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# CHARGED PARTICLE NUCLEAR CROSS SECTIONS FOR ADVANCED FUSION FUELS

Rainer Feldbacher

Alternate Energy Physics Program, Institute for Theoretical Physics,
Graz University of Technology, Petersgasse 16, A-8010 Graz, Austria

Abstract: A nuclear reaction cross section data compilation is being developed for nuclear reactions among light charged isotopes ($Z \leq 5$). This compilation aims to meet nuclear data requirements in the frame of the investigation of advanced fusion fuel cycles. Important reactions that have an impact on the properties of advanced fuels are identified. The compilation contains experimental as well as evaluated data from the literature and a comprehensive bibliography. The status of the data and the reliability of existing evaluations are reviewed. For many reactions recommended cross sections have been identified based on a qualitative assessment of the different data sources. The data are presented in a unique form on plots and files. A few examples are shown in this paper.

(cross sections, compilation, charged particles, advanced fusion fuels)

## Introduction

The main emphasis of the fusion related work on nuclear data measurement, evaluation and compilation is on the 14 MeV-neutrons originating from the DT-reaction and interacting with various fusion device materials.

However, charged particle data for nuclear reactions among fuel isotopes are also required. There is apparently no doubt that the reaction

$$T(d,n)\alpha + 17589 \text{ keV}$$

will be the basis for the proof of fusion feasibility, and the first generations of fusion reactors are expected to operate utilizing this nuclear reaction. The integral cross section for this reaction is now considered to be sufficiently known, due to measurements at Los Alamos /1/.

Subject of existing efforts, although at a much lower level compared to DT-fusion research, is the search for a way to get around the well known problems associated with DT-fusion by investigation of other mixtures of light isotopes, so-called advanced fusion fuels. The prospects for a neutron- and radioactivity lean fusion are a good motivation for basic research on advanced fusion fuels, even if this way is accompanied by larger physical problems and by preliminary pessimistic results in particular for exotic, proton based fuels in magnetically confined systems. However, the physics of high temperature advanced fuel fusion plasmas is not well understood, and the commonly used plasma description may not properly account for crucial high temperature effects in advanced fuels.

A point of particular interest is the nuclear data base for the variety of nuclear reactions occuring among the various isotopes contained or produced in a burning advanced fuel. That data base is still rather poor compared to the nuclear data files for neutron reactions.

This paper discusses data requirements, exemplarily reports the status of data and presents a new compilation containing light isotope charged particle nuclear cross section data.

## Data requirements

### General

In the frame of the investigation of the intrinsic properties and potentials of advanced fusion fuels, there is a nuclear cross section data need for

(i) reactions determining the energy production in the fuel (exothermic main reactions of the main fuel isotopes);

(ii) reactions determining the dynamical behaviour of a burning fuel (subsequent reactions, competing channels, nuclear scattering, etc.);

(iii) reactions producing neutrons, radionuclides and gamma radiation, in order to investigate the radiological properties of a fuel.

### Isotopes

There is reason to believe that presently it is not a serious restriction if data include isotopes up to 11B only.

### Quantities

In case of reactions, the total cross section $\sigma(E)$, Maxwellian averaged reaction rate $\langle\sigma v\rangle(T)$, and beam-Maxwellian averaged reaction rate $\langle\sigma v\rangle(E,T)$ are required.

The total cross section and the angular distribution $d\sigma/d\omega(E,\theta)$ are required in the case of nuclear elastic and inelastic scattering.

### Energy range

Cross section data should cover an energy range up to about 10 times kT (T: fuel temperature). Data for reactions involving product nuclei or injected ions must cover the range up to their birth energy. In order to be on the safe side and in view of uncertainties regarding future advanced fuel reactor concepts data knowledge should cover energies up to 20 MeV.

## Charged particle library DATLIB

A light charged particle nuclear cross section compilation DATLIB /2/ is being developed in order to meet the requirements mentioned above, respectively in order to make possible an overview of the data knowledge and status. The present version of this compilation containes appr. 200 data sets (total cross sections, Maxwellian averaged reaction rates) for 80 nuclear reactions among isotopes up to 11B, and a comprehensive

bibliography. The most important items are described in the following.

Identification of reactions

A comprehensive list of approximately 300 reactions among isotopes up to 11B has been assembled. From this list those reactions have been identified that are important in the sense of the preceding chapter (see table 1). This identification has been done by accounting for their threshold energy, energy gain, reaction products, and abundance of the reactants in the burning fuel.

Bibliography

A comprehensive bibliography, subdivided by reactions, is part of the compilation. It is mainly condensed from /3/-/5/. which are only partly redundant. Those references have been selected that are interesting in our context.

Compilation of data

Several data compilations, mainly published in reports, exist and have been used as data source for our work /6/-/14/. Nevertheless, the original literature remains the most important source for light charged particle nuclear cross section data. Our compilation is nearly complete for Boron isotopes. Work is being continued for the other fuel cycles.

The original literature very often contains data in an inconvenient form, gives graphical data on small figures or gives only exemplary results. It is highly recommended to avoid these disadvantages by publishing data in tables in an internationally accessible file such as EXFOR /14/.

The ECPL /15/ is the only international available evaluated file for charged particle nuclear reaction data. It is optimized for user and computer application. Thus many information about evaluation method, data base, etc., is missing. To some extent the data show significant deviations to (recent) experiments. The 1982-version of ECPL has been included in DATLIB, the inclusion of an updated tape (1986-version) is in progress.

Recommended cross section

Based on this data compilation, a set of recommended cross sections could be identified and included in DATLIB. This recommendation is a result of a more or less qualitative evaluation of the different data sources. Anyway it represents the currently best known data for the majority of the reactions, and is recommended to be used until higher sophisticated evaluations are available.

## Data discussion

The data compilation developed by us renders possible an overview of existence and accuracy of the existing, widely spread published experimental data and an assessment of the reliability of existing evaluations. A data review in this sense has been published, e.g., in /16/.

In the following a few examples are shown. They are cases where the status of the data is pretty good compared to that of most reactions in table 1. In figs. 1-6 the data are indicated by author and year, and no further reference is given due to lack of space. The comprehensive bibliography in /2/ is available from the author.

3He(d,p)α

Existing discrepancies in older measurements seem to have been clarified by more recent experiments in the resonance region as well as at low energies. Fig.1 shows the cross section indicating several measurements and evaluations. Fig.2 shows the low energy region in terms of the astronomical S-function. At the resonance, the ECPL data fit quite well the recent measurements, a strange hump at the very top should be explained. At low energies, the Krauss fit should be used rather than the ECPL data.

A verification of the experimental data and a careful reevaluation should be performed for this very important reaction.

T(t,nn)α

Figs. 3 and 4 show the cross section and the S-function, resp. The ECPL data are identical with the evaluation by Hale and seem to be quite well. Recent measurements not yet included in our work /17/ improve the situation at low energies.

11B(p,αα)α, 11B(p,n)11C

The quality of the fit of evaluations to experimental data can be seen for these two reactions on figs. 5 and 6, resp. The solid curve signed 'AEP' is the recommended data of this work.

## Conclusion

A light charged particle nuclear cross section library is being developed. Evidently there are severe lacks of data regarding existence and availability of measurements and evaluations, both with respect to reactions and with respect to the energy range covered. Gaps and large deviations between different sources exist. Sophisticated evaluation methods (e.g. R-matrix analysis) have been applied to only a few reactions.

## Acknowledgement

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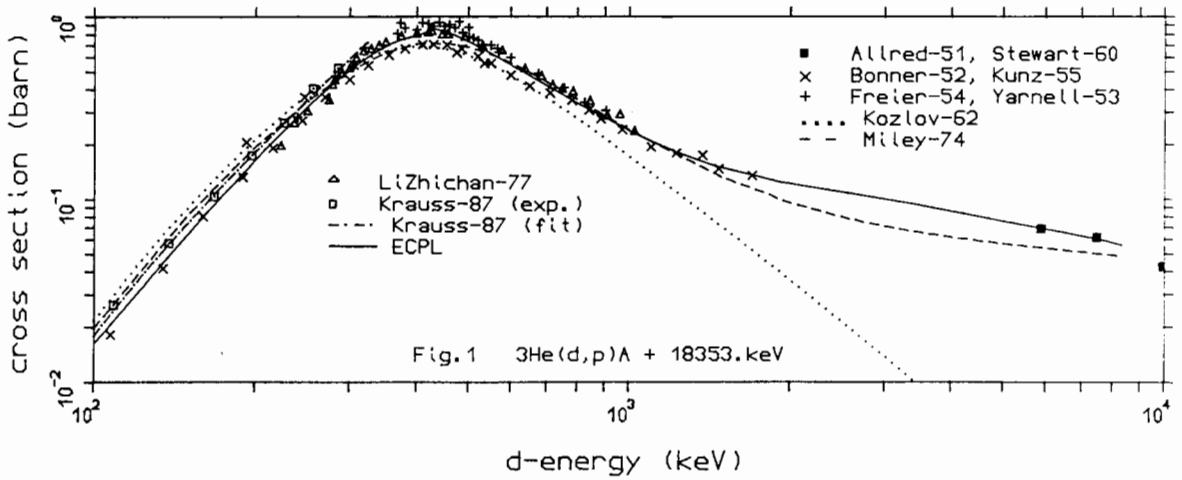
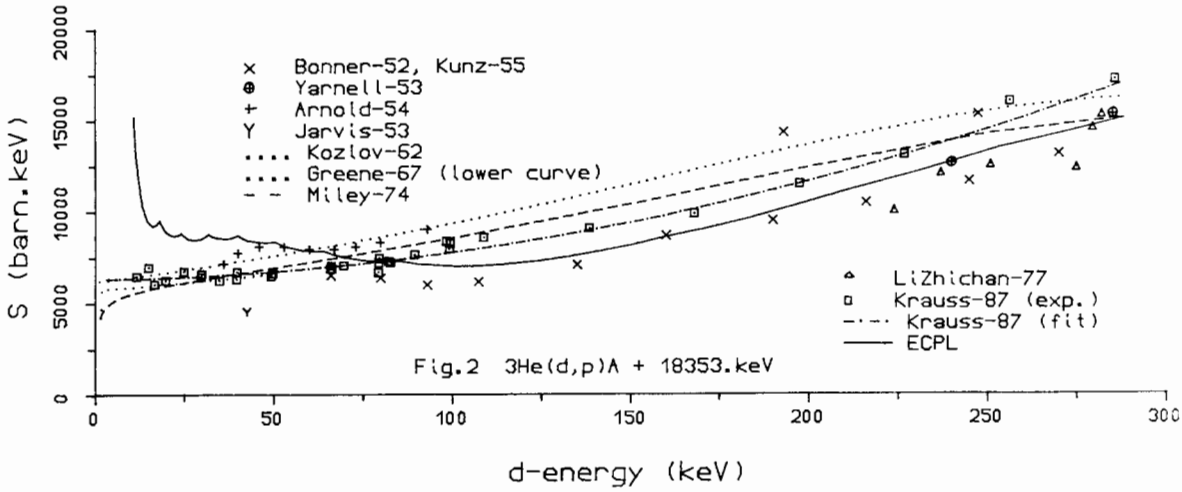
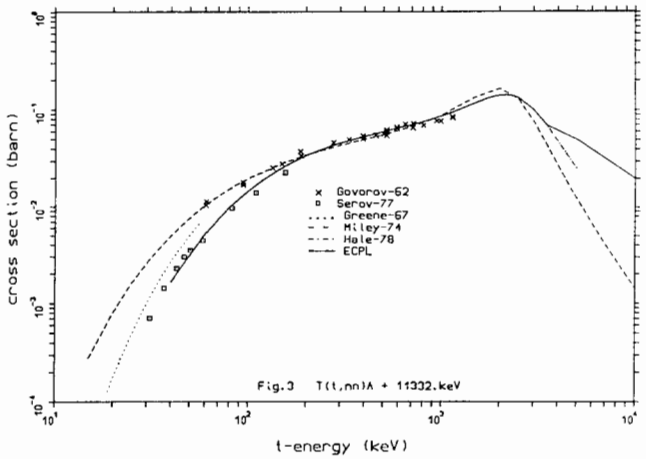
Table 1. Key reactions in D-3He, p-6Li resp. D-6Li, and p-11B fuel.
Overview of relevant information contained in several compilations and evaluations.

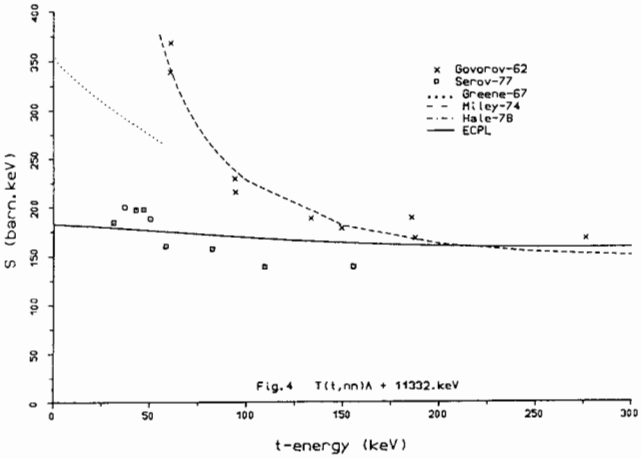
| Reaction (1) | Q [keV] | Jarmie (2) | EXFOR (3) | Fowler (4) | McNally (5) | others (6) | ECPL (7) 82 | ECPL (7) 86 | DATLIB (8) | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3He ( d , p ) α | + 18353 | + | + | + | + | G D M H P | + | (+) | 16 + 4 | * |
| D ( d , n ) 3He | + 3269 | + | + | + | + | G D M H P | + | (+) | 1 + 2 | * |
| D ( d , p ) T | + 4033 | + | + | + | + | G D M H P | + | (+) | 1 + 3 | * |
| T ( d , n ) α | + 17589 | + | + | + | + | G D M H P | + | + | 2 + 4 | * |
| 3He ( 3He, pp ) α | + 12860 | | | + | + | | | | 6 + 3 | * |
| 3He ( t , np ) α | + 12096 | + | | + | + | G M | | + | 10 + 5 | * |
| 3He ( t , d ) α | + 14320 | + | | + | + | G M | | + | 4 + 3 | * |
| T ( t , nn ) α | + 11332 | + | + | + | + | G M P | + | (+) | 6 + 3 | * |
| D ( p , np ) P | - 2225 | | (+) | + | | | | | 3 + 2 | * |
| T ( p , n ) 3He | - 764 | + | + | + | + | | + | + | 2 + 3 | * |
| T ( p , np ) D | - 6257 | | (+) | | | | | | | |
| T ( p , nnp ) P | - 8482 | | (+) | | | | | | | |
| α ( d , np ) α | - 2225 | + | + | | | | | + | | |
| T ( d , nγ ) α | + 17589 | | | | | | | | | |
| 3He ( d , pγ ) α | + 18353 | | | | | | | | | |
| D ( p , γ ) 3He | + 5494 | + | | + | | | | | 3 + 2 | * |
| D ( d , γ ) α | + 23847 | | | | | | | | | |
| T ( p , γ ) α | + 19814 | + | | + | | | + | (+) | 2 + 2 | * |
| α ( d , γ ) 6Li | + 1475 | | | | | | | | | |
| α ( t , γ ) 7Li | + 2468 | | | + | | | | | 0 + 1 | |
| α ( 3He, γ ) 7Be | + 1588 | | + | + | | | | | 1 + 1 | |
| 6Li ( p , 3He ) α | + 4018 | + | + | + | + | | + | (+) | 1 + 3 | * |
| 6Li ( 3He, pα ) α | + 16878 | | | | + | | | + | 0 + 5 | |
| 6Li ( 3He, n ) 8B | - 1975 | | | | | | | | | |
| 6Li ( 3He, np ) 7Be | - 2112 | | | | | | | | | |
| 6Li ( 3He, d ) 7Be | + 112 | | + | | + | | + | (+) | 1 + 2 | * |
| 6Li ( d , α ) α | + 22371 | + | + | | + | G | + | (+) | 1 + 2 | * |
| 6Li ( d , n ) 7Be | + 3381 | + | + | | + | G | + | (+) | 1 + 2 | * |
| 6Li ( d , n3He ) α | + 1794 | + | (+) | | + | | | + | 0 + 1 | |
| 6Li ( d , p ) 7Li | + 5025 | + | + | | + | G | + | (+) | 1 + 2 | * |
| 6Li ( d , pt ) α | + 2557 | + | + | | + | G | + | (+) | 1 + 2 | * |
| 6Li ( α , p ) 9Be | - 2126 | | | | | | | + | | |
| 6Li ( α , dα ) α | - 1475 | | | | | | | + | | |
| 6Li ( 6Li, n ) 11C | + 9450 | | | | + | | | | 0 + 1 | |
| 6Li ( 6Li, n3Heα ) α | + 318 | | | | | | | | | |
| 6Li ( 6Li, nα ) 7Be | + 1906 | | + | | + | | | | 1 + 1 | * |
| 6Li ( 6Li, p ) 11B | + 12215 | | | | + | | | | 0 + 1 | |
| 6Li ( 6Li, pp ) 10Be | + 986 | | | | | | | | | |
| 6Li ( 6Li, ptα ) α | + 1082 | | | | + | | | | 0 + 1 | |
| 6Li ( 6Li, pα ) 7Li | + 3550 | | | | | | | | | |
| 6Li ( 6Li, d ) 10B | + 2985 | | | | + | | | | 0 + 1 | |
| 6Li ( 6Li, 3He ) 9Be | + 1892 | | | | | | | | | |
| 6Li ( 6Li, αα ) α | + 20896 | | | | + | | | | 0 + 1 | |
| 7Li ( p , α ) α | + 17346 | + | + | + | + | | + | (+) | 1 + 3 | * |
| 7Li ( d , nα ) α | + 15121 | + | (+) | + | + | | | + | 0 + 2 | |
| 7Li ( 3He, npα ) α | + 9628 | | | + | + | | | + | 0 + 2 | |
| 7Li ( 3He, p ) 9Be | + 11201 | | | | | | | + | | |
| 7Li ( 3He, dα ) α | + 11852 | | | | | | | + | | |
| 7Li ( 3He, α ) 6Li | + 13328 | | | | | | | + | | |
| 7Be ( d , pα ) α | + 16766 | | | + | + | | | | 0 + 2 | |
| 7Be ( 3He, ppα ) α | + 11272 | | | + | + | | | | 0 + 2 | |
| 6Li ( p , p ) 6Li | scatt. | | | | | | | | | |
| 6Li ( 3He, 3He ) 6Li | scatt. | | | | | | | | | |
| 6Li ( α , α ) 6Li | scatt. | | | | | | | | | |
| 11B ( p , αα ) α | + 8681 | + | + | + | + | M | + | (+) | 17 + 4 | * |
| 11B ( p , γ ) 12C | + 15956 | + | | + | | | | | 6 + 3 | * |
| 11B ( p , n ) 11C | - 2764 | + | + | + | | | + | (+) | 6 + 3 | * |
| 11B ( α , n ) 14N | + 157 | + | | | | | | | 3 + 1 | * |
| 11B ( α , p ) 14C | + 783 | | + | | | | | | 4 + 1 | * |
| 11B ( α , t ) 12C | - 3858 | | | | | | | | | |
| 11B ( 11B, x ) X | | | | | | | | | 2 + 1 | * |
| 10B ( p , 3Heα ) α | - 442 | + | | | | | + | (+) | 1 + 1 | * |
| 10B ( p , α ) 7Be | + 1146 | + | (+) | + | | | + | (+) | 5 + 2 | * |
| 10B ( α , n ) 13N | + 1058 | + | + | | | | | | 1 + 0 | * |
| 10B ( α , p ) 13C | + 4061 | + | | | | | | | | |
| 10B ( α , d ) 12C | + 1339 | + | | | | | | | | |
| 11B ( d , γ ) 13C | + 18678 | | | | | | | | | |
| 11B ( d , n ) 12C | + 13732 | + | | | | | + | (+) | 1 + 1 | * |
| 11B ( d , p ) 12B | + 1145 | + | + | | | | + | (+) | 2 + 1 | * |
| 11B ( d , α ) 9Be | + 8031 | | | | | | | | | |
| 10B ( d , γ ) 12C | + 25186 | | | | | | | | | |
| 10B ( d , n ) 11C | + 6465 | + | + | | | | + | (+) | 5 + 1 | * |
| 10B ( d , p ) 11B | + 9230 | + | | | | | + | (+) | 9 + 1 | * |
| 10B ( d , αα ) α | + 17911 | | | | | | + | (+) | 4 + 1 | * |
| 11B ( p , p ) 11B | scatt. | | | | | | | | | |
| 11B ( α , α ) 11B | scatt. | | | | | | | | | |

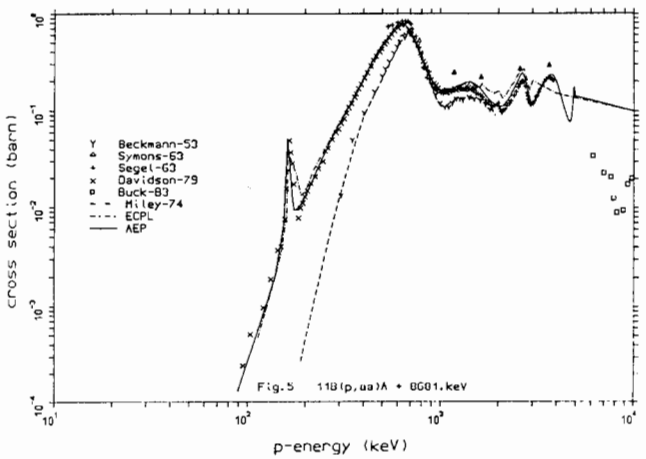
(1) Selection of most important reactions in the frame of advanced fusion fuel research, energy gain in keV, 'scatt': elastic and inelastic nuclear scattering.
(2) Source: /6/; '+': data contained.
(3) Exfor retrieval 15.9.1986; '+': directly evaluable data type; '(+)': not directly evaluable.
(4),(5) Sources: /7/,/8/,resp.; '+': data contained; completely included in DATLIB.
(6) Sorces: G:/10/, D:/11/, M:/9/, H:/12/, P:/13/; /9/ included in DATLIB, others partly redundant.
(7) 82-version: '+': data types of interest contained;
86-version: '(+)': no update since 1982; '+': new or updated data included since 1982.
(8) Source: /2/; 1. and 2. number: number of data files for σ(E) and <σv>(T), resp.;
'*': recommended data defined.

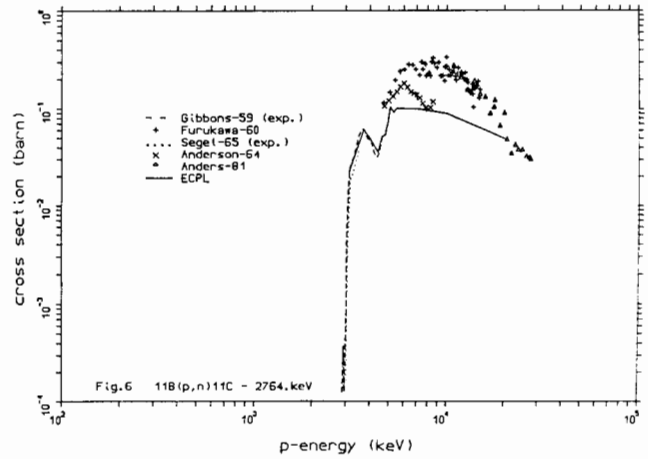

cross section (barn)
d-energy (keV)
Allred-51, Stewart-60
Bonner-52, Kunz-55
Freier-54, Yarnell-53
Kozlov-62
Miley-74
LiZhichan-77
Krauss-87 (exp.)
Krauss-87 (fit)
ECPL
Fig.1 3He(d,p)A + 18353.keV


S (barn.keV)
d-energy (keV)
Bonner-52, Kunz-55
Yarnell-53
Arnold-54
Jarvis-53
Kozlov-62
Greene-67 (lower curve)
Miley-74
LiZhichan-77
Krauss-87 (exp.)
Krauss-87 (fit)
ECPL
Fig.2 3He(d,p)A + 18353.keV


cross section (barn)
t-energy (keV)
Govorov-62
Serov-77
Greene-67
Miley-74
Hale-78
ECPL
Fig.3 T(t,nn)A + 11332.keV


S (barn.keV)
t-energy (keV)
Govorov-62
Serov-77
Greene-67
Miley-74
Hale-78
ECPL
Fig.4 T(t,nn)A + 11332.keV


cross section (barn)
p-energy (keV)
Beckmann-53
Symons-63
Segel-63
Davidson-79
Buck-83
Miley-74
ECPL
AEP
Fig.5 11B(p,aa)A + 8601.keV


cross section (barn)
p-energy (keV)
Gibbons-59 (exp.)
Furukawa-60
Segel-65 (exp.)
Anderson-64
Anders-81
ECPL
Fig.6 11B(p,n)11C - 2764.keV