightarrow t + \text{Li7} - 10.4^* \text{ MeV [Ref. 7]}$
 $n + \text{Be9} \rightarrow \text{He4} + \text{He6} \rightarrow \text{Li6} + e^- + 2.40^* \text{ MeV [Ref. 1]}$
 $n + \text{B10} \rightarrow n + d + 2\text{He4} - 5.87^* \text{ MeV [Ref. 1]}$
 $n + \text{B10} \rightarrow 2n + \text{B9} \rightarrow p + 2\text{He4} - 8.19^* \text{ MeV [Ref. 1]}$
 $n + \text{B10} \rightarrow p + \text{Be10} + 0.224^* \text{ MeV [Ref. 1]}$
 $n + \text{B10} \rightarrow d + \text{Be9} - 4.30^* \text{ MeV [Ref. 1]}$
 $n + \text{B10} \rightarrow t + \text{Be8} \rightarrow 2\text{He4} + 0.323^* \text{ MeV [Ref. 7]}$
 $n + \text{B10} \rightarrow \text{He4} + \text{Li7} + 2.786 \text{ MeV [Ref. 1]}$
 $n + \text{B11} \rightarrow \alpha + \text{B12} \rightarrow e^- + \text{C12} + 16.2^* \text{ MeV [Ref. 7]}$
 $n + \text{B11} \rightarrow \alpha + \text{B12} \rightarrow \text{He4} + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4} + 8.95^* \text{ MeV [Ref. 7]}$
 $n + \text{B11} \rightarrow \alpha + \text{B12} \rightarrow \text{He4} + \text{Li8} \rightarrow 2\text{He4} + 9.46^* \text{ MeV [Ref. 7]}$
 $n + \text{B11} \rightarrow 2n + \text{B10} - 11.5^* \text{ MeV [Ref. 7]}$

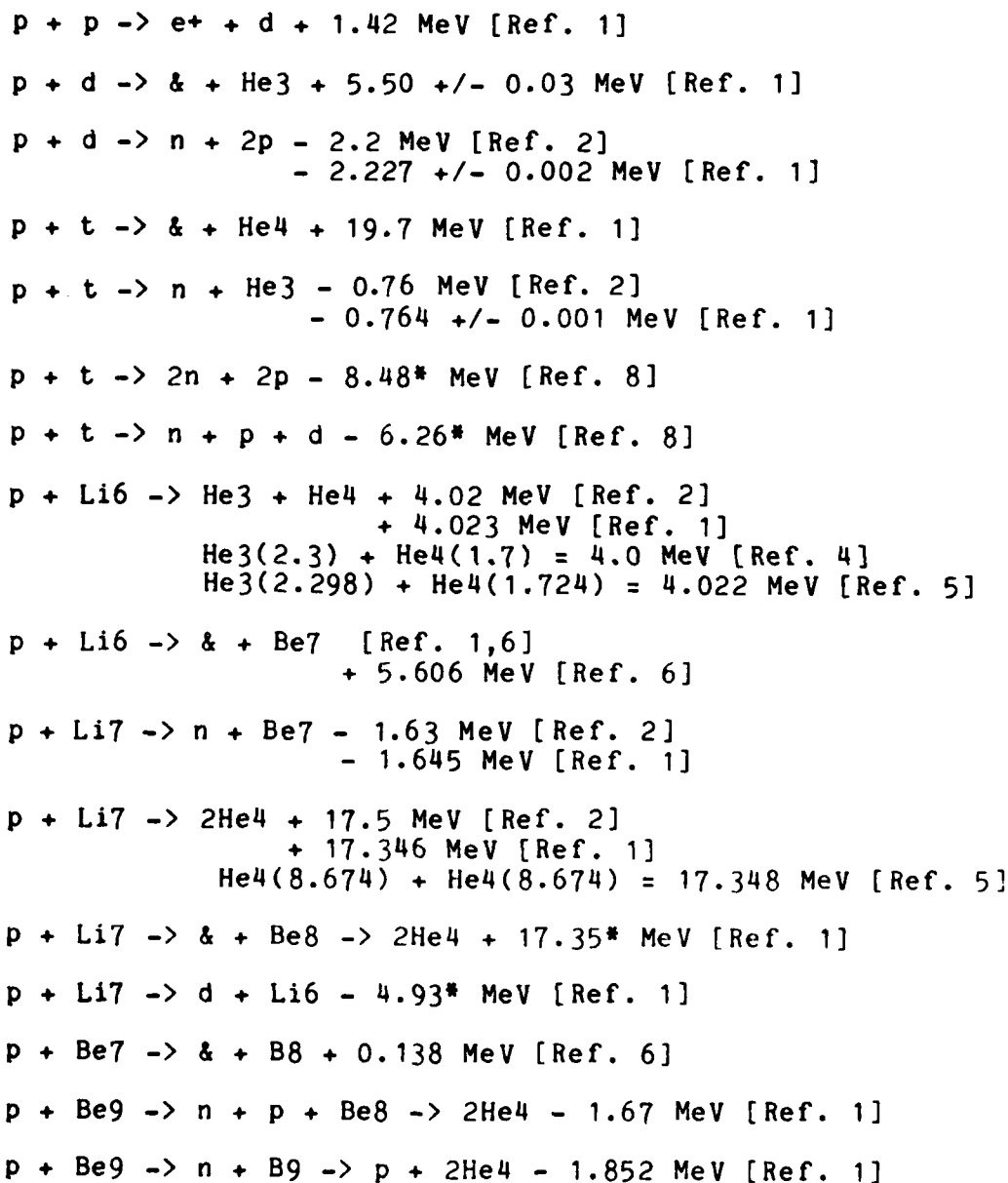
$n + B_{11} \rightarrow p + Be_{11} \rightarrow e^- + B_{11} + 0.271^* \text{ MeV [Ref. 7]}$

$n + B_{11} \rightarrow t + Be_9 - 9.56^* \text{ MeV [Ref. 7]}$

$n + B_{11} \rightarrow He_4 + Li_8 \rightarrow e^- + Be_8 \rightarrow 2He_4$
 $+ 8.97^* \text{ MeV [Ref. 1]}$

PROTON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.



$p + \text{Be9} \rightarrow \text{He4} + \text{Li6} + 2.126 \text{ MeV} \text{ [Ref. 1]}$
 $\text{He4}(1.275) + \text{Li6}(0.850) = 2.125 \text{ MeV} \text{ [Ref. 5]}$

$p + \text{Be9} \rightarrow \alpha + \text{B10} \text{ [Ref. 1,6]}$
 $+ 6.585 \text{ MeV} \text{ [Ref. 6]}$

$p + \text{Be9} \rightarrow d + \text{Be8} \rightarrow 2\text{He4} \text{ [Ref. 1,6]}$
 $+ 0.651 \text{ MeV} \text{ [Ref. 6]}$
 $d(0.326) + \text{He4}(0.163) + \text{He4}(0.163)$
 $= 0.652 \text{ MeV} \text{ [Ref. 5]}$

$p + \text{Be9} \rightarrow t + \text{Be7} - 12.1^* \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B10} \rightarrow \text{He4} + \text{Be7} + 1.148 \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B10} \rightarrow n + \text{C10} \rightarrow \text{B10} + e^+ - 4.35 \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B10} \rightarrow \alpha + \text{C11} \rightarrow \text{B11} + e^+ \text{ [Ref. 1,6]}$
 $+ 8.690 \text{ MeV} \text{ [Ref. 6]}$

$p + \text{B10} \rightarrow d + \text{B9} \rightarrow p + 2\text{He4} - 5.87^* \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B10} \rightarrow t + \text{B8} \rightarrow e^+ + \text{Be8} \rightarrow 2\text{He4} - 1.00 \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B10} \rightarrow \text{He3} + \text{Be8} \rightarrow 2\text{He4} \text{ [Ref. 1,6]}$
 $- 0.442 \text{ MeV} \text{ [Ref. 6]}$

$p + \text{B11} \rightarrow \text{He4} + \text{Be8} \rightarrow 2\text{He4} + 8.585 \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B11} \rightarrow 3\text{He4} + 8.7 \text{ MeV} \text{ [Ref. 4]}$
 $\text{He4}(2.888) + \text{He4}(2.888) + \text{He4}(2.888)$
 $= 8.664 \text{ MeV} \text{ [Ref. 5]}$

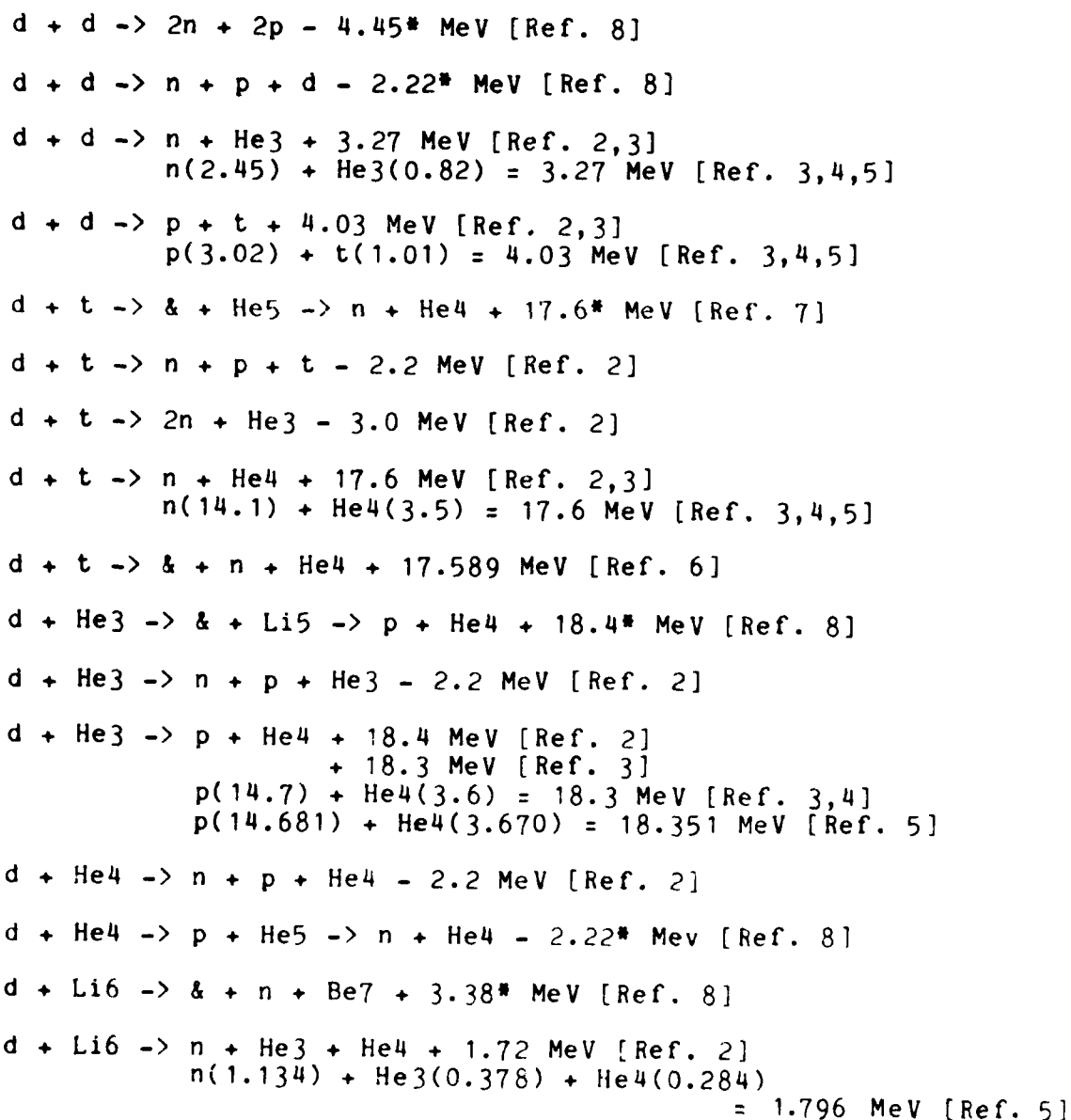
$p + \text{B11} \rightarrow n + \text{C11} \rightarrow \text{B11} + e^+ - 2.762 \text{ MeV} \text{ [Ref. 1]}$

$p + \text{B11} \rightarrow \alpha + \text{C12} \text{ [Ref. 1,6]}$
 $+ 15.956 \text{ MeV} \text{ [Ref. 6]}$

$p + \text{B11} \rightarrow d + \text{B10} - 9.10 \text{ MeV} \text{ [Ref. 1]}$

DEUTERON-INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.



$d + \text{Li6} \rightarrow n + \text{Be7} + 3.34 \text{ MeV [Ref. 2]}$
 $\quad \quad \quad + 3.40 \text{ MeV [Ref. 1]}$
 $\quad \quad \quad n(2.957) + \text{Be7}(0.423) = 3.380 \text{ MeV [Ref. 5]}$

$d + \text{Li6} \rightarrow p + \text{Li7} + 5.02 \text{ MeV [Ref. 2]}$
 $\quad \quad \quad + 5.027 \text{ MeV [Ref. 1]}$
 $\quad \quad \quad p(4.398) + \text{Li7}(0.628) = 5.026 \text{ MeV [Ref. 5]}$

$d + \text{Li6} \rightarrow p + \text{Li7}' \rightarrow \& + \text{Li7} + (4.54 + 0.45) \text{ MeV [Ref. 2]}$

$d + \text{Li6} \rightarrow p + t + \text{He4} + 2.557 \text{ MeV [Ref. 6]}$

$d + \text{Li6} \rightarrow t + \text{Li5} \rightarrow p + \text{He4} + (0.9 + 1.6) \text{ MeV [Ref. 2]}$
 $\quad \quad \quad t(0.539) + p(1.618) + \text{He4}(0.404)$
 $\quad \quad \quad = 2.561 \text{ MeV [Ref. 5]}$

$d + \text{Li6} \rightarrow \text{He3} + \text{He5} \rightarrow n + \text{He4} + 1.79^* \text{ MeV [Ref. 8]}$

$d + \text{Li6} \rightarrow 2\text{He4} + 22.4 \text{ MeV [Ref. 2,4]}$
 $\quad \quad \quad + 22.39 \text{ MeV [Ref. 1]}$
 $\quad \quad \quad \text{He4}(11.187) + \text{He4}(11.187) = 22.374 \text{ MeV [Ref. 5]}$

$d + \text{Li7} \rightarrow \& + 2n + \text{Be7} - 3.87^* \text{ MeV [Ref. 8]}$

$d + \text{Li7} \rightarrow \& + p + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4} + 15.4^* \text{ MeV [Ref. 8]}$

$d + \text{Li7} \rightarrow \& + p + \text{Li8} \rightarrow 2\text{He4} + 15.9^* \text{ MeV [Ref. 8]}$

$d + \text{Li7} \rightarrow 2n + \text{Be7} - 3.869 \text{ MeV [Ref. 6]}$

$d + \text{Li7} \rightarrow n + \text{Be8} \rightarrow 2\text{He4} + 15.0 \text{ MeV [Ref. 2,1]}$
 $\quad \quad \quad n(10.082) + \text{He4}(2.521) + \text{He4}(2.521)$
 $\quad \quad \quad = 15.124 \text{ MeV [Ref. 5]}$

$d + \text{Li7} \rightarrow p + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4}$
 $\quad \quad \quad + (-0.26 + 16.0) \text{ MeV [Ref. 2]}$

$d + \text{Li7} \rightarrow t + \text{Li6} - 0.995 \text{ MeV [Ref. 2]}$

$d + \text{Li7} \rightarrow \text{He4} + \text{He5} \rightarrow n + \text{He4} + 14.2 \text{ MeV [Ref. 1]}$

$d + \text{Be7} \rightarrow p + 2\text{He4} + 16.766 \text{ MeV [Ref. 6]}$
 $\quad \quad \quad p(11.179) + \text{He4}(2.795) + \text{He4}(2.795)$
 $\quad \quad \quad = 16.769 \text{ MeV [Ref. 5]}$

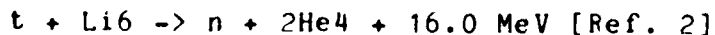
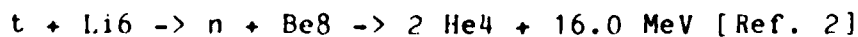
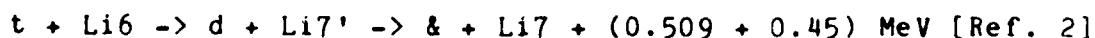
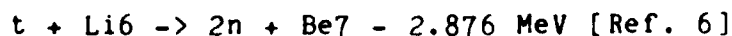
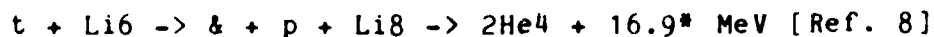
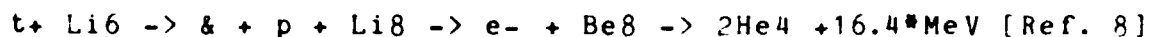
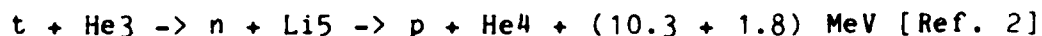
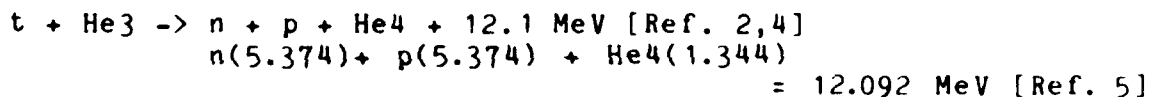
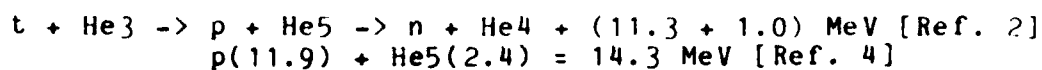
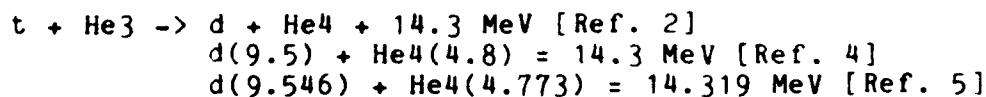
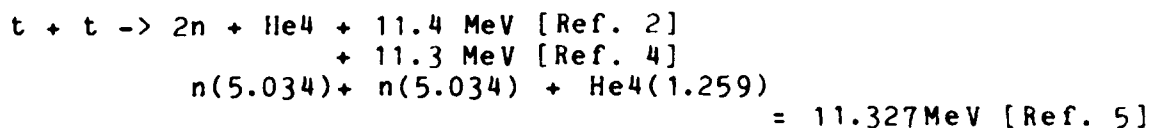
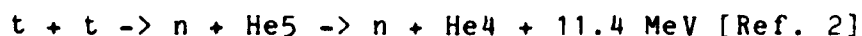
$d + \text{Be9} \rightarrow \& + \text{B11} + 15.8^* \text{ MeV [Ref. 8]}$

$d + \text{Be9} \rightarrow p + \text{Be10} + 4.588 \text{ MeV [Ref. 1]}$

$d + \text{Be9} \rightarrow n + \text{B10} + 4.35 \text{ MeV [Ref. 1]}$
 $d + \text{Be9} \rightarrow t + \text{Be8} \rightarrow 2\text{He4} + 4.68^* \text{ MeV [Ref. 8]}$
 $d + \text{Be9} \rightarrow \text{He4} + \text{Li7} + 7.153 \text{ MeV [Ref. 1]}$
 $d + \text{B10} \rightarrow p + \text{B11} + 9.235 \text{ MeV [Ref. 1]}$
 $d + \text{B10} \rightarrow n + \text{C11} \rightarrow \text{B11} + e^+ + 6.6 \text{ MeV [Ref. 1]}$
 $d + \text{B10} \rightarrow \text{He4} + \text{Be8} \rightarrow 2\text{He4} + 17.86 \text{ MeV [Ref. 1]}$
 $d + \text{B11} \rightarrow n + \text{C12} + 13.8 \text{ MeV [Ref. 1]}$
 $d + \text{B11} \rightarrow 2n + \text{C11} - 4.99^* \text{ MeV [Ref. 8]}$
 $d + \text{B11} \rightarrow p + \text{B12} \rightarrow e^- + \text{C12} + 1.137 \text{ MeV [Ref. 1]}$
 $d + \text{B11} \rightarrow p + \text{B12} \rightarrow \text{He4} + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4}$
 $\qquad\qquad\qquad + 1.137 \text{ MeV [Ref. 1]}$
 $d + \text{B11} \rightarrow \text{He4} + \text{Be9} + 8.018 \text{ MeV [Ref. 1]}$

TRITON-INDUCED REACTIONS

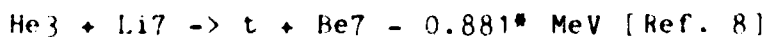
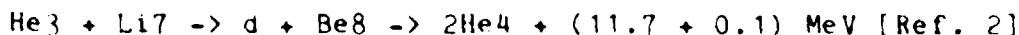
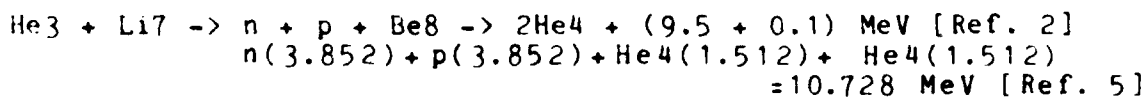
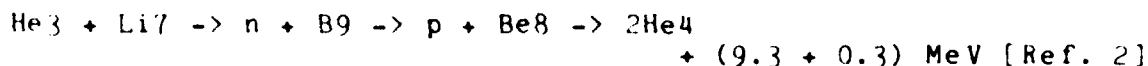
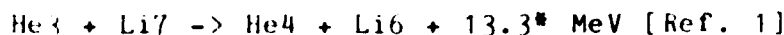
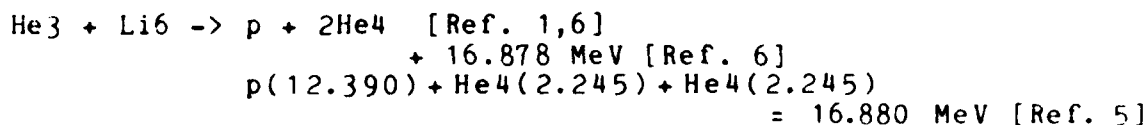
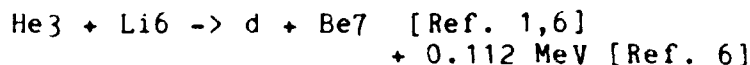
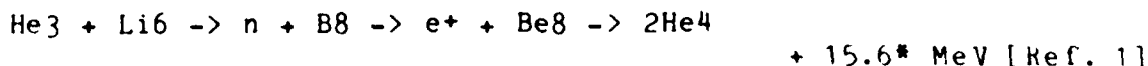
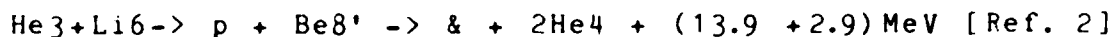
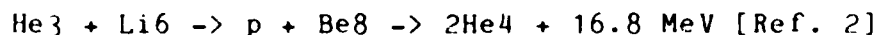
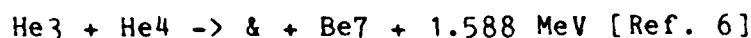
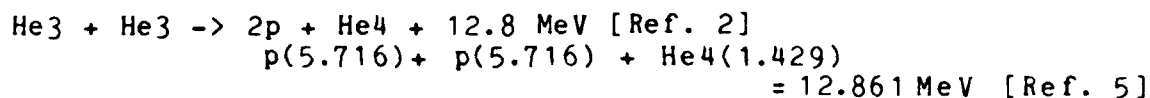
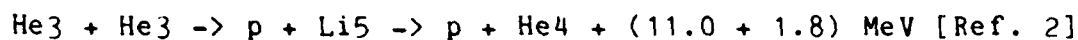
These reactions are listed by increasing atomic number of the target nuclide.

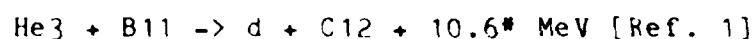
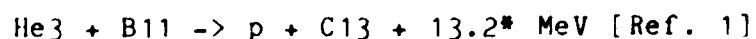
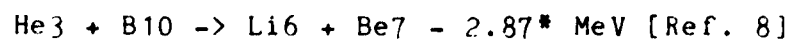
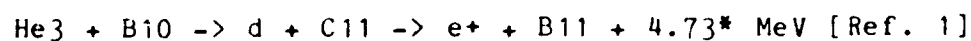
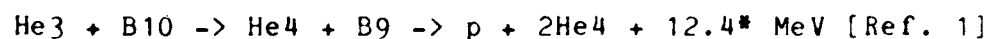
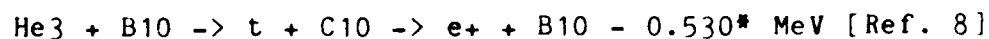
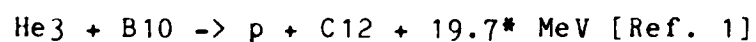
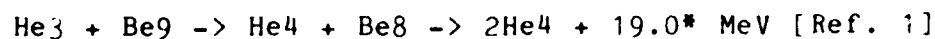
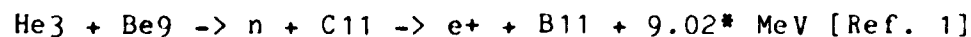
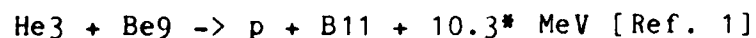
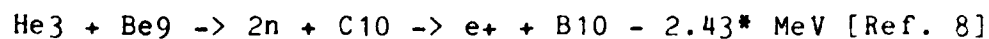
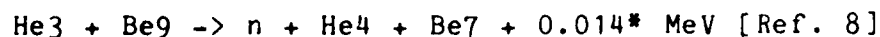
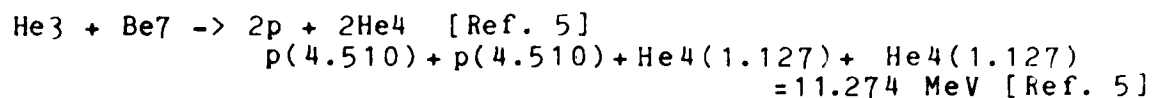


$t + \text{Li6} \rightarrow \alpha + \text{Be9} + 17.7^* \text{ MeV [Ref. 1]}$
 $t + \text{Li6} \rightarrow \text{He4} + \text{He5} \rightarrow n + \text{He4} + 16.1^* \text{ MeV [Ref. 1]}$
 $t + \text{Li7} \rightarrow \alpha + d + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4} + 11.4^* \text{ MeV [Ref. 8]}$
 $t + \text{Li7} \rightarrow \alpha + d + \text{Li8} \rightarrow 2\text{He4} + 11.9^* \text{ MeV [Ref. 8]}$
 $t + \text{Li7} \rightarrow 2n + 2\text{He4} + 8.88 \text{ MeV [Ref. 2]}$
 $n(6.049) + n(6.049) + \text{He4}(1.512) + \text{He4}(1.512)$
 $= 15.122 \text{ MeV [Ref. 5]}$
 $t + \text{Li7} \rightarrow n + \text{Be9} + 10.52 \text{ MeV [Ref. 2]}$
 $t + \text{Li7} \rightarrow 2n + \text{Be8} \rightarrow 2\text{He4} + 3.83 \text{ MeV [Ref. 2]}$
 $t + \text{Li7} \rightarrow n + \text{He4} + \text{He5} \rightarrow n + \text{He4} + (8.08 + 1.0) \text{ MeV [Ref. 2]}$
 $t + \text{Li7} \rightarrow p + \text{Li9} \rightarrow e^- + \text{Be9} + 10.7^* \text{ MeV [Ref. 8]}$
 $t + \text{Li7} \rightarrow p + \text{Li9} \rightarrow n + 2\text{He4} + 9.65^* \text{ MeV [Ref. 8]}$
 $t + \text{Li7} \rightarrow d + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4} + 11.4^* \text{ MeV [Ref. 8]}$
 $t + \text{Li7} \rightarrow d + \text{Li8} \rightarrow 2\text{He4} + 11.9^* \text{ MeV [Ref. 8]}$
 $t + \text{Li7} \rightarrow \text{He4} + \text{He6} \rightarrow e^- + \text{Li6} + 9.83 \text{ MeV [Ref. 2]}$
 $t + \text{Be7} \rightarrow p + n + 2\text{He4} \text{ [Ref. 5]}$
 $p(4.204) + n(4.204) + \text{He4}(1.051) + \text{He4}(1.051)$
 $= 10.510 \text{ MeV [Ref. 5]}$
 $t + \text{Be9} \rightarrow n + \text{B11} + 9.56^* \text{ MeV [Ref. 8]}$
 $t + \text{B10} \rightarrow \text{Be7} + \text{He6} \rightarrow e^- + \text{Li6} + 3.36^* \text{ MeV [Ref. 8]}$
 $t + \text{B10} \rightarrow p + \text{B12} \rightarrow e^- + \text{C12} + 19.2^* \text{ MeV [Ref. 8]}$
 $t + \text{B10} \rightarrow p + \text{B12} \rightarrow \text{He4} + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow 2\text{He4}$
 $+ 11.9^* \text{ MeV [Ref. 8]}$
 $t + \text{B10} \rightarrow p + \text{B12} \rightarrow \text{He4} + \text{Li8} \rightarrow 2\text{He4} + 11.4^* \text{ MeV [Ref. 8]}$
 $t + \text{B10} \rightarrow p + \text{He4} + \text{Li8} \rightarrow e^- + \text{Be8} \rightarrow \text{He4}$
 $+ 11.9^* \text{ MeV [Ref. 8]}$
 $t + \text{B10} \rightarrow p + \text{He4} + \text{Li8} \rightarrow 2\text{He4} + 11.4^* \text{ MeV [Ref. 8]}$
 $t + \text{B11} \rightarrow 2\text{He4} + \text{He6} \rightarrow e^- + \text{Li6} + 39.4^* \text{ MeV [Ref. 8]}$

HELIUM-3--INDUCED REACTIONS

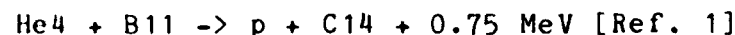
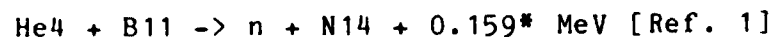
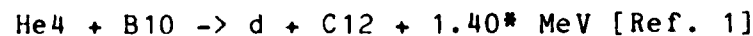
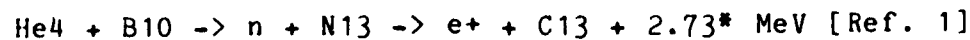
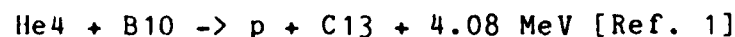
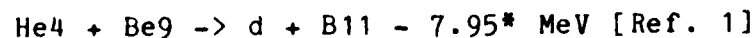
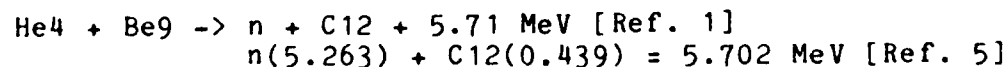
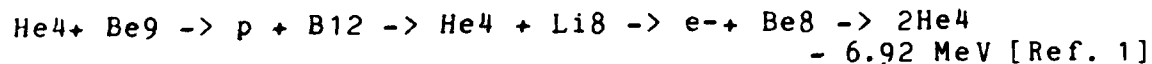
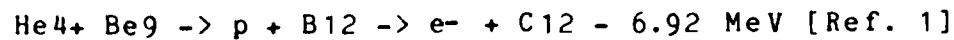
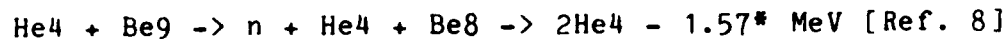
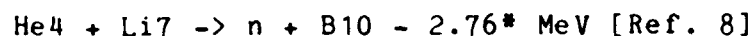
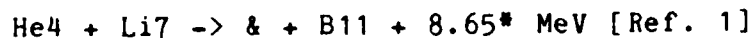
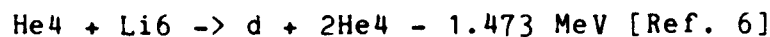
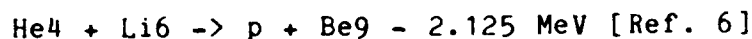
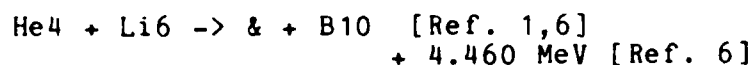
These reactions are listed by increasing atomic number of the target nuclide.





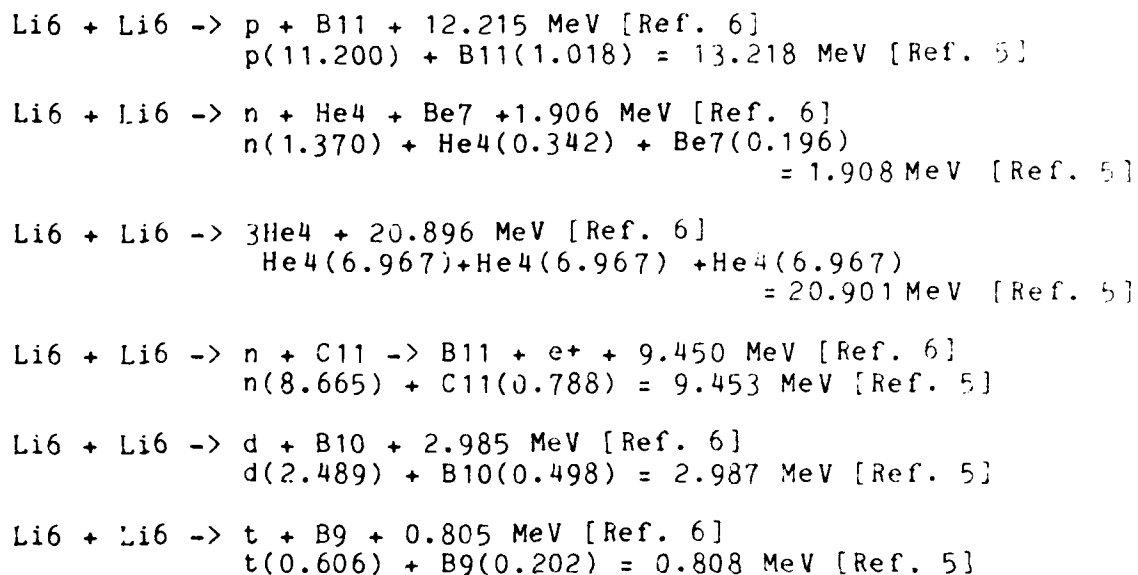
HELIUM-4--INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.



LITHIUM-6--INDUCED REACTIONS

These reactions are listed by increasing atomic number of the target nuclide.



CANDIDATE REACTIONS FOR FUSION PROPULSION SYSTEMS

Using the reaction bibliography as a reference, the following charged particle reactions listed on the next four pages were chosen to be of special interest for advanced reactors for propulsion based on the following criteria:

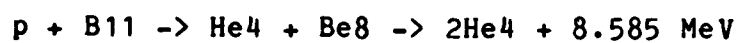
- 1) Reaction produces no neutrons.
- 2) Reaction produces no gamma-rays.
- 3) Reactions are exothermic.
- 4) Reacting isotopes occurring naturally on Earth.

There were many other reactions that met the criteria of 1, 2, and 3, but couldn't be included because one of the reacting isotopes doesn't occur naturally on Earth in sufficient quantities to be extracted economically from present sources, i.e., Helium-3 and tritium.

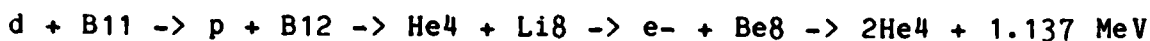
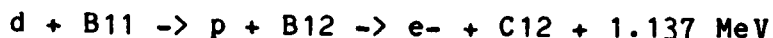
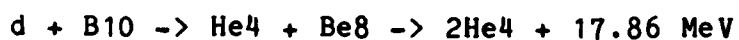
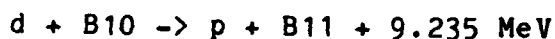
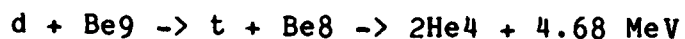
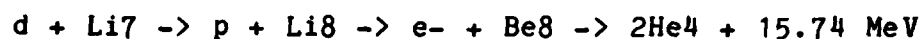
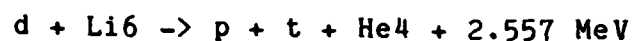
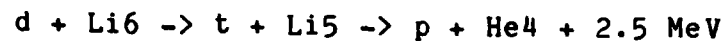
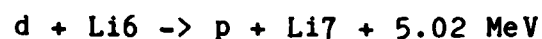
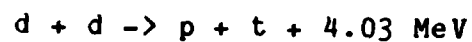
These reactions are arranged in ascending order by the atomic number of the incident particle. All reactions are of equal value with respect to this list.

This list will be used as the starting point for further study to determine the best fuel cycle to use for a fusion powered propulsion system.

PROTON-INDUCED REACTIONS



DEUTERON-INDUCED REACTIONS



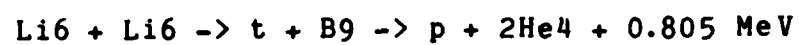
HELIUM-4--INDUCED REACTIONS

$\text{He4} + \text{B10} \rightarrow \text{p} + \text{C13} + 4.08 \text{ MeV}$

$\text{He4} + \text{B10} \rightarrow \text{d} + \text{C12} + 1.40 \text{ MeV}$

$\text{He4} + \text{B11} \rightarrow \text{p} + \text{C14} + 0.75 \text{ MeV}$

LITHIUM-6--INDUCED REACTIONS



REFERENCES

1. Flugge, S., Encyclopedia of Physics-Nuclear Reactions 1, Vol. 40, Springer-Verlag oHG, Berlin-Göttingen-Heidelberg, 1957.
2. Crocker, V. S., Blow, S., and Watson, C. J. H., Nuclear Cross-Section Requirements for Fusion Reactors, CLM-P240, Culham Laboratory, Abingdon, Berkshire, England, 1970.
3. Glasstone, G. and Loveberg, R. H., Controlled Thermonuclear Reactions, ISBN 0-88275-326-6, Litton Educational Publishing, INC., Huntington, New York, 1960.
4. Book, D. L., NRL Plasma Formulary, NRL Publication, 0084-4040.
5. McNally, J. R., Jr., Fusion Reactivity Graphs and Tables for Charged Particle Reactions, ORNL/TM-6914, August 1979.
6. Miley, G., Feldbacher, R., and Heindler, M., Requirements for Charged Particle Light Isotopes Reaction Data for Advanced Fuel Cycles, Including Two Step Reaction Mechanism, Alternate Energy Physics Program, Technical University Graz, Austria, and University of Illinois, 1986.
7. Mughabghab, S.F., and Garber, D. I., Neutron Cross Sections, Volume 1, Resonance Parameters, BNL-325, 3rd. Ed., Vol. 1, June 1973.
8. EXFOR Library, Brookhaven National Laboratory, Upton, Long Island, New York.

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