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TITLE: Evaluation of the $d+t$ Cross Sections Based on an R-Matrix Analysis of the ^{5}He System

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Los Alamos

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EVALUATION OF THE $d+t$ CROSS SECTIONS BASED ON AN R-MATRIX ANALYSIS OF THE ^{5}HE SYSTEM

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Arguments Against:

Theory-based evaluation

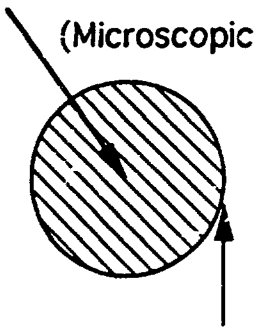
- Harder to do; takes longer.
- Limited ranges of mass, energy over which any one theory (model) is practical.
- Too much (approximate) theory $\Rightarrow$ bad representations of data.

Curve-fitting evaluation

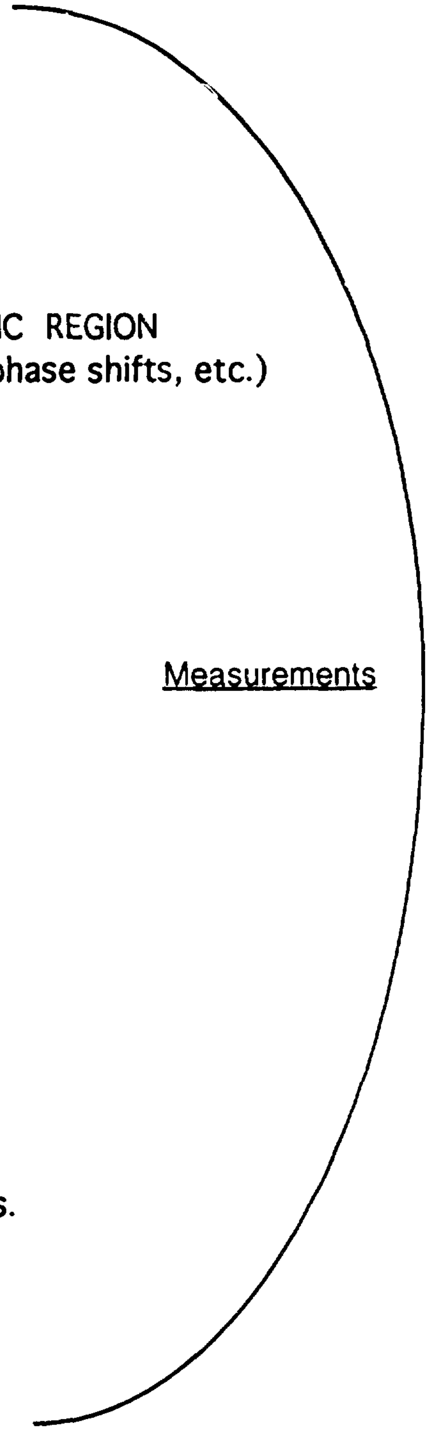
- Completely unconstrained by physical principles.
- Burden falls entirely on measurements to get reliable results.
- Can get *good* representations of *bad* data.

ASYMPTOTIC REGION
(S matrix, phase shifts, etc.)

INTERIOR REGION
(Microscopic Calculations)



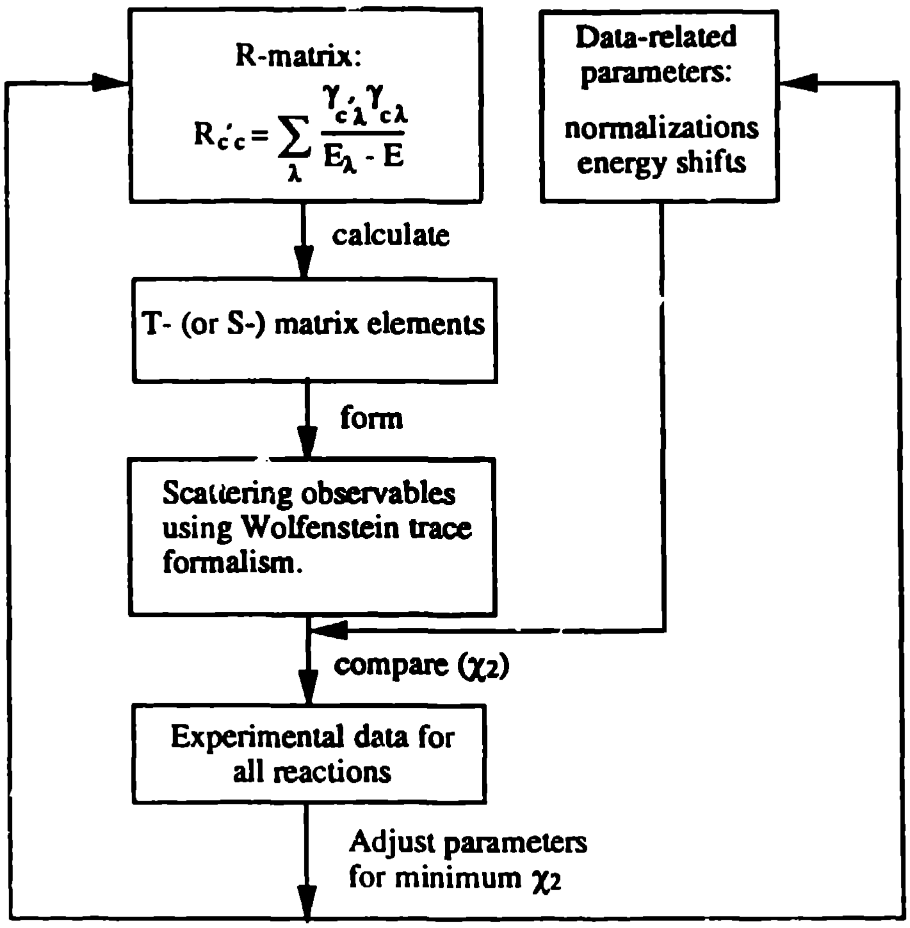
SURFACE



$$R_{c'c} = (c'|[H+\mathcal{L}-E]^{-1}|c) = \sum_{\lambda} \frac{\gamma_{c'\lambda}\gamma_{c\lambda}}{E_\lambda - E}$$

- builds in fundamental conservation laws, symmetries, and analytic properties (causality, unitarity, etc.) of nuclear reactions.
- parametrizes only interior quantities (correct Coulomb, angular-momentum barrier penetration built in).
- explicit energy dependence (poles) ideal for describing resonances.

Energy Dependent Analysis Code



Capabilities and Features

1) Accomodates general (spins, masses, charges) two-body channels

2) Uses relativistic kinematics and R-matrix formulation

3) Calculates general scattering observables for $2 \rightarrow 2$ processes

4) Has rather general data-handling capabilities

5) Uses modified variable-metric search algorithm that gives parameter covariances at a solution.

^5He System Analysis

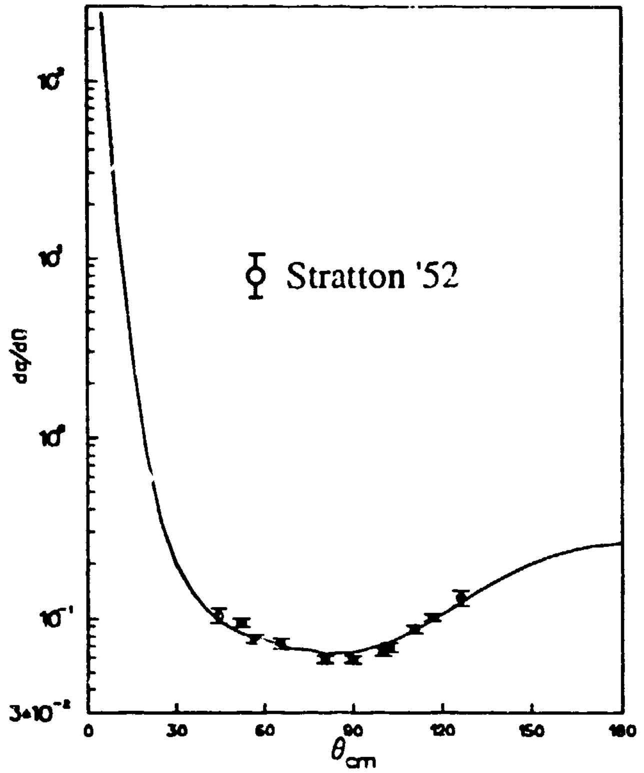
Channel	l_{max}	a_c (fm)
d-t	5	5.1
n-^{4}He	5	3.0
n-^{4}He*	1	5.0

Reaction	Energy Range	# Observable Types	# Data Points	χ^2
T(d,d)T	E_d=0-8 MeV	6	683	1284
T(d,n)^{4}He	E_d=0-10 MeV	14	1241	1727
T(d,n)^{4}He*	E_d=4.8-8 MeV	1	10	15
^{4}He(n,n)^{4}He	E_n=0-28 MeV	2	813	1108
	Totals:	23	2747	4134

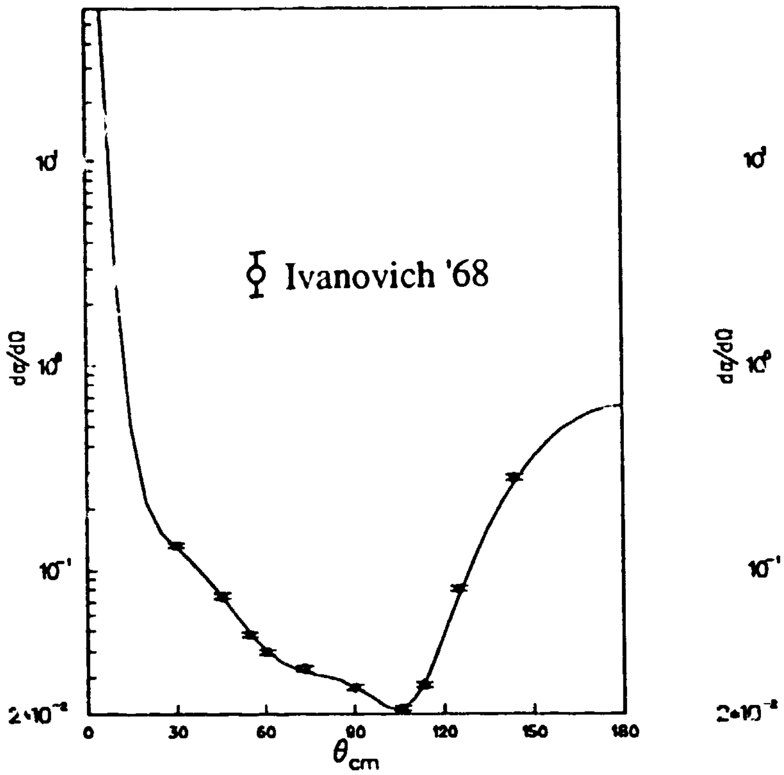
parameters = 117 $\Rightarrow \chi^2$ per degree of freedom = 1.57

[109 phase parameters are necessary to describe the S matrix at a single energy]

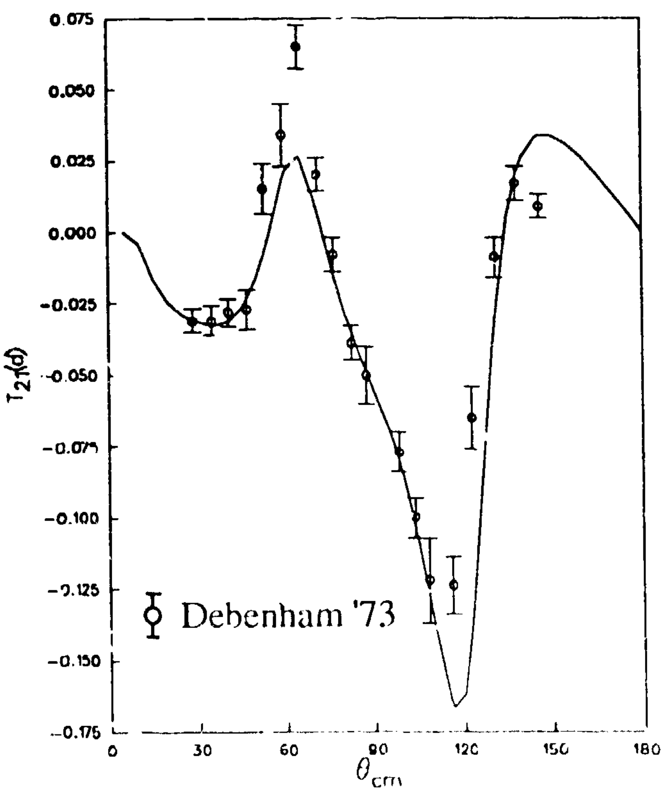
T(d,d)T 1.97 MeV



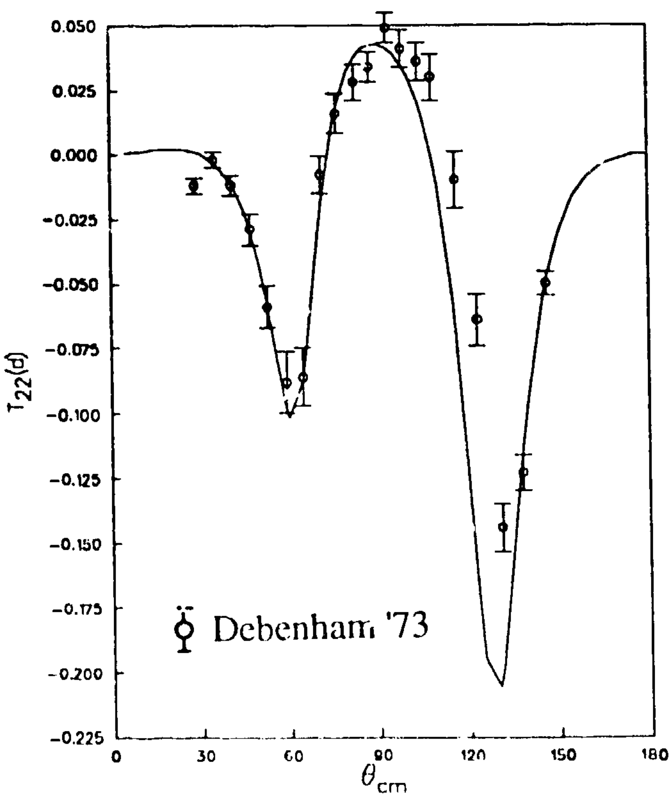
T(d,d)T 3.97 MeV



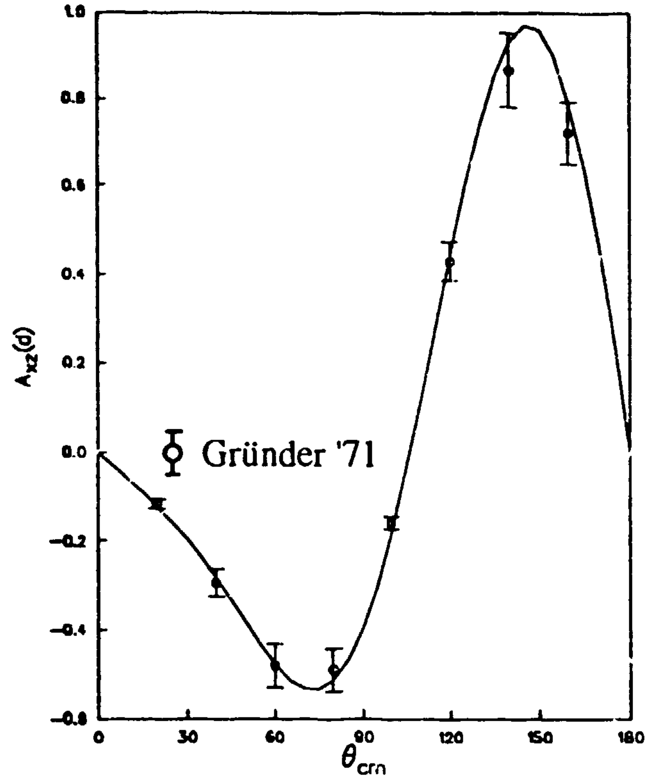
T(d,d)T 6.)0 MeV



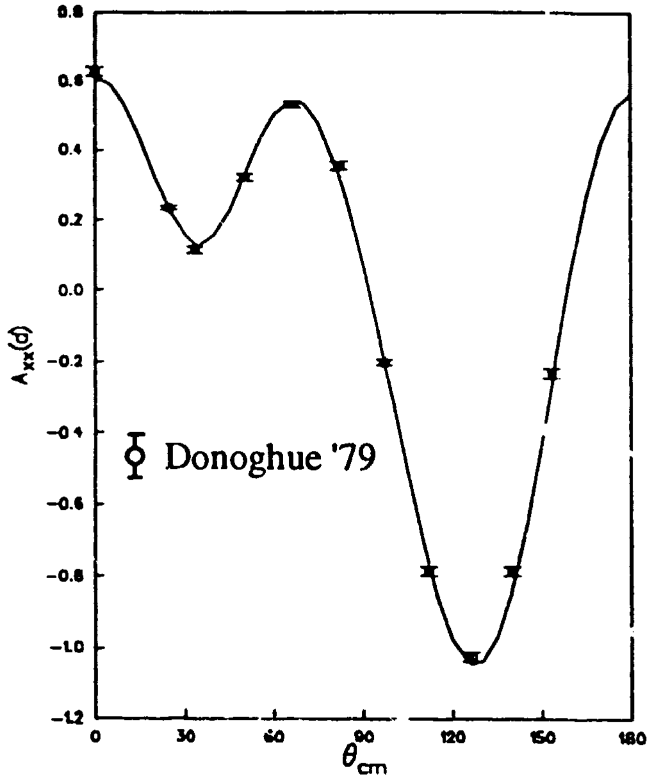
T(d,d)T 8.00 MeV



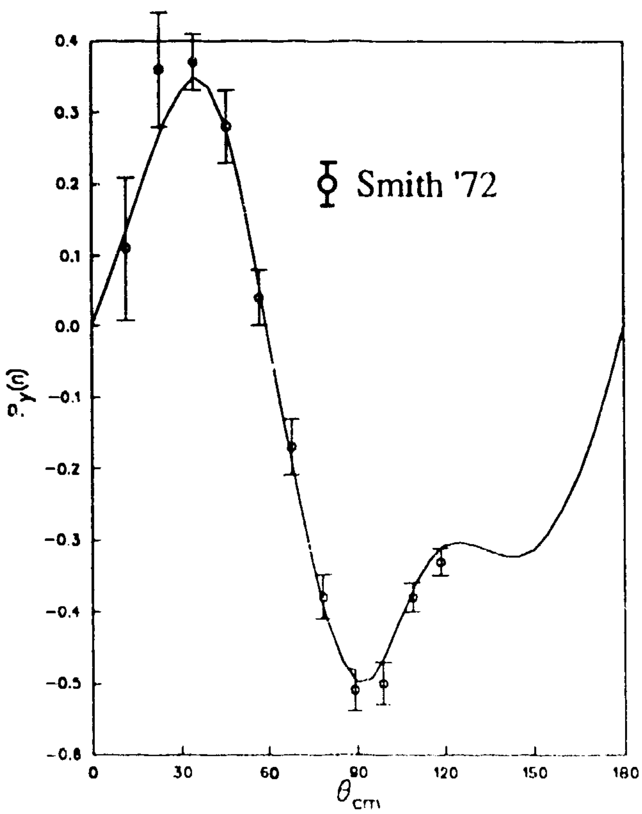
$T(d,n)^4He$ 1.00 MeV



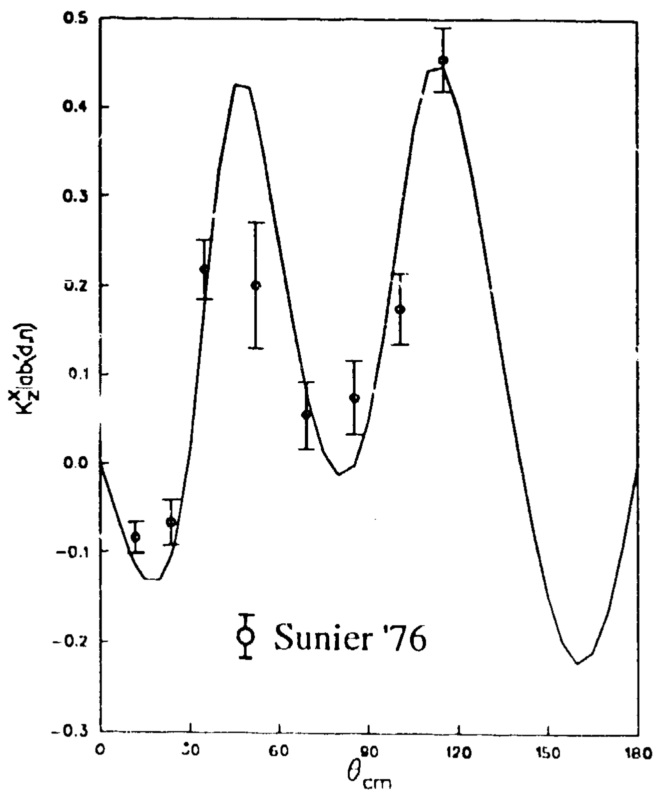
$T(d,n)^4He$ 3.00 MeV



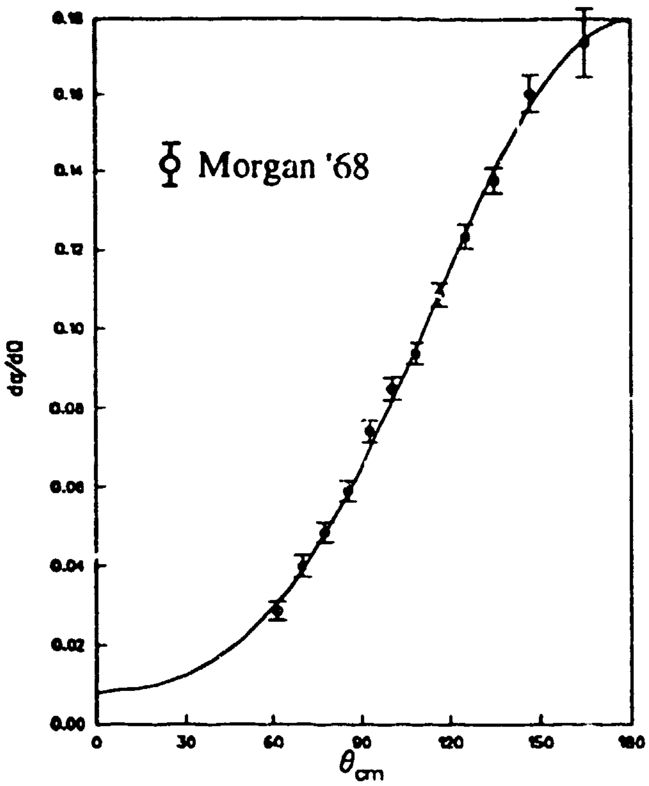
$T(d,n)^4He$ 5.00 MeV



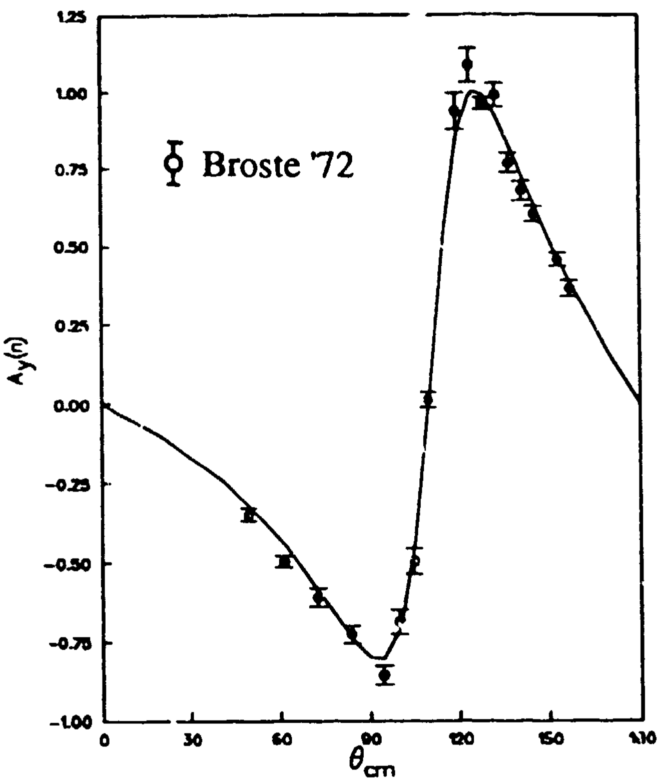
$T(d,n)^4He$ 7.00 MeV



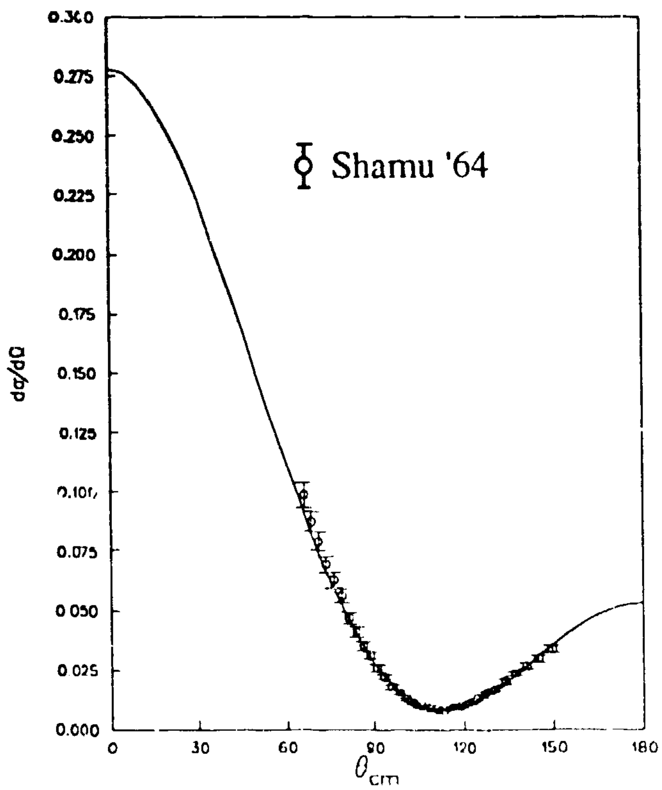
$^4He(n,n)^4He$ 0.31 MeV



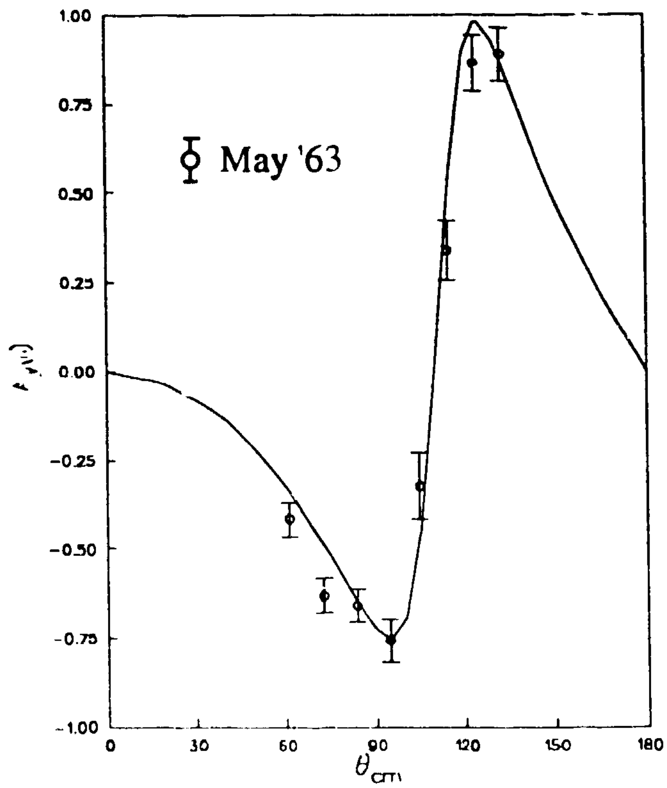
$^4He(n,n)^4He$ 11.0 MeV



$^4He(n,n)^4He$ 16.4 MeV



$^4He(n,n)^4He$ 16.4 MeV



Renormalization Factors for T(d,n) Cross-Section Data

Data set	Type	E_d (MeV)	Scale factor	Scale error (%)
Jarmie '84	$\sigma(E)$	0.008 - 0.070	1.017	1.26
Brown '87	$\sigma(E)$	0.053 - 0.116	1.025	- (rel.)
Bame '57	$\sigma(\theta)$	0.50	0.939	10
Bame '57	$\sigma(\theta)$	0.75	0.931	10
Bame '57	$\sigma(\theta)$	1.0	0.949	10
Bame '57	$\sigma(\theta)$	1.3	0.929	10
Bame '57	$\sigma(\theta)$	1.5	0.912	10
Bame '57	$\sigma(\theta)$	2.5	0.973	10
Bame '57	$\sigma(\theta)$	3.0	0.977	10
Bame '57	$\sigma(\theta)$	3.5	0.994	10
Bame '57	$\sigma(\theta)$	4.0	1.004	10
Bame '57	$\sigma(\theta)$	4.5	0.981	10
Bame '57	$\sigma(\theta)$	5.0	0.986	10
Bame '57	$\sigma(\theta)$	6.0	0.977	10
Bame '57	$\sigma(\theta)$	7.0	0.980	10
Paulsen '64	$\sigma(\theta)$	1.0	0.956	- (rel.)
Paulsen '64	$\sigma(\theta)$	3.0	0.974	- (rel.)
Ivanovich '68	$\sigma(\theta)$	4.2 - 10	1.016*	1.0
McDaniels '90**	$\sigma(\theta)$	5.0	0.996	1.5
McDaniels '90	$\sigma(\theta)$	6.0	0.980	1.5
Drosg '82	$\sigma(\theta)$	3.973	1.024	3.0
Drosg '78	$\sigma(0^\circ)$	7 - 10	0.986	1.5
Drosg '90	$\sigma(180^\circ)$	4.7 - 10	1.009	1.0
Goldberg '61	$\sigma(\theta)$	7.9	1.004	- (rel.)

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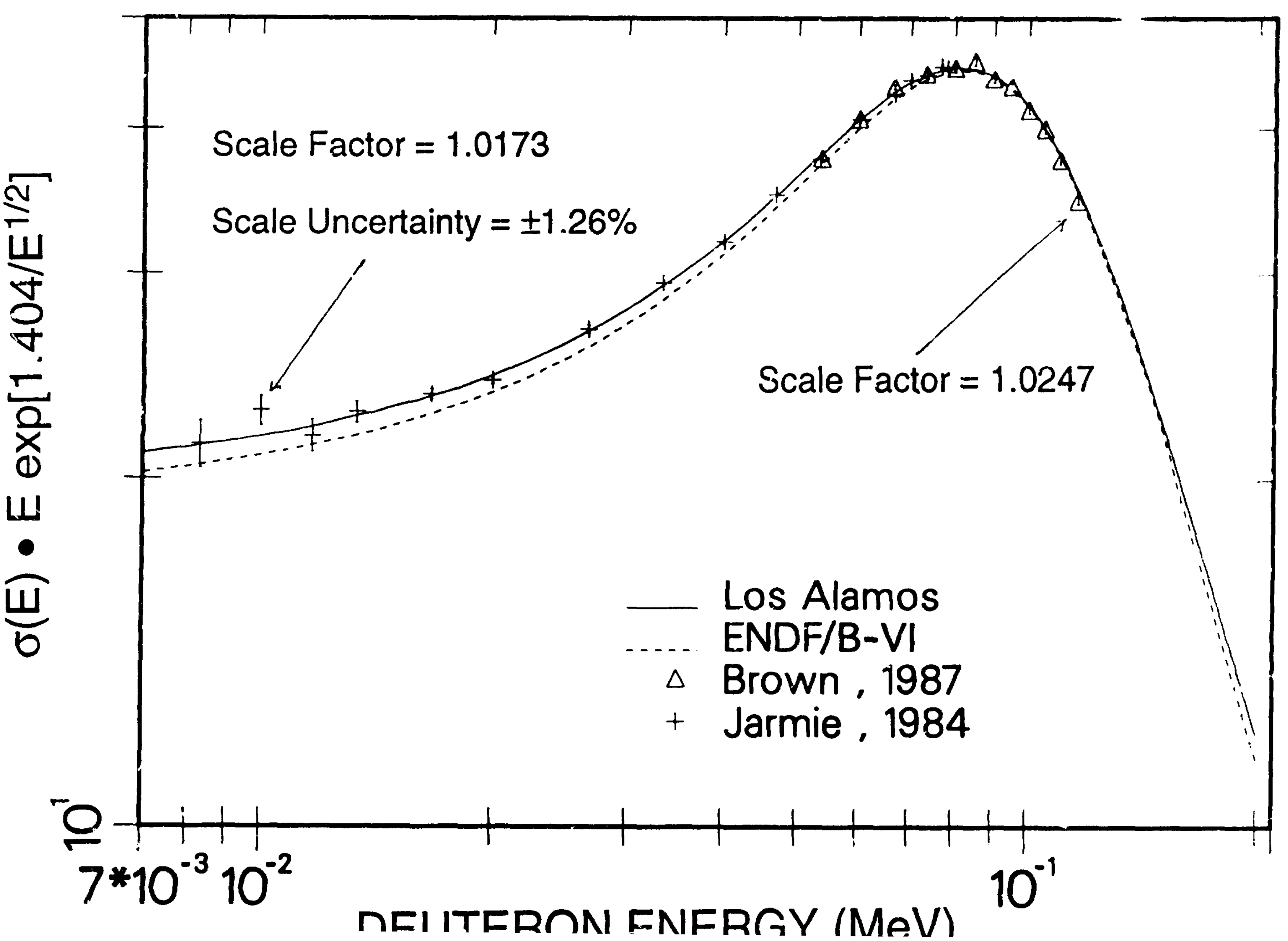
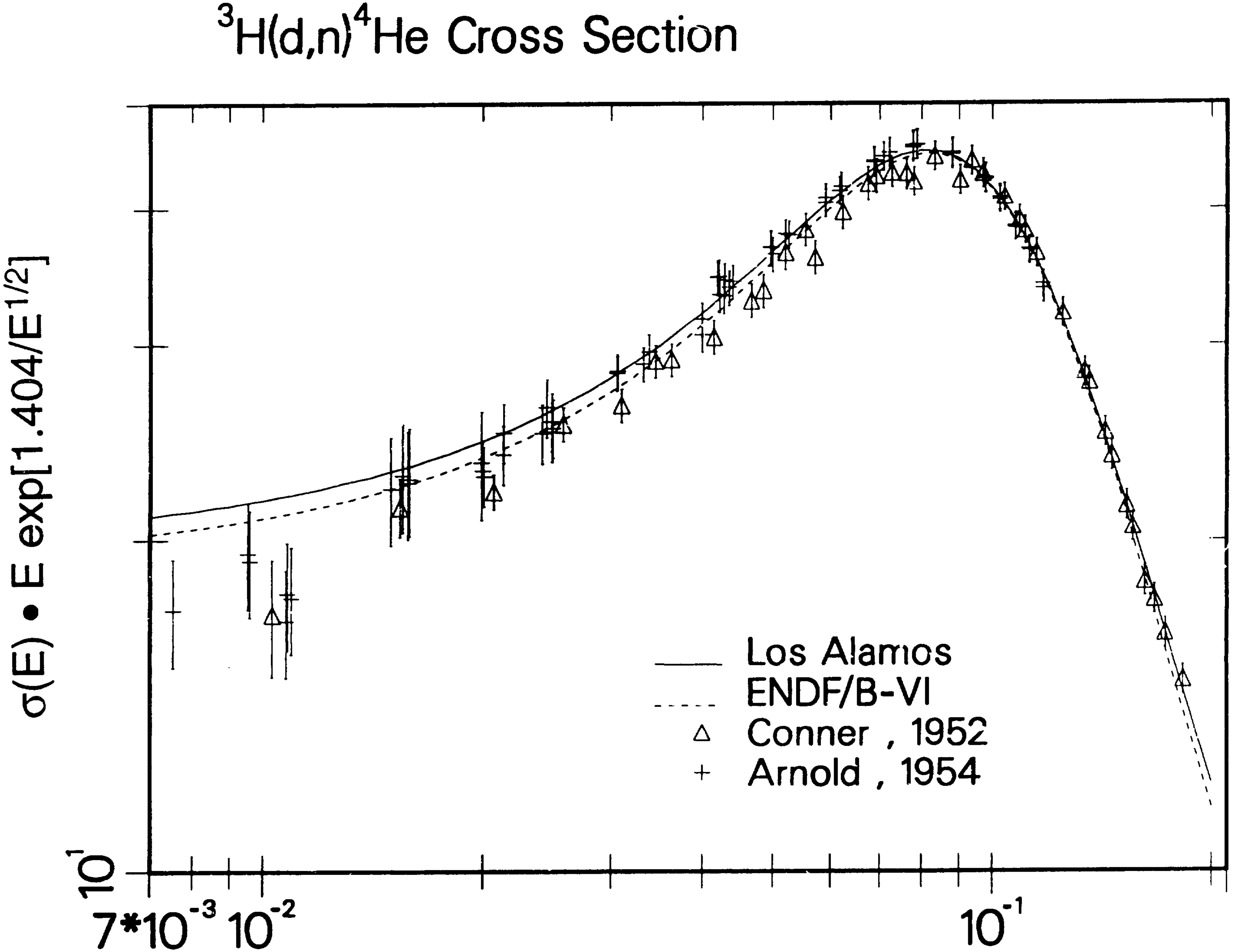
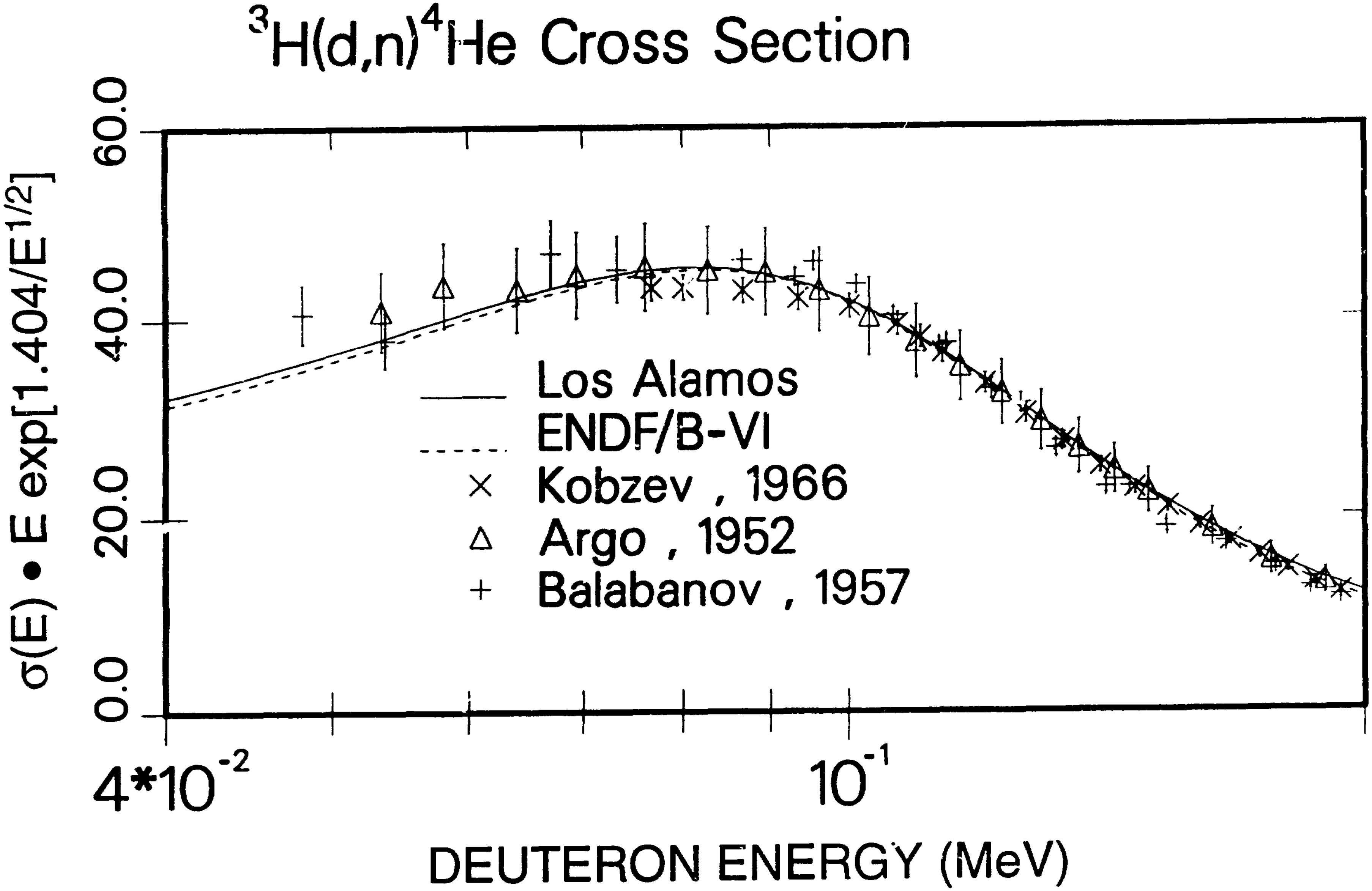
* Experimental scale value of 1.028 ±0.01 determined by Drosg

** Based on McDaniels '73 as revised by Drosg

$^3H(d,n)^4He$ Cross Section

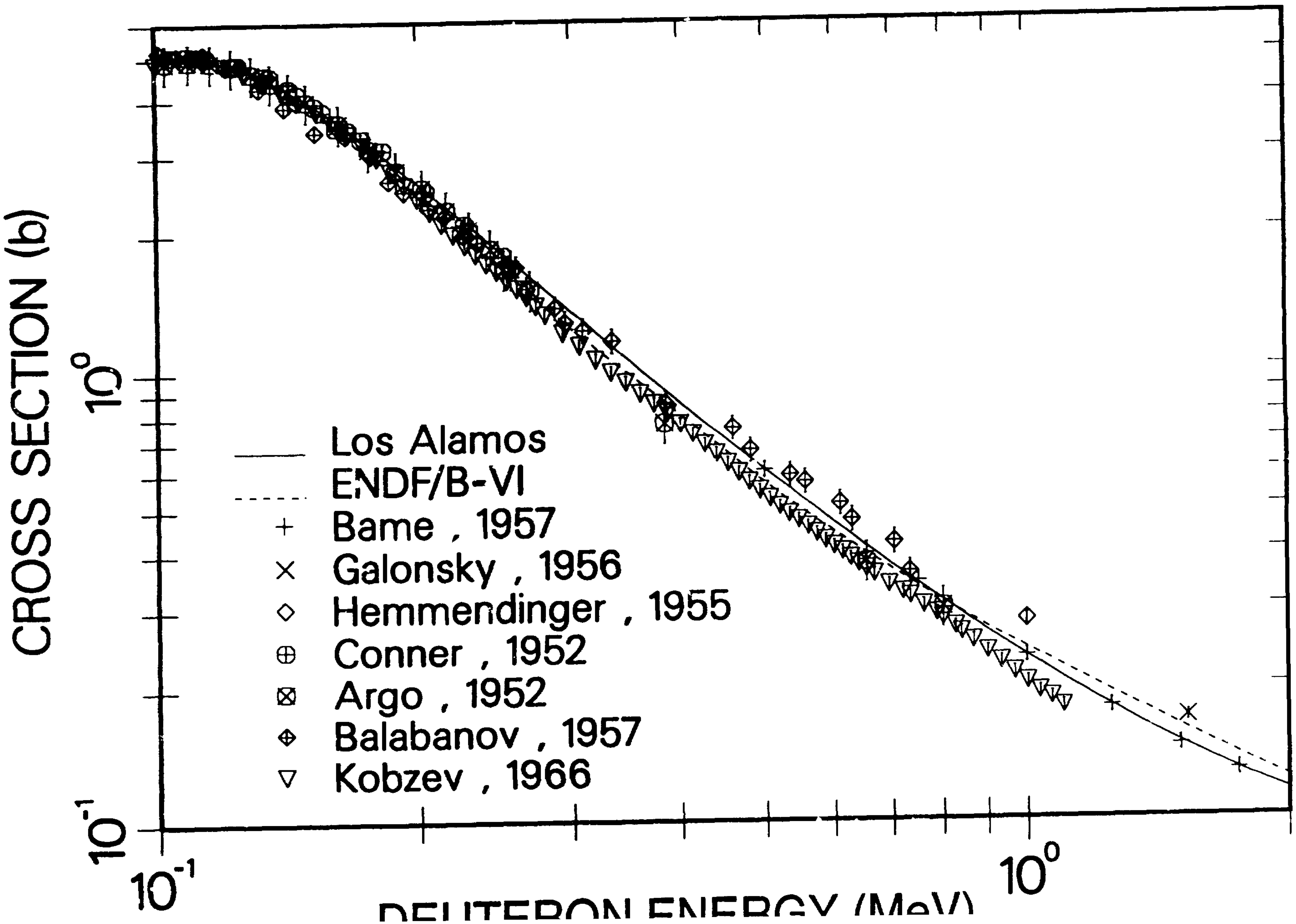


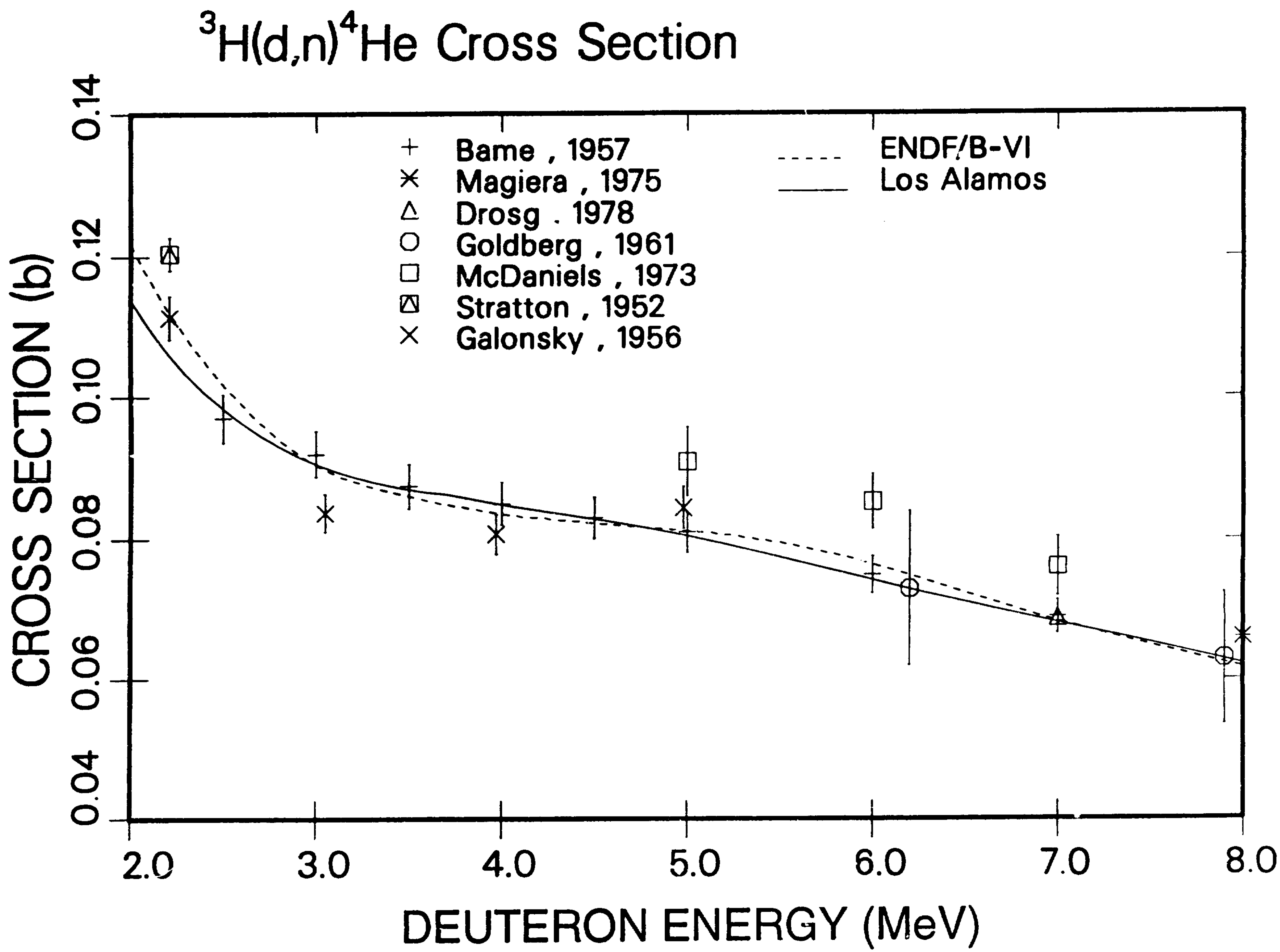

$^3H(d,n)^4He$ Cross Section
σ(E) • E exp[1.404/E^1/2]
10^1
7*10^-3 10^-2
10^-1
Los Alamos
ENDF/B-VI
Conner , 1952
Arnold , 1954



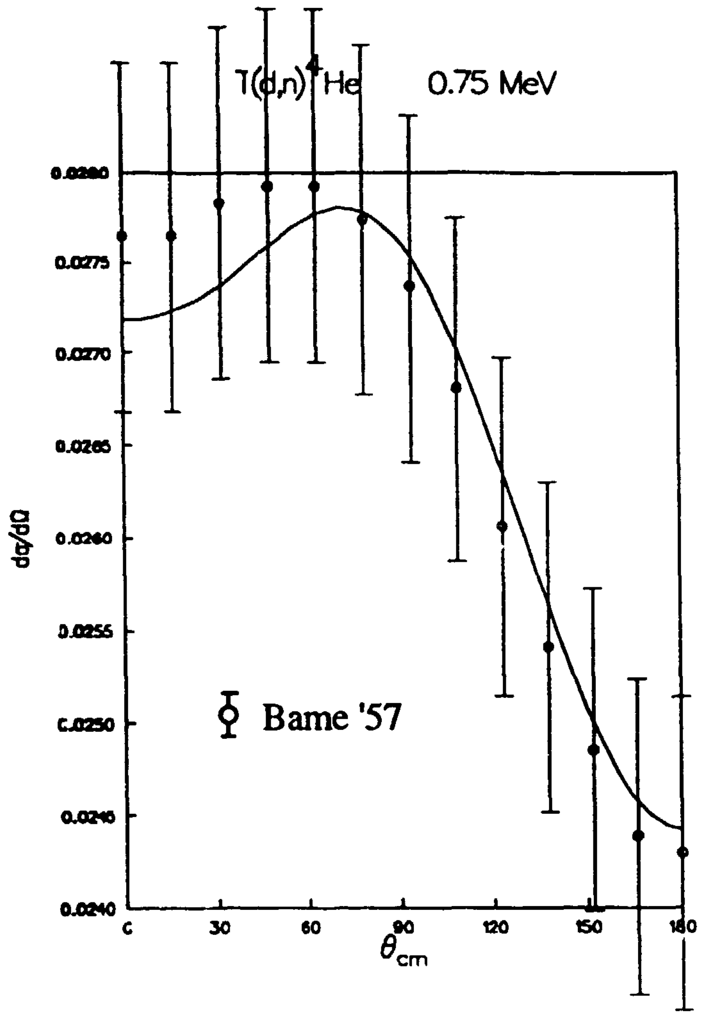
$^3H(d,n)^4He$ Cross Section
σ(E) • E exp[1.404/E^(1/2)]
60.0
40.0
20.0
0.0
Los Alamos
ENDF/B-VI
Kobzev , 1966
Argo , 1952
Balabanov , 1957
4*10^-2
10^-1
DEUTERON ENERGY (MeV)

$^3H(d,n)^4He$ Cross Section

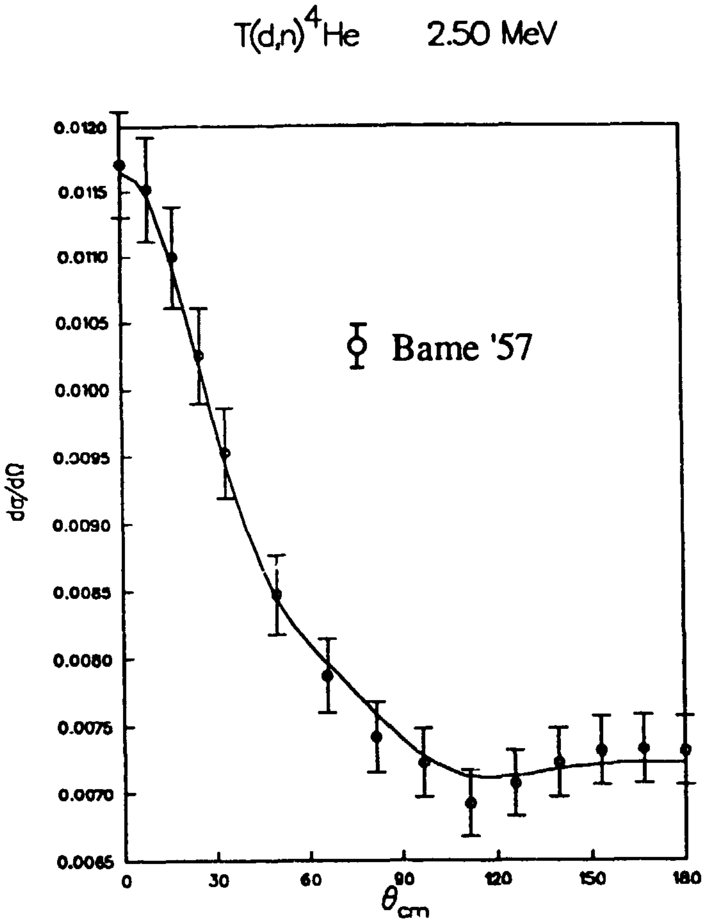




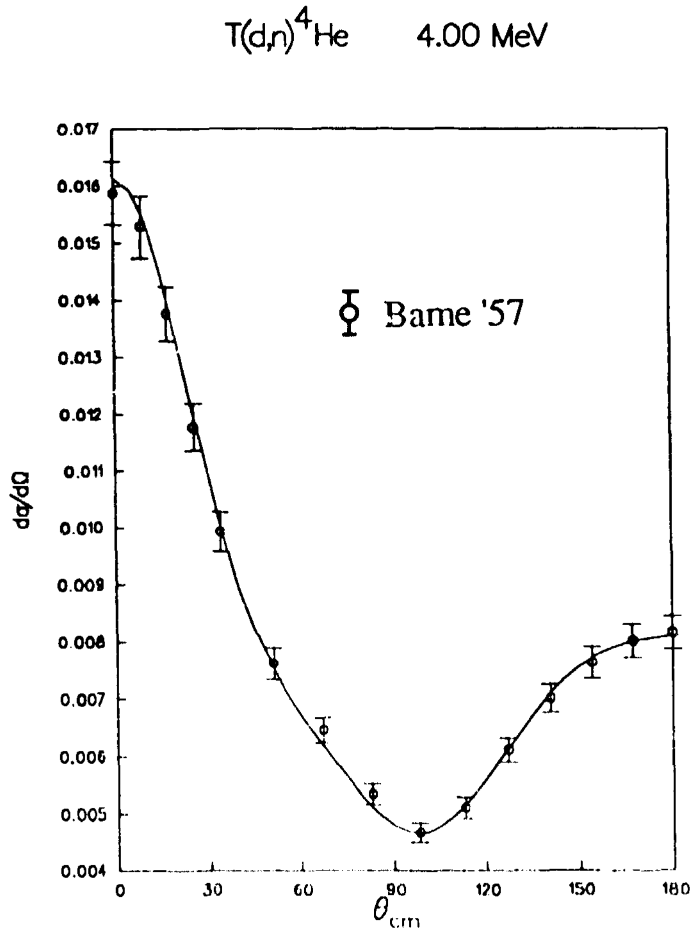
$^3H(d,n)^4He$ Cross Section
CROSS SECTION (b)
0.14
0.12
0.10
0.08
0.06
0.04
2.0
3.0
4.0
5.0
6.0
7.0
8.0
DEUTERON ENERGY (MeV)
Bame , 1957
Magiera , 1975
Drosg . 1978
Goldberg , 1961
McDaniels , 1973
Stratton , 1952
Galonsky , 1956
ENDF/B-VI
Los Alamos



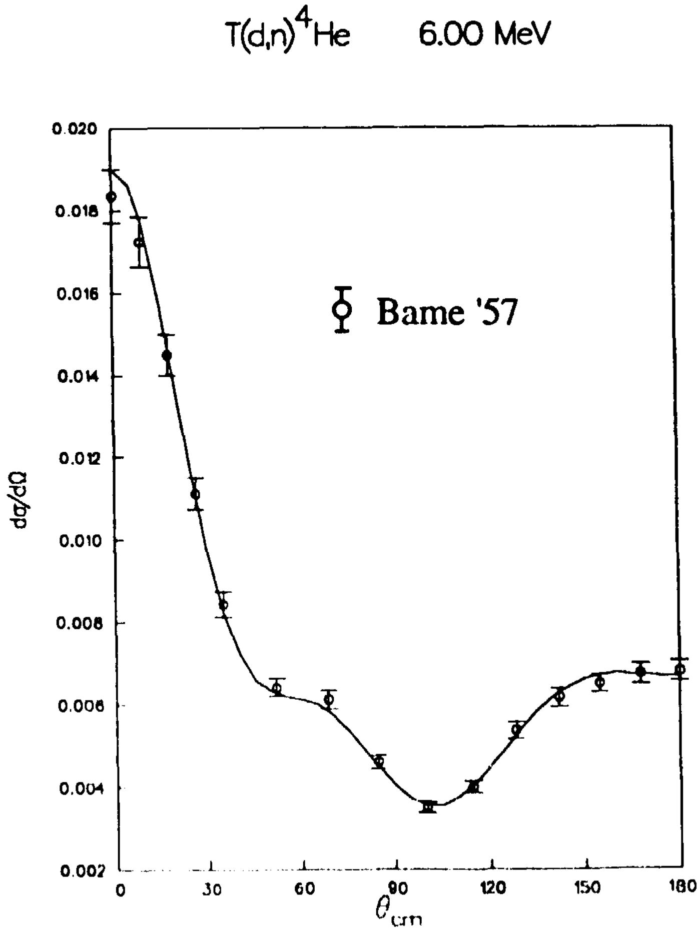
T(d,n)4He 0.75 MeV
Bame '57
dσ/dΩ
θcm



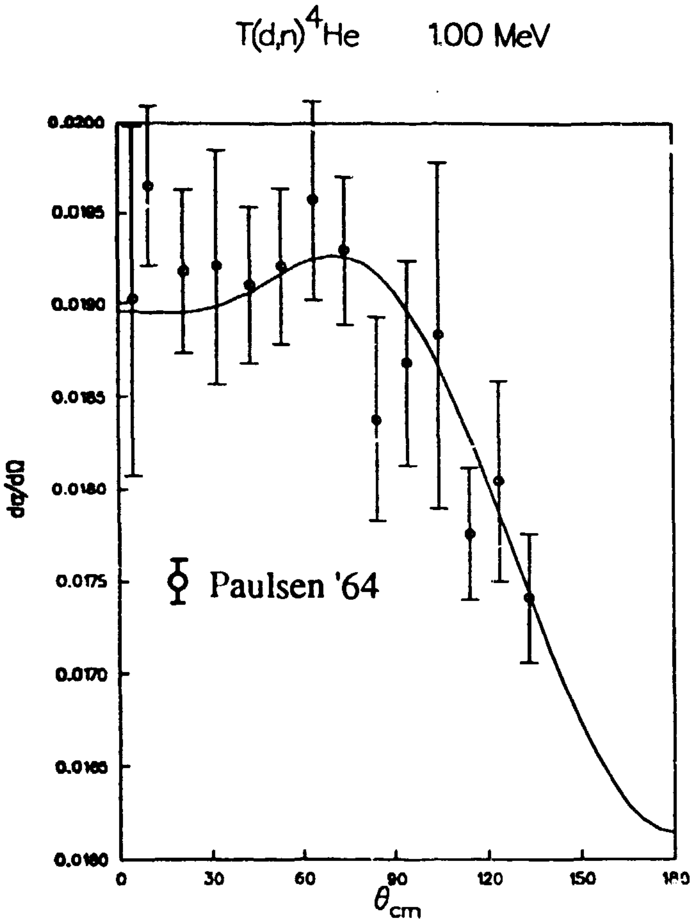
T(d,n)4He 2.50 MeV
Bame '57
dσ/dΩ
θcm

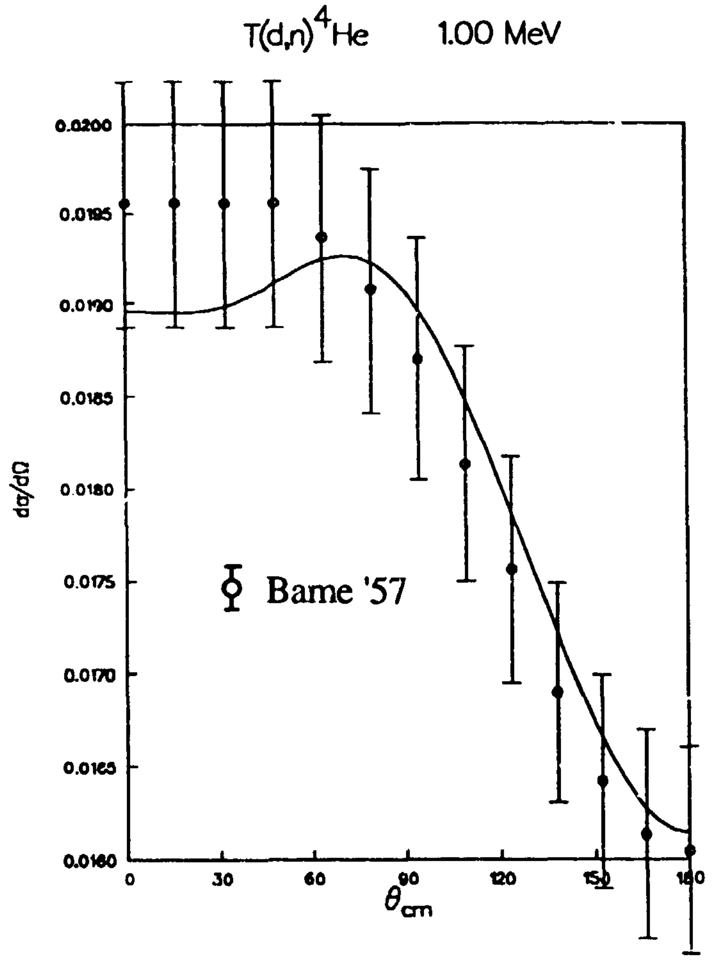


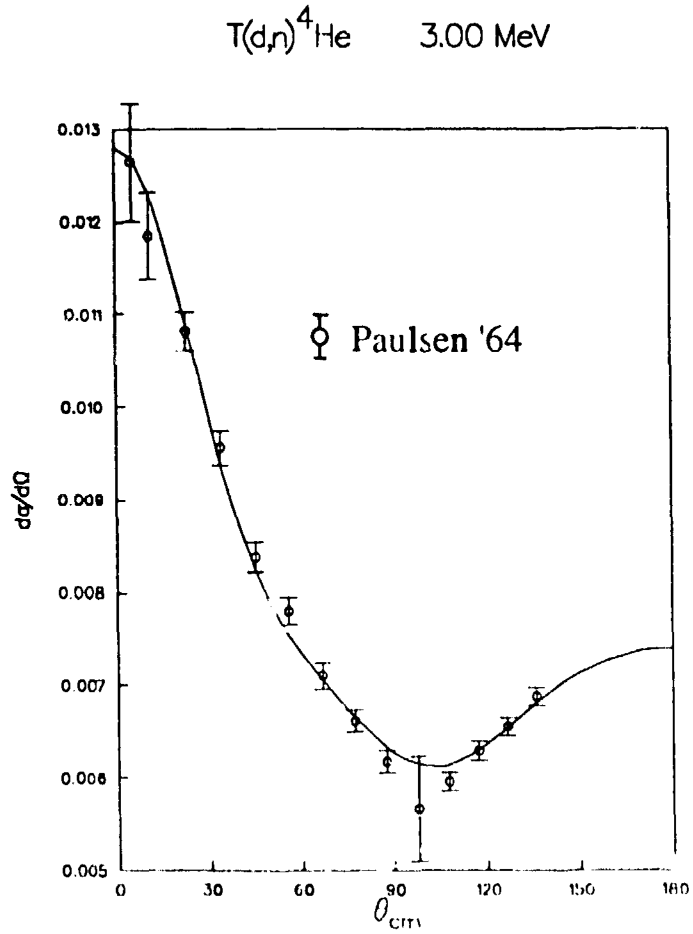
T(d,n)4He 4.00 MeV
Bame '57
dσ/dΩ
θcm

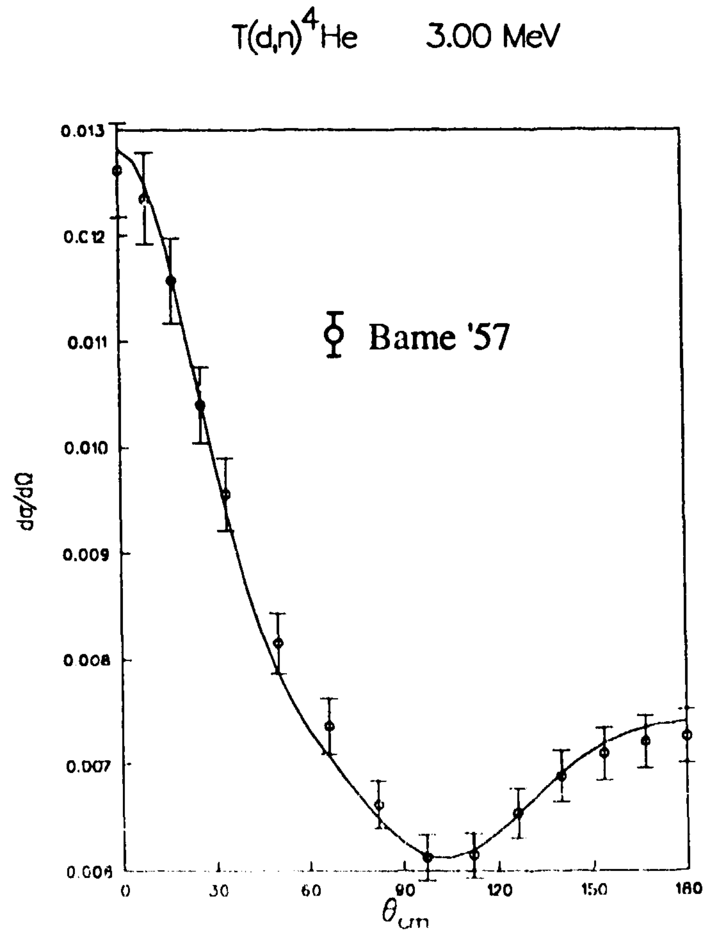


T(d,n)4He 6.00 MeV
Bame '57
dσ/dΩ
θcm

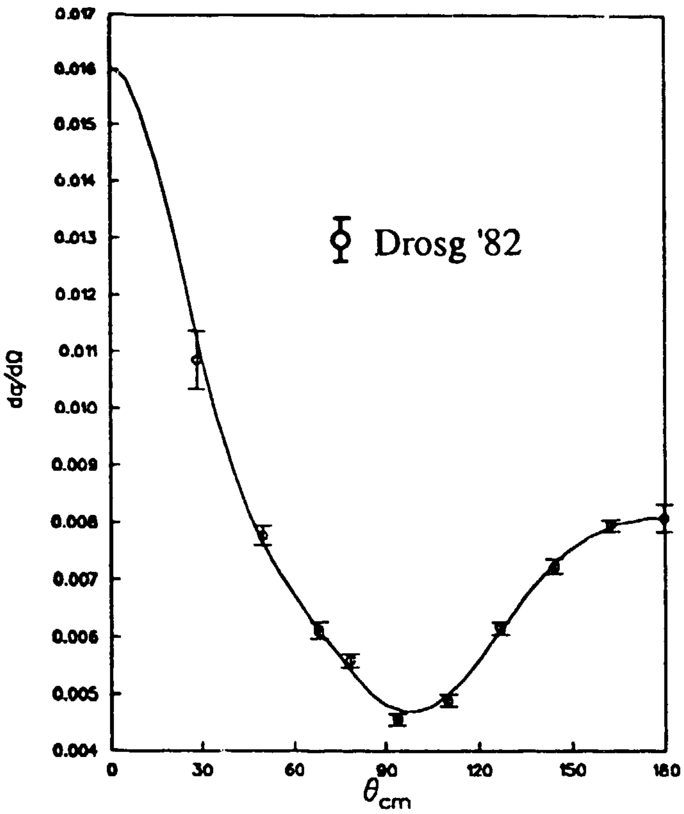

T(d,n)4He 1.00 MeV
Paulsen '64
dσ/dΩ
θcm


T(d,n)4He 1.00 MeV
Bame '57
dσ/dΩ
θcm

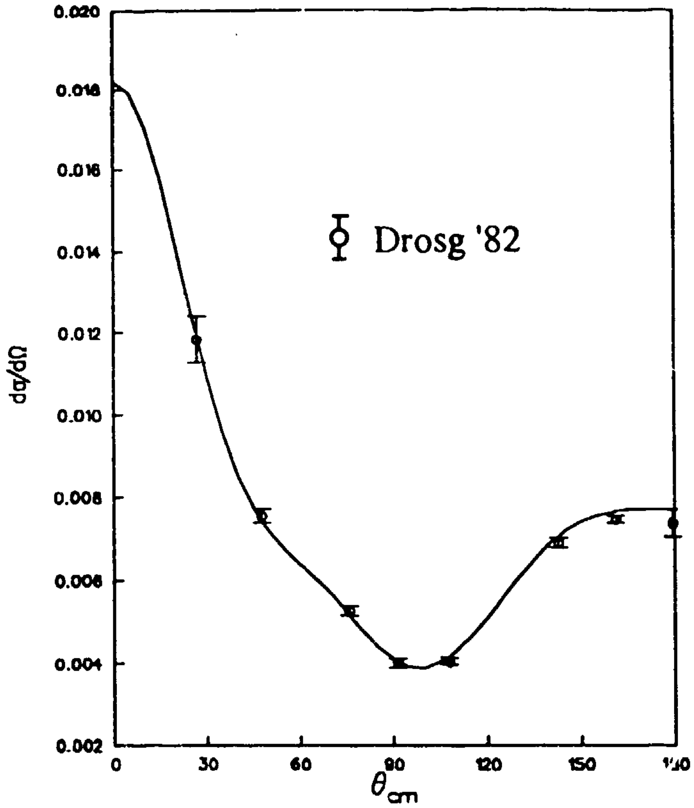

T(d,n)4He 3.00 MeV
Paulsen '64
dσ/dΩ
θcm


T(d,n)4He 3.00 MeV
Bame '57
dσ/dΩ
θcm

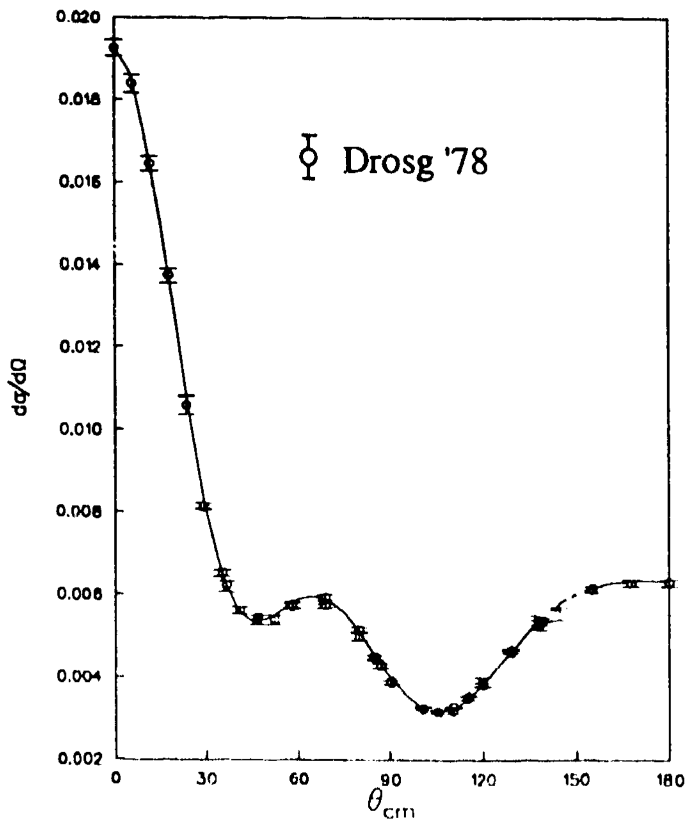
T(d,n)^{4}He 3.97 MeV



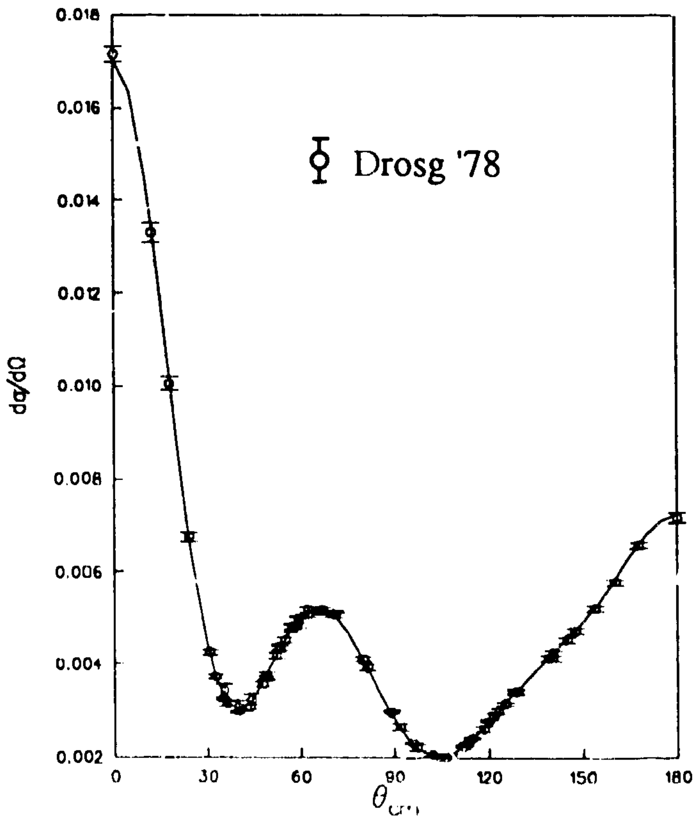
T(d,n)^{4}He 4.97 MeV

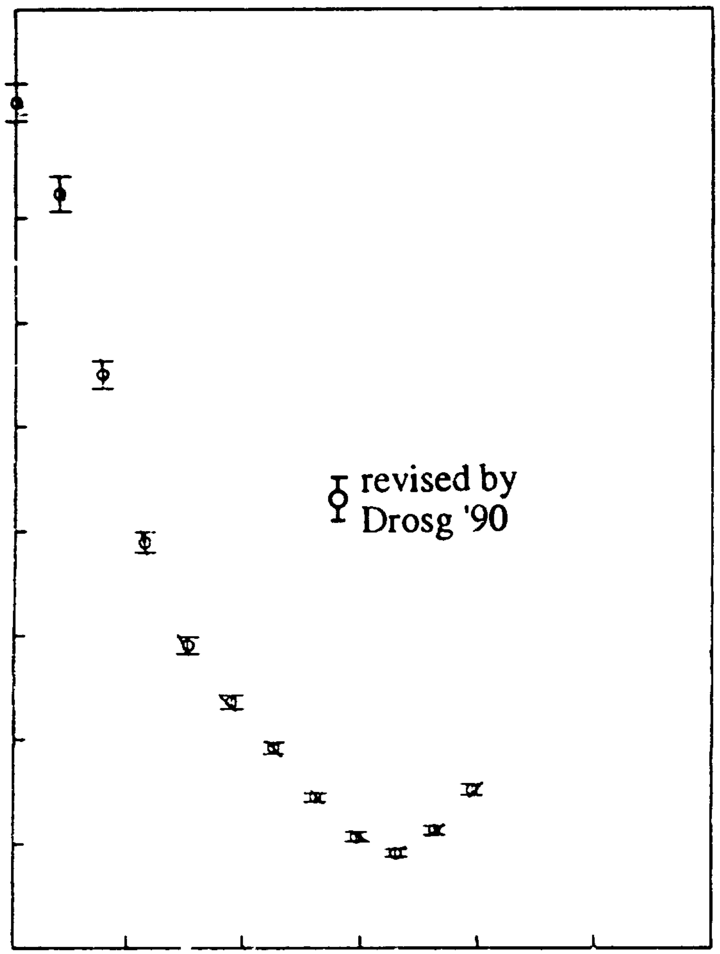


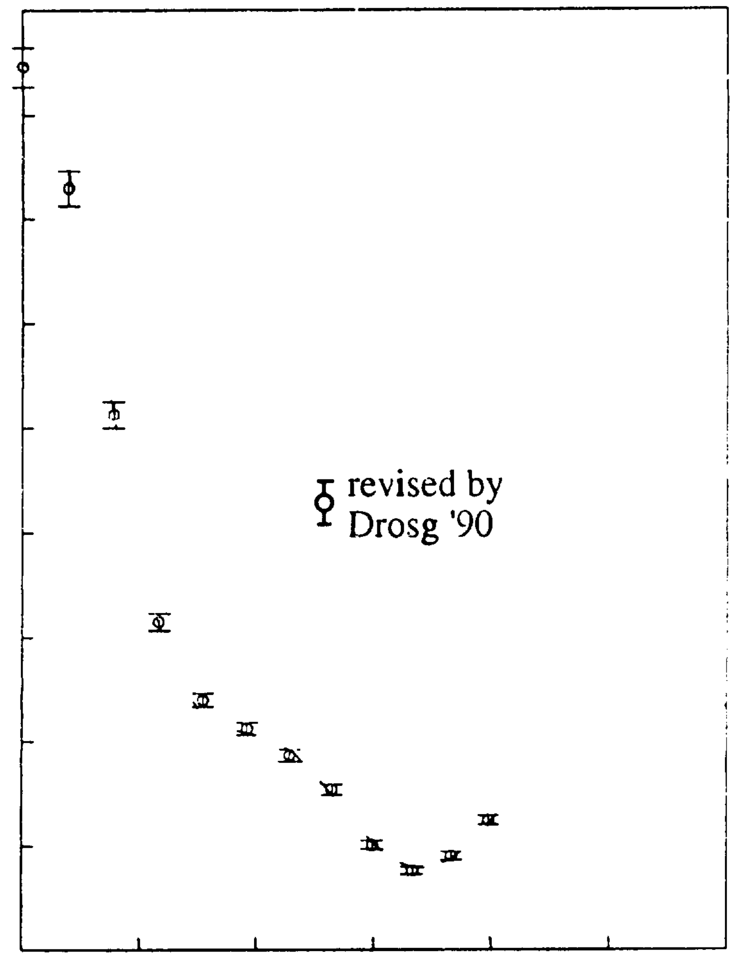
T(d,n)^{4}He 7.00 MeV

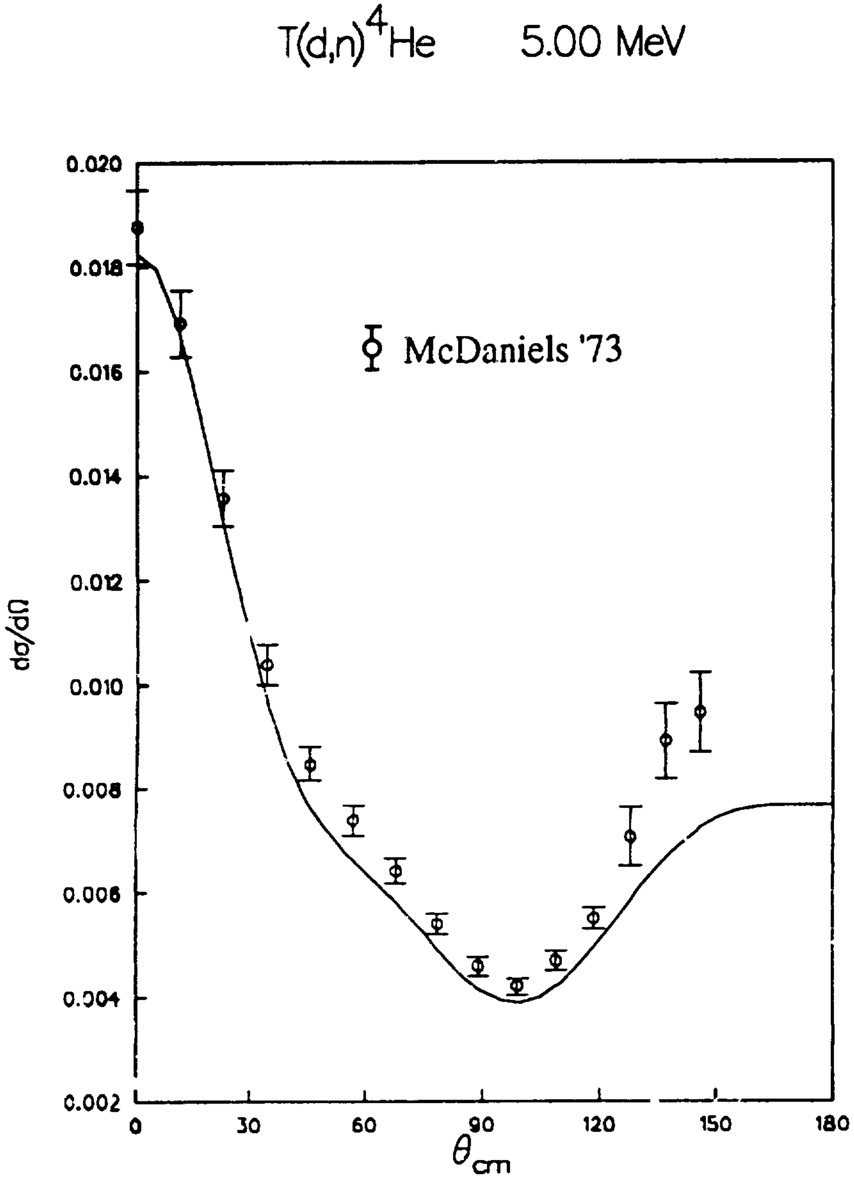


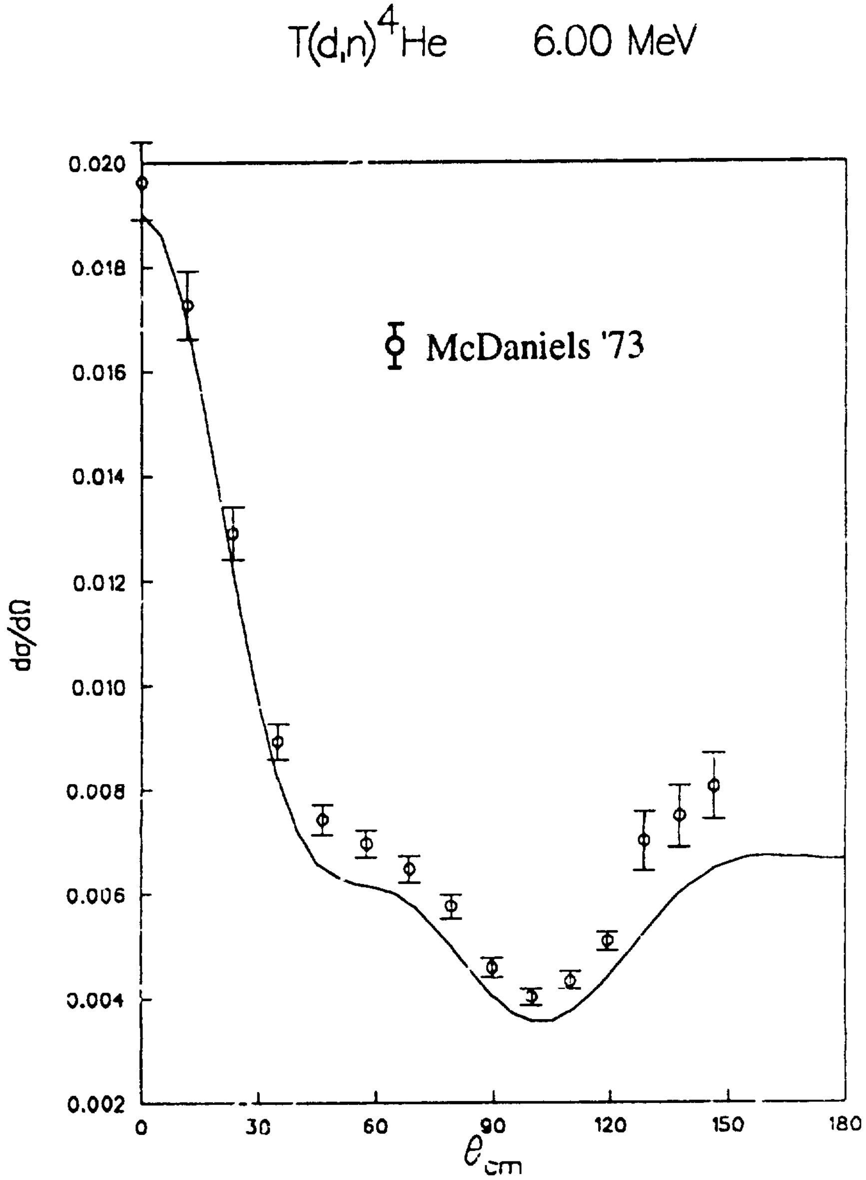
T(d,n)^{4}He 10.0 MeV

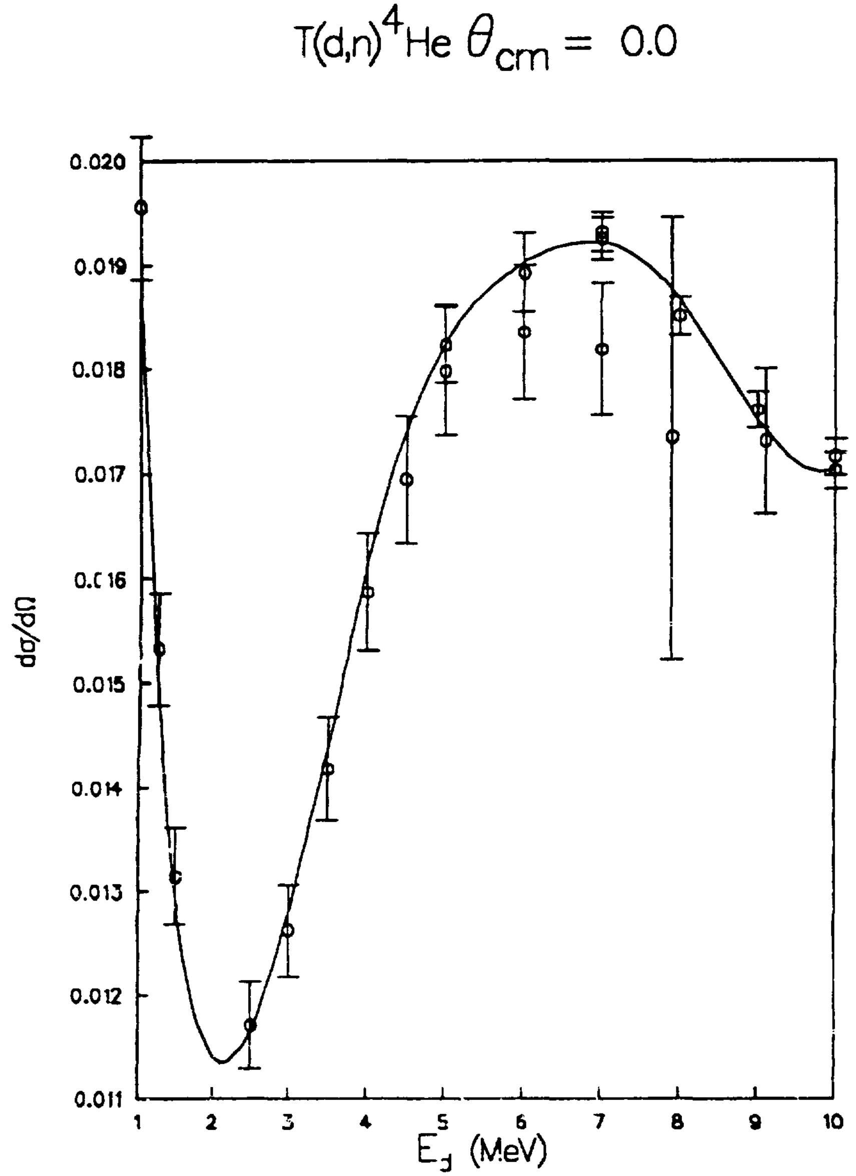


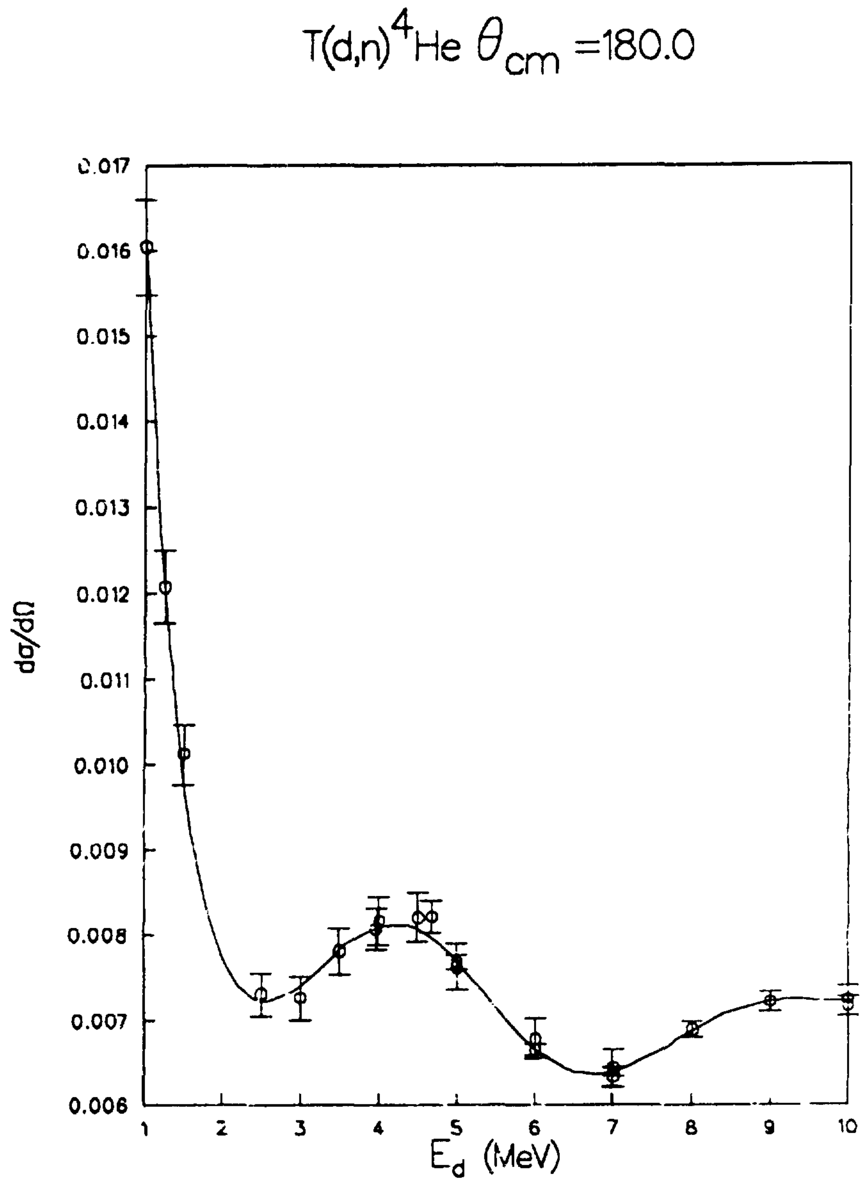

revised by
Drosg '90

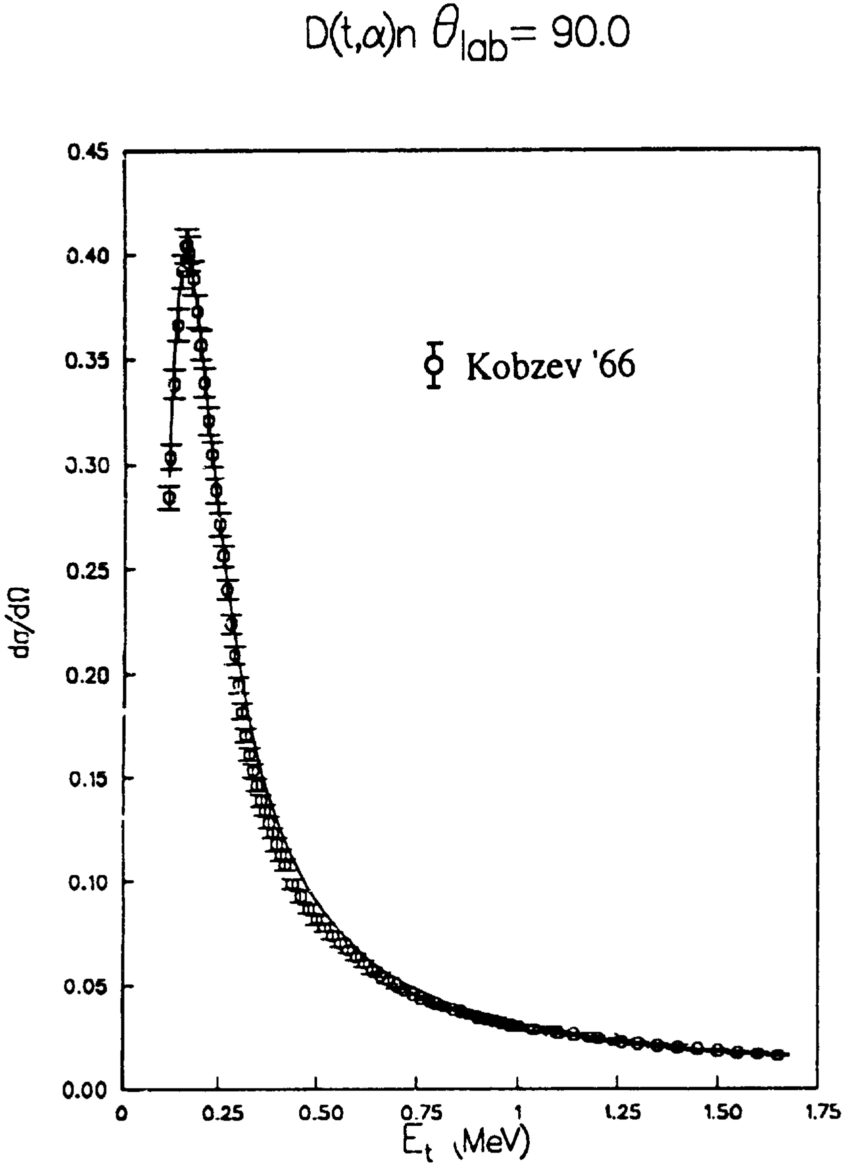

revised by
Drosg '90


T(d,n)^{4}He 5.00 MeV
McDaniels '73
dσ/dΩ
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
30
60
90
120
150
180
θ_{cm}

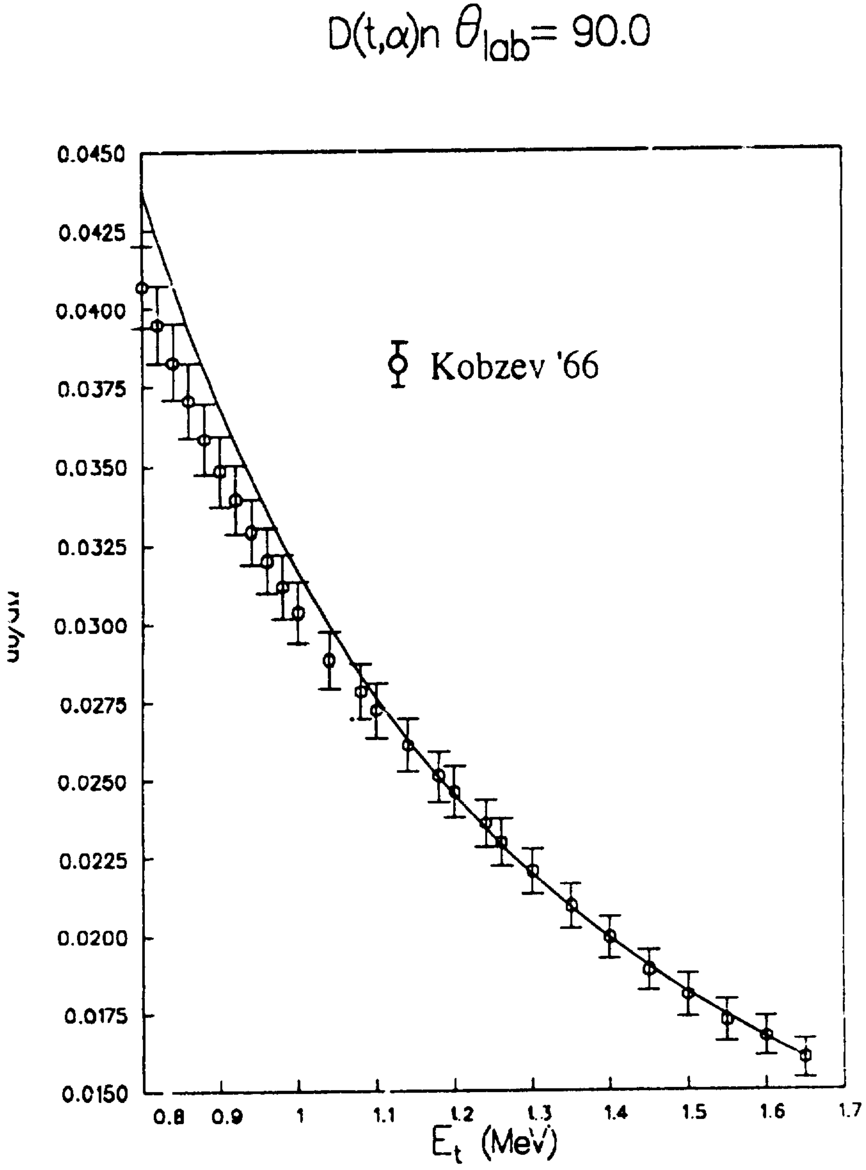

T(d,n)^{4}He 6.00 MeV
McDaniels '73
dσ/dΩ
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
30
60
90
120
150
180
θ_{cm}


T(d,n)^{4}He θ_{cm} = 0.0
dσ/dΩ
E$_d$ (MeV)


T(d,n)^{4}He θ_{cm} =180.0
dσ/dΩ
E$_d$ (MeV)



D(t,α)n θlab= 90.0
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
dσ/dΩ
Kobzev '66
0
0.25
0.50
0.75
1
1.25
1.50
1.75
Et (MeV)



D(t,α)n θlab= 90.0
0.0450
0.0425
0.0400
0.0375
0.0350
0.0325
0.0300
0.0275
0.0250
0.0225
0.0200
0.0175
0.0150
Kobzev '66
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Et (MeV)

Stability of Low-Energy Cross-Section Extrapolation

Present value of $\sigma_{d,n}(100\ \mathrm{eV}) = 2.0506 \times 10^{-56}$ b

$\Rightarrow S(0) = 11.75$ MeV-b]

is:

5.5% higher than the value we had in 1979 (pre-Jarmie&Brown)

0.2% higher than the value we had in 1986 (used in Bosch&Hale)

0.5% higher than the value we had in 1992 (CSEWG 1993)

Conclusions

1. R-matrix theory, when used in its full multilevel, multichannel form, is an extremely useful tool for doing charged-particle evaluations for reactions in light systems at moderate energies.

2. No other evaluation for the d+t reactions has considered more data, and has been constrained by as much theory as the R-matrix calculations reported here. They give a good fit to all the data in the system, and especially for the $T(d,n)^4He$ cross sections at energies below 10 MeV.

3. A single-level representation of the $J^\pi=3/2^+$ R-matrix in the ^5He system gives a cross-section extrapolation to low energies that is adequate to only about 5%. There are two other $J^\pi=3/2^+$ resonances in the range below E_d=8 MeV, plus higher background-level contributions, that contribute 2.3% of the total reaction R-matrix element (or about 4.6% in the cross section) at low energies.

4. The calculations presented here allow a consistent evaluated file of cross sections and angular distributions to be constructed for all the d+t reactions [T(d,d), T(d,n), and T(d,n*)] at energies below 10 MeV, which give all the information necessary to do charged-particle transport .

5. The results of the R-matrix calculation at energies up to 10 MeV match well with the evaluation that has been done recently by Drosg for the T(d,n) cross section at higher energies.