LA-UR- 94-1272

Conf-940415--1
Vugraph

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

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

AUTHOR(S): Hale, G. M., T-2

SUBMITTED TO: To be presented at the IAEA Specialists' Meeting on Charged Particle and Photonuclear Data Evaluation's for FENDL
Smolenice, Slovakia, April 18-21, 1994

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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

G. M. Hale
Theoretical Division
Los Alamos National Laboratory

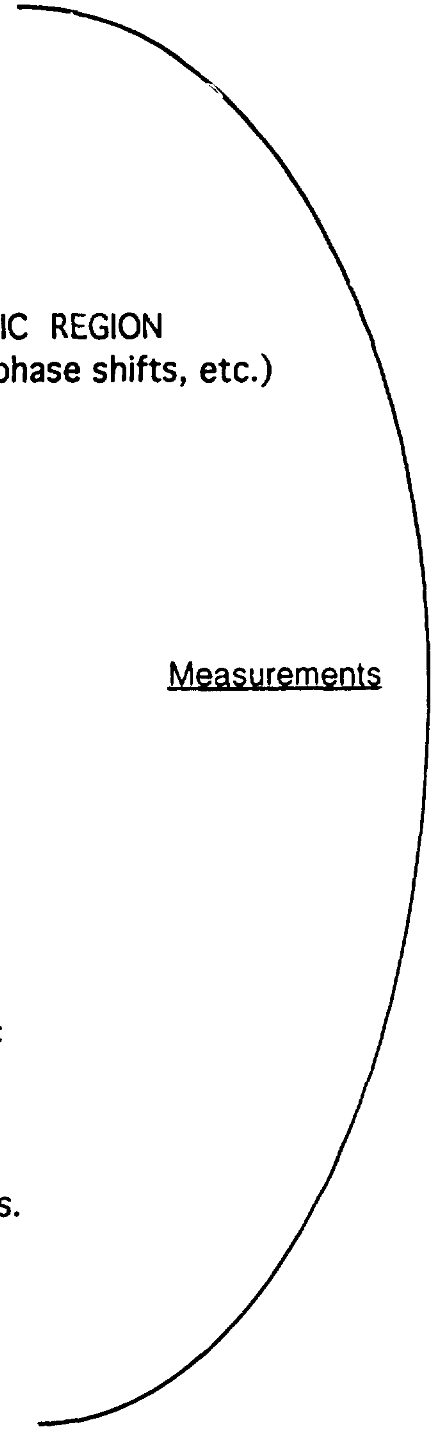
Arguments Against:

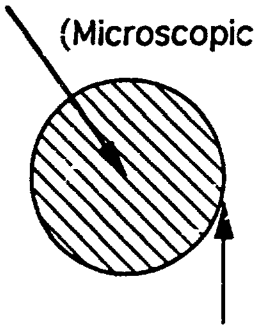
Theory-based evaluation

- 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.

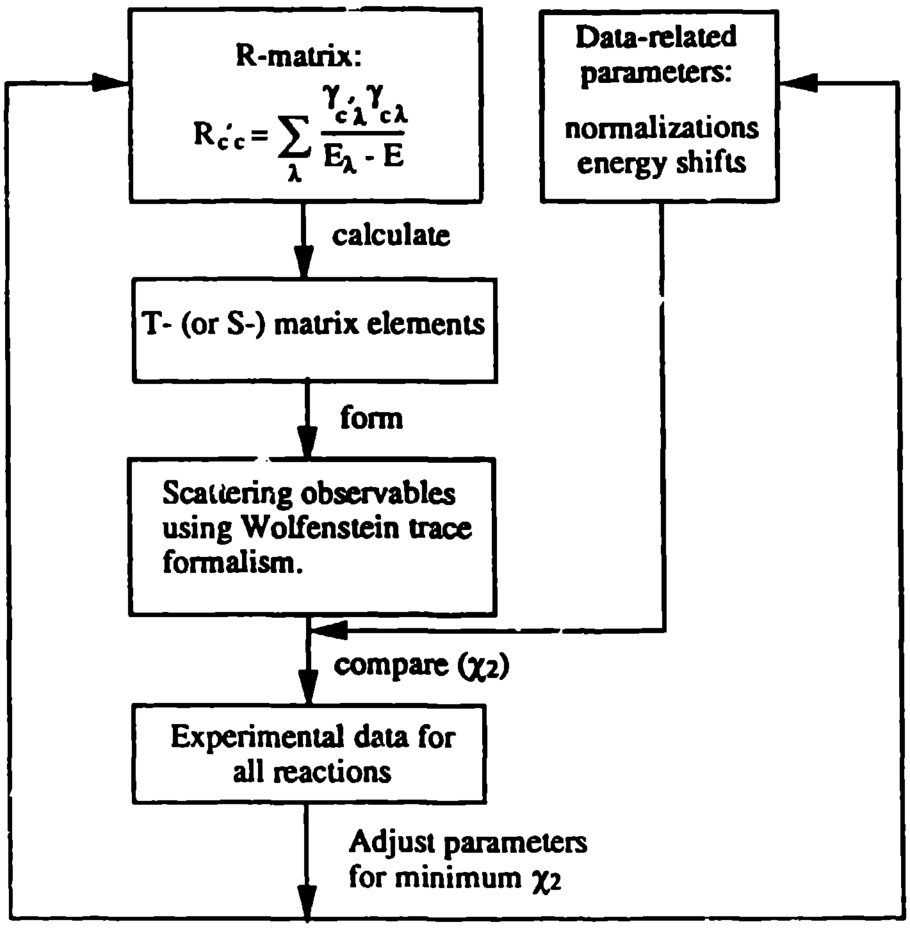




$$R_{c'c} = (c'|[H+\mathcal{L}-E]^{-1}|c) = \sum_{\lambda} \frac{\gamma_{c'\lambda}\gamma_{c\lambda}}{E_{\lambda}-E}$$

- 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.

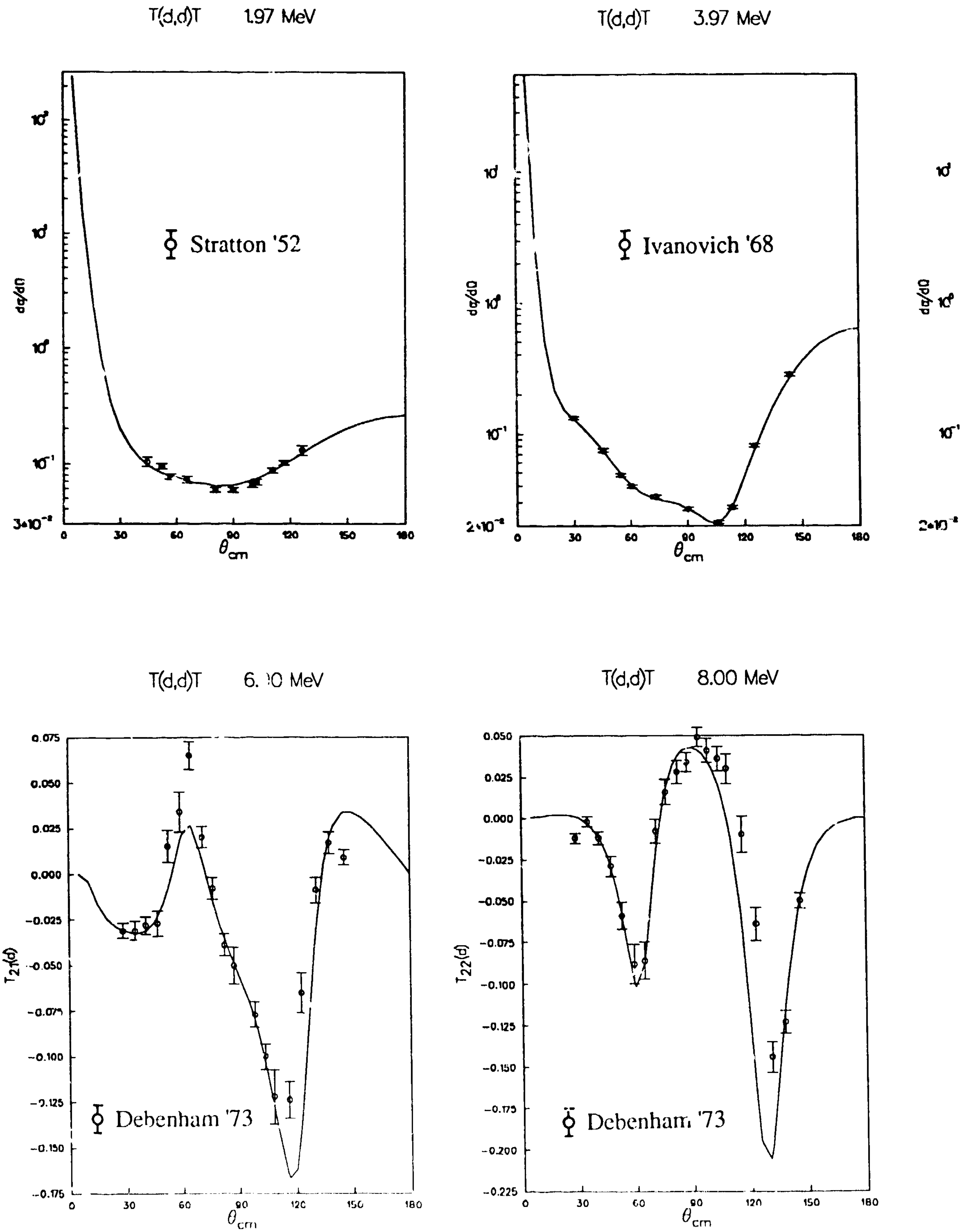
^{5}He System Analysis

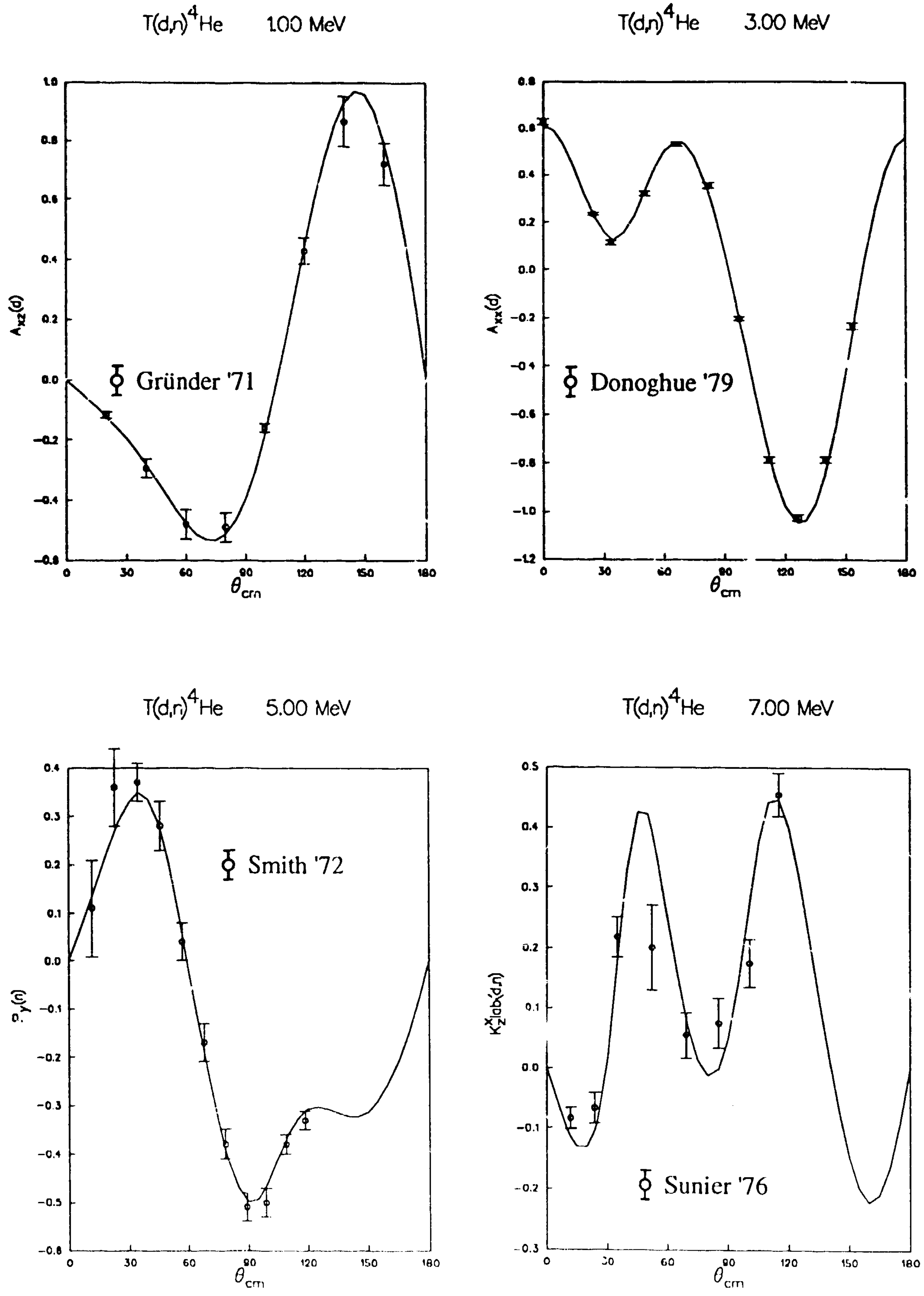
Channel	l_{max}	a_c (fm)
d-t	5	5.1
n-^{4}He	5	3.0
n-^{4}He*	1	5.0

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

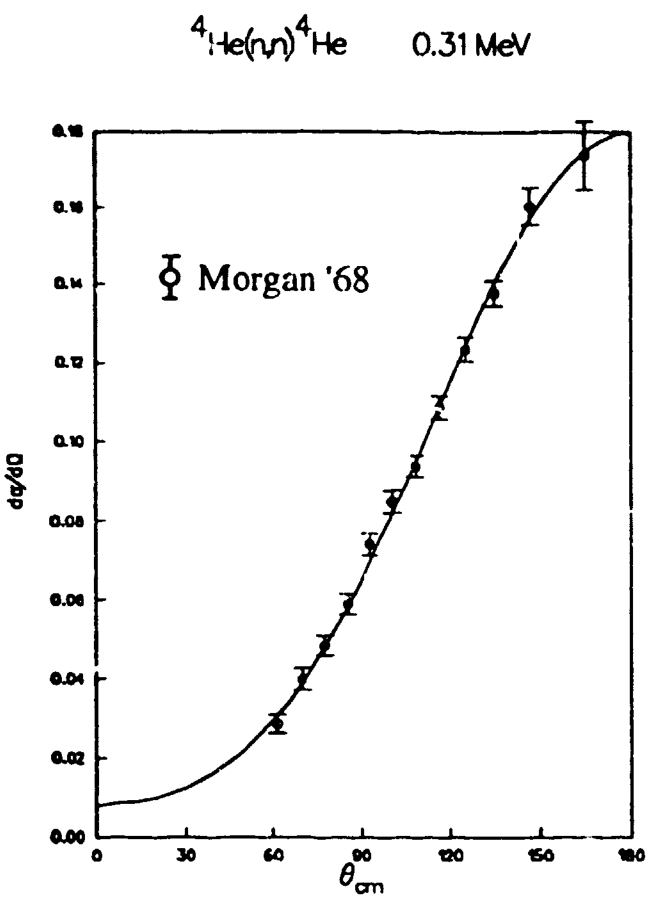
parameters = 117 $\Rightarrow$ χ^2 per degree of freedom = 1.57

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

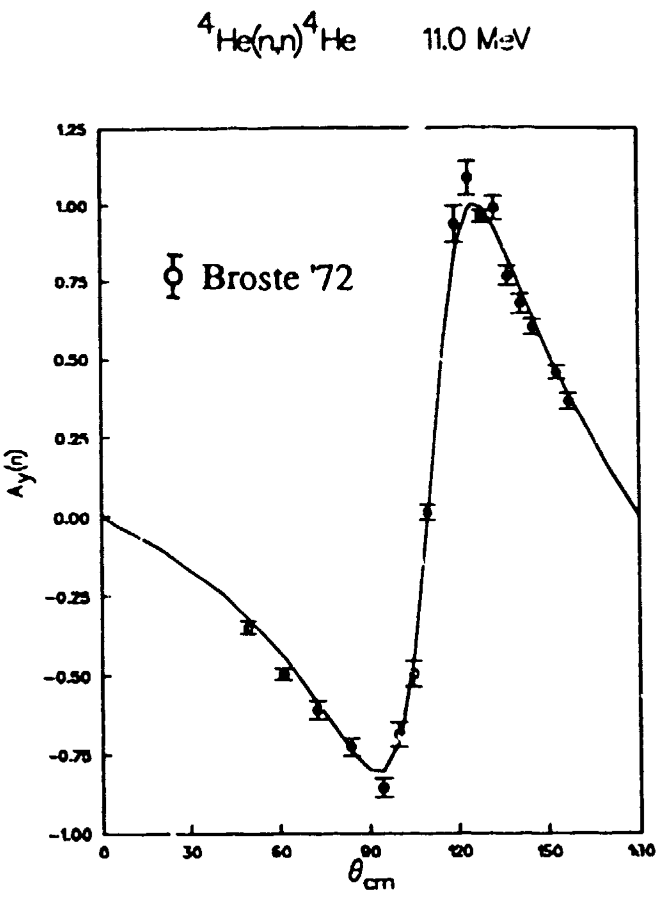

T(d,d)T 1.97 MeV
Stratton '52
dσ/dΩ
θcm
T(d,d)T 3.97 MeV
Ivanovich '68
dσ/dΩ
θcm
T(d,d)T 6. !0 MeV
T21(d)
Debenham '73
θcm
T(d,d)T 8.00 MeV
T22(d)
Debenham '73
θcm



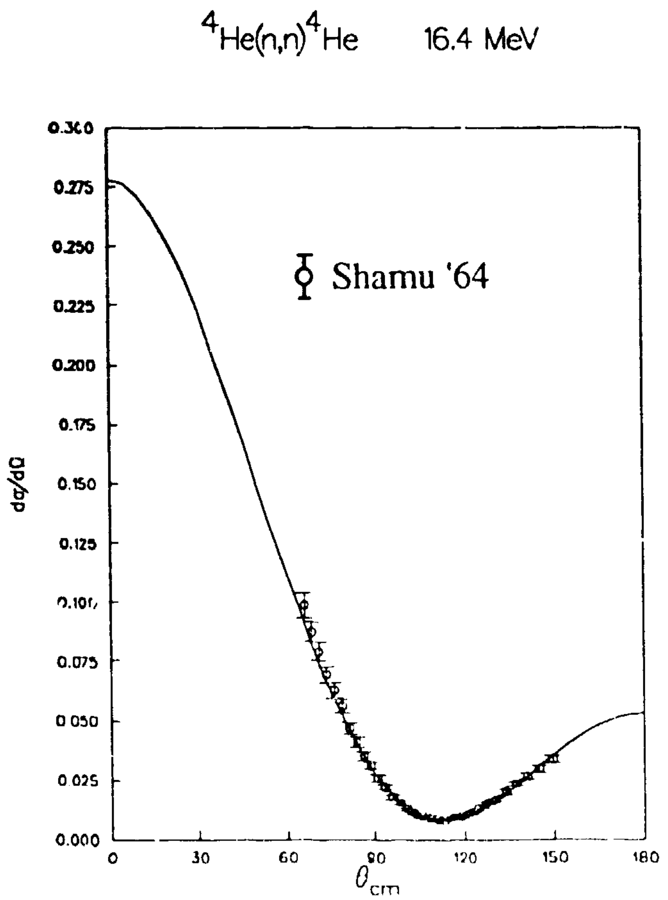
T(d,n)^{4}He 1.00 MeV
$A_{xz}(d)$
Gründer '71
θ_{cm}
T(d,n)^{4}He 3.00 MeV
$A_{xx}(d)$
Donoghue '79
θ_{cm}
T(d,n)^{4}He 5.00 MeV
$P_y(n)$
Smith '72
θ_{cm}
T(d,n)^{4}He 7.00 MeV
$K_z^x{}_{lab}(d,n)$
Sunier '76
θ_{cm}



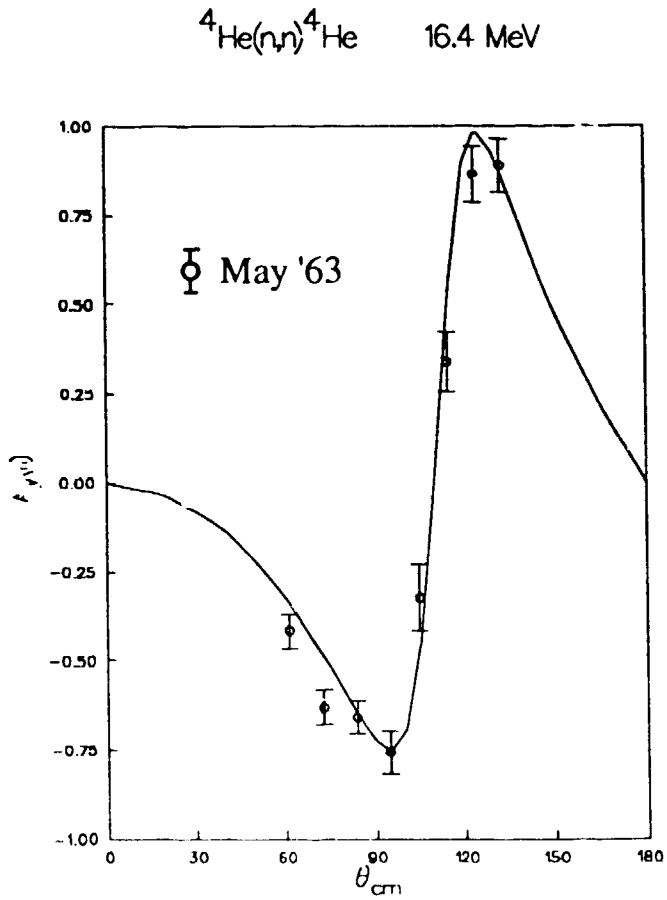
⁴He(n,n)⁴He 0.31 MeV
Morgan '68
dσ/dΩ
θcm
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0
30
60
90
120
150
180



⁴He(n,n)⁴He 11.0 MeV
Broste '72
Ay(n)
θcm
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
0
30
60
90
120
150



⁴He(n,n)⁴He 16.4 MeV
Shamu '64
dσ/dΩ
θcm
0.275
0.250
0.225
0.200
0.175
0.150
0.125
0.075
0.050
0.025
0.000
0
30
60
90
120
150
180



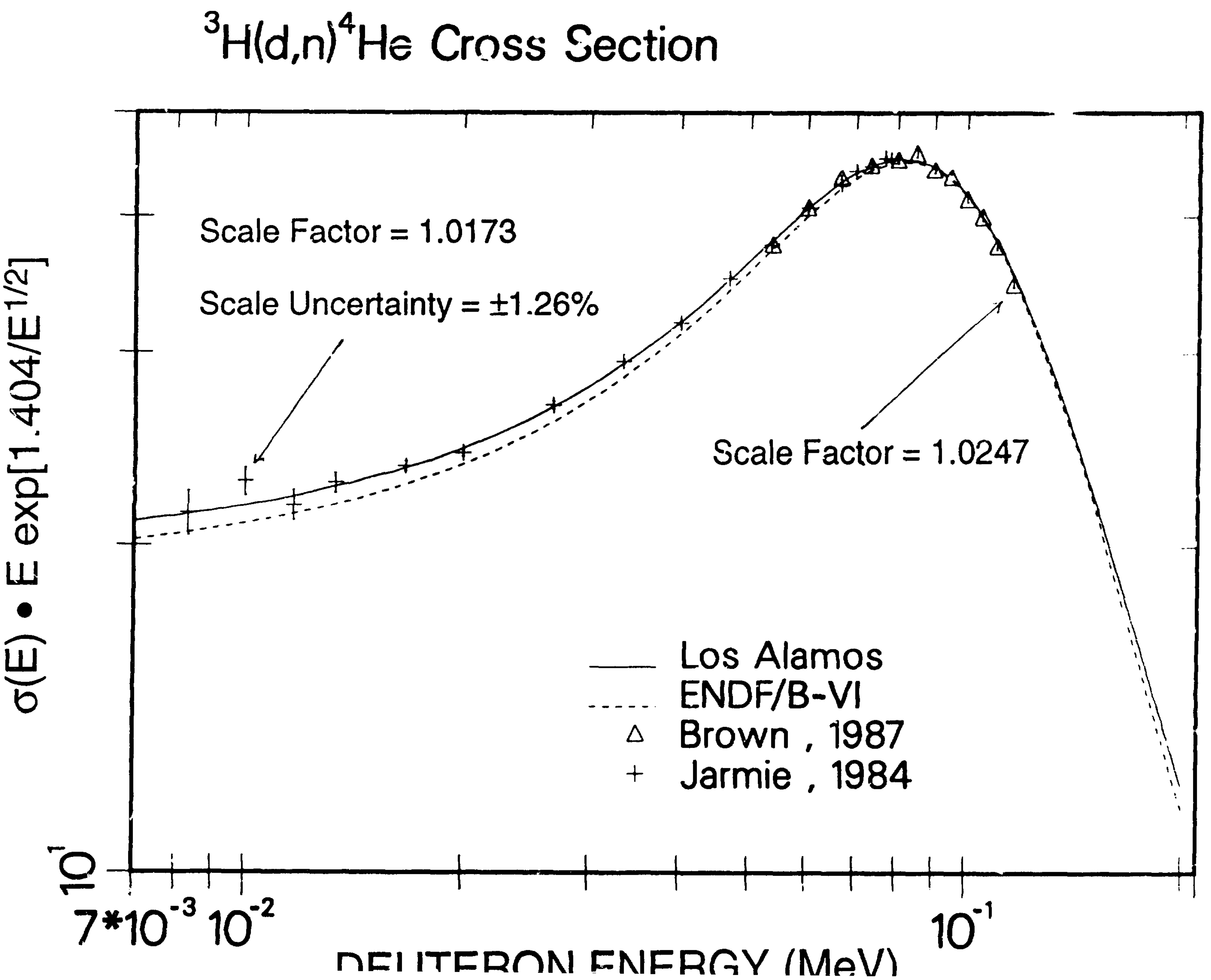
⁴He(n,n)⁴He 16.4 MeV
May '63
θcm
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
0
30
60
90
120
150
180

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

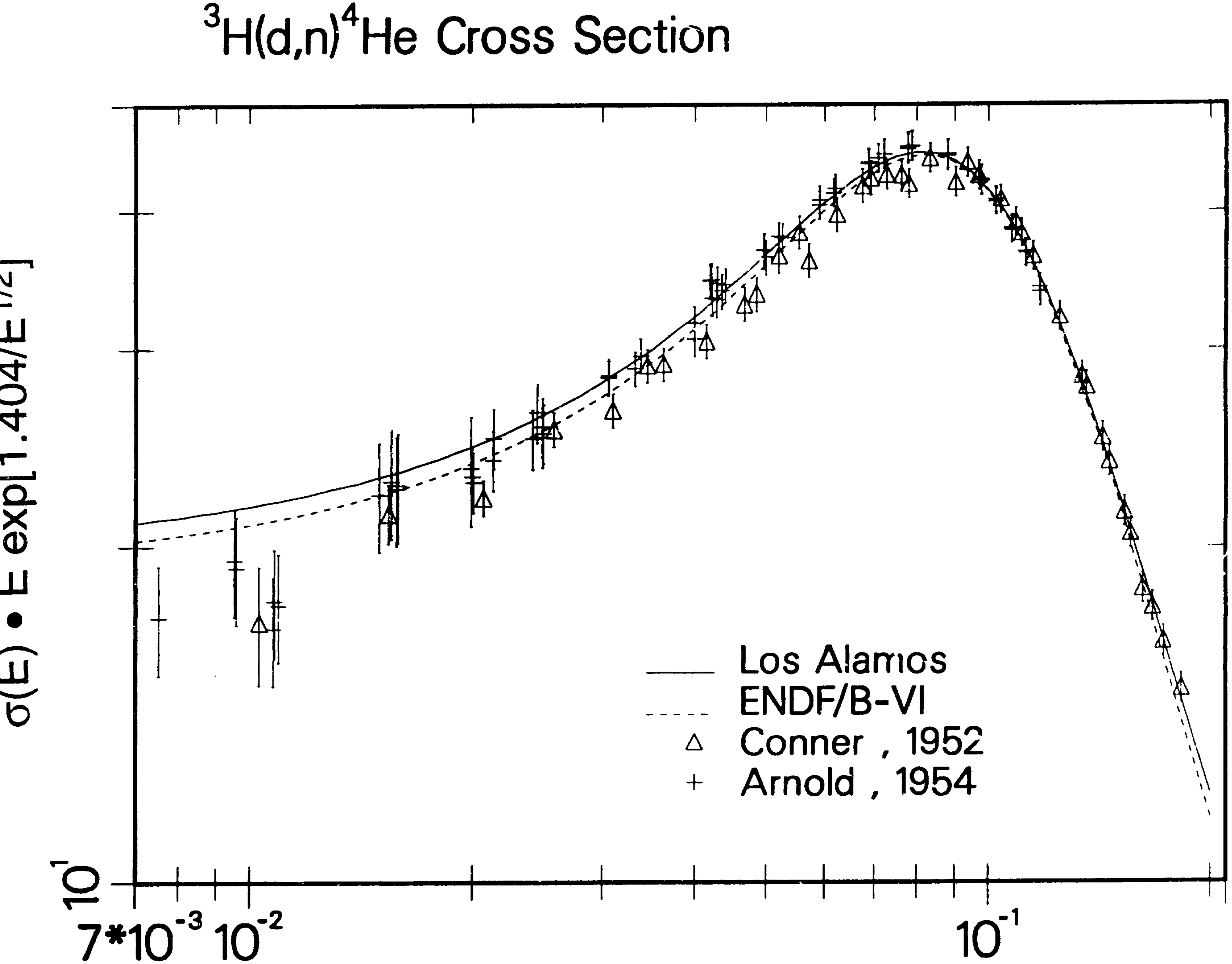
Data set	Type	E_d (MeV)	Scale factor	Scale error (%)
Jarmie '84	$\sigma(E)$	0.008 - 0.070	1.017	1.26
Brown '87	$\sigma(E)$	0.053 - 0.116	1.025	- (rel.)
Bame '57	$\sigma(\theta)$	0.50	0.939	10
Bame '57	$\sigma(\theta)$	0.75	0.931	10
Bame '57	$\sigma(\theta)$	1.0	0.949	10
Bame '57	$\sigma(\theta)$	1.3	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.)

* Experimental scale value of 1.028 ±0.01 determined by Drosg

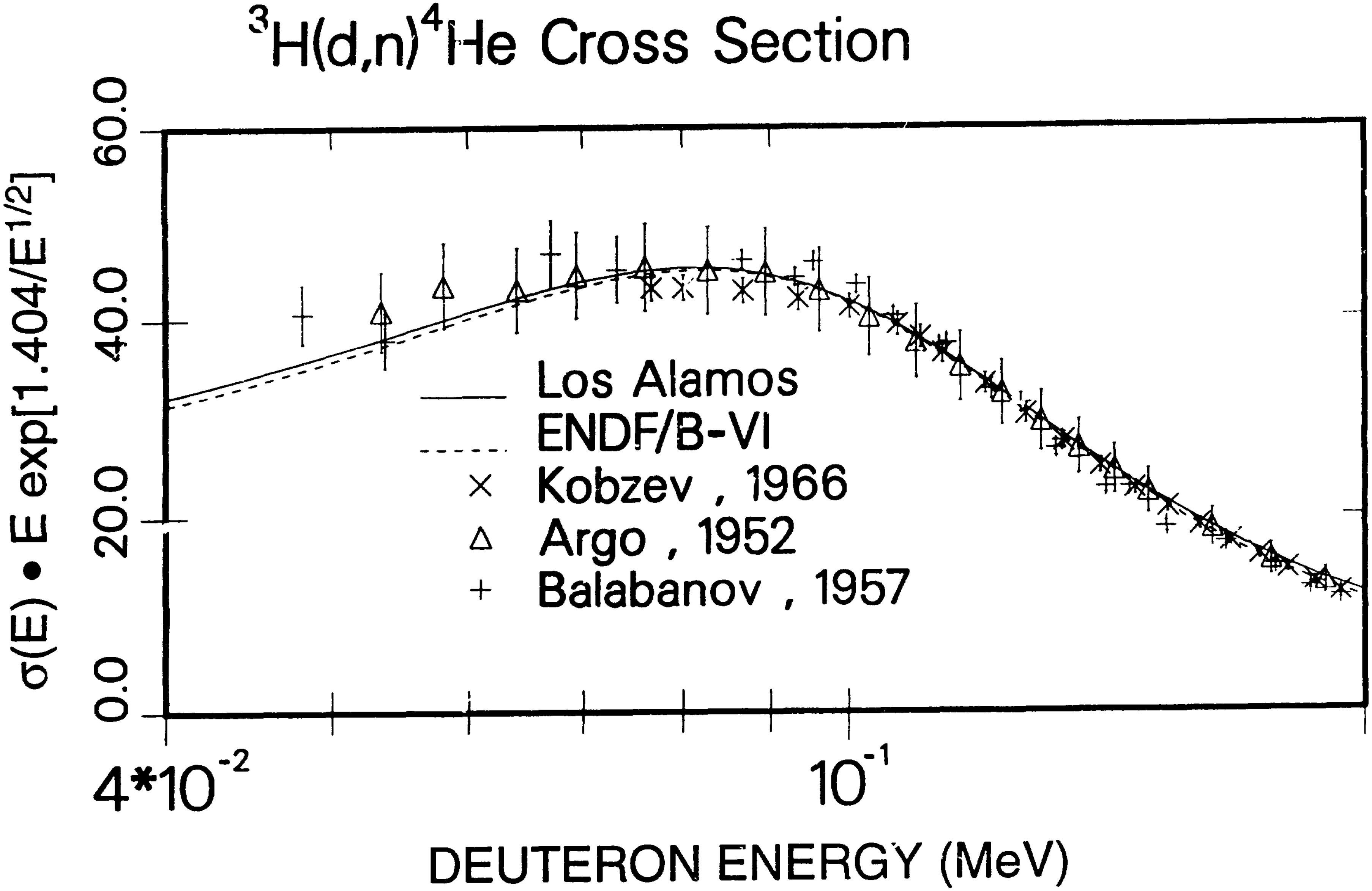
** Based on McDaniels '73 as revised by Drosg



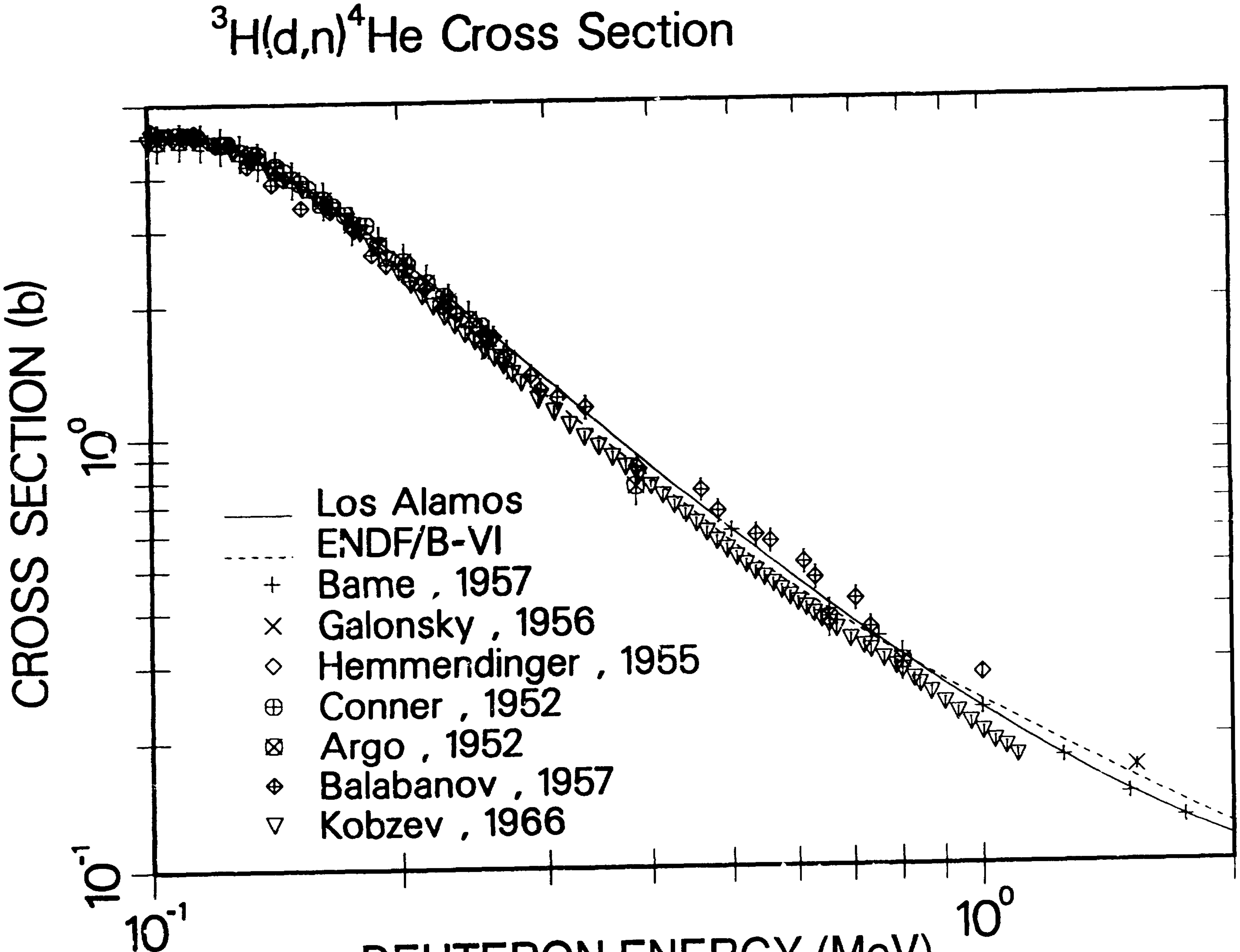
$^3H(d,n)^4He$ Cross Section
Scale Factor = 1.0173
Scale Uncertainty = ±1.26%
Scale Factor = 1.0247
Los Alamos
ENDF/B-VI
Brown , 1987
Jarmie , 1984
σ(E) • E exp[1.404/E^{1/2}]
10^1
7*10^-3
10^-2
10^-1
DEUTERON ENERGY (MeV)



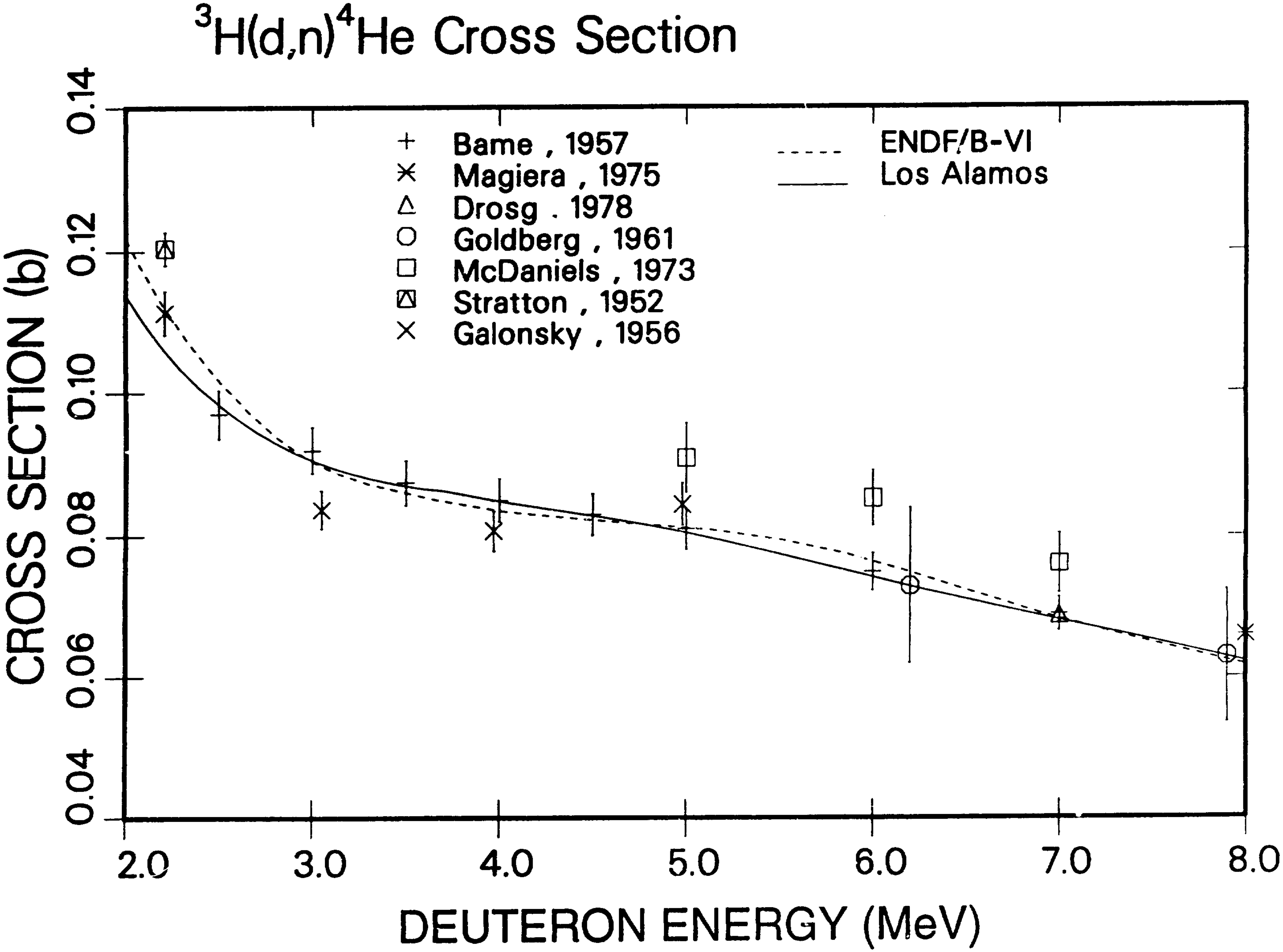
$^{3}H(d,n)^{4}He$ Cross Section
$\sigma(E) \bullet E \exp[1.404/E^{1/2}]$
10^{1}
$7*10^{-3}$
10^{-2}
10^{-1}
Los Alamos
ENDF/B-VI
Conner , 1952
Arnold , 1954



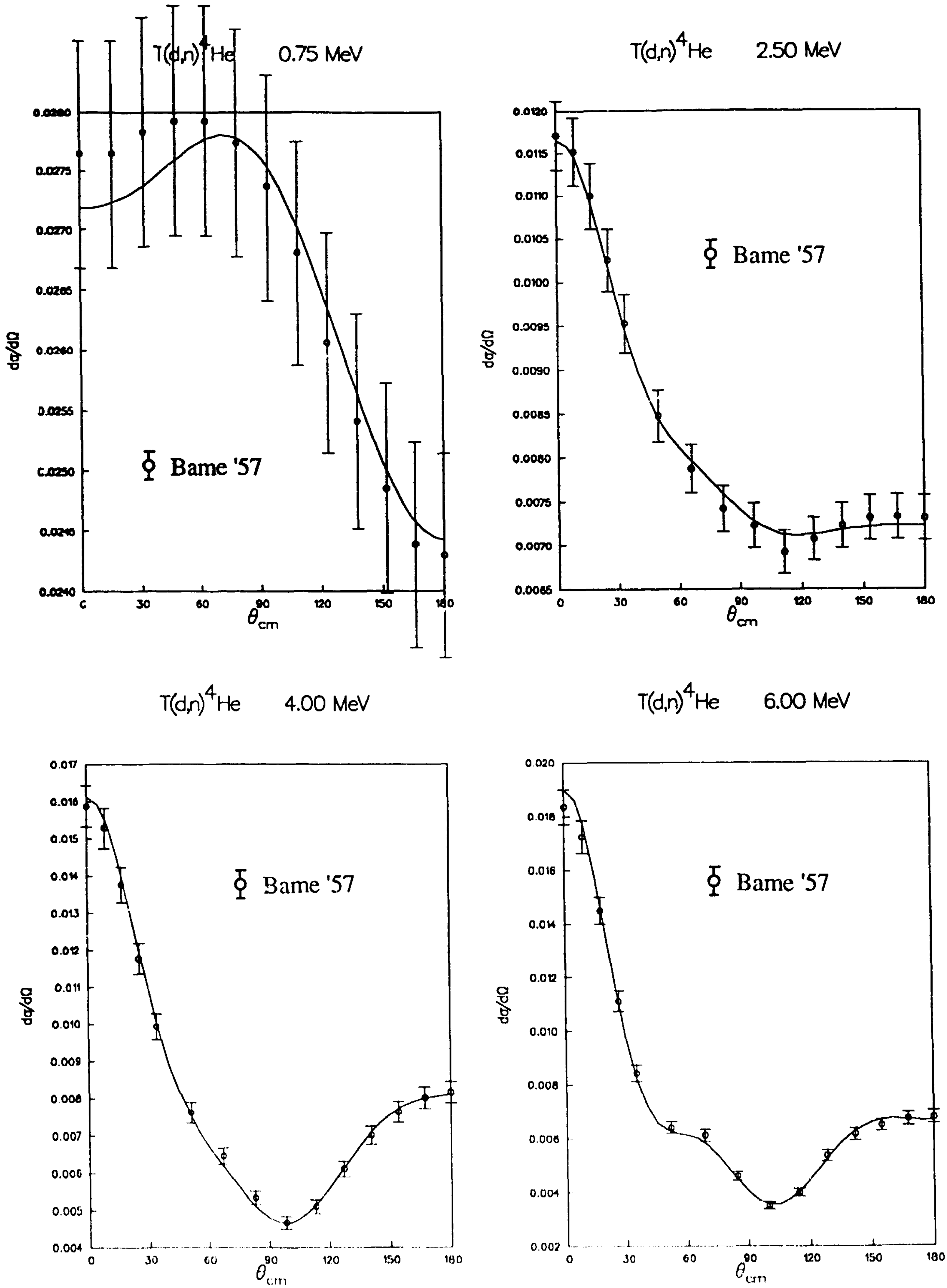
³H(d,n)⁴He Cross Section
σ(E) • E exp[1.404/E^1/2]
60.0
40.0
20.0
0.0
Los Alamos
ENDF/B-VI
Kobzev , 1966
Argo , 1952
Balabanov , 1957
4*10^-2
10^-1
DEUTERON ENERGY (MeV)



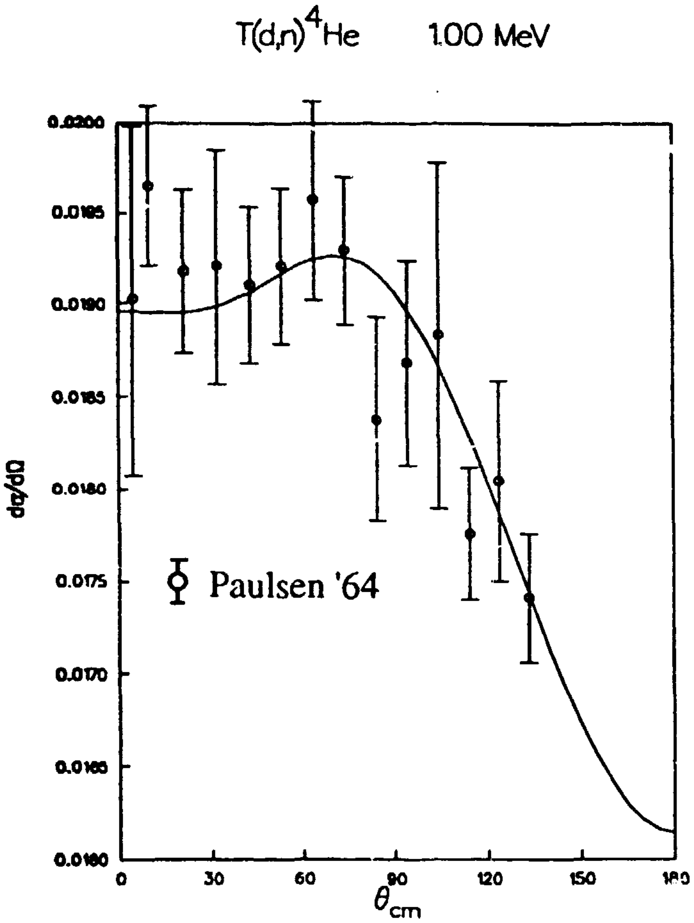
$^3H(d,n)^4He$ Cross Section
CROSS SECTION (b)
10^0
10^{-1}
10^{-1}
10^0
DEUTERON ENERGY (MeV)
Los Alamos
ENDF/B-VI
Bame , 1957
Galonsky , 1956
Hemmendinger , 1955
Conner , 1952
Argo , 1952
Balabanov , 1957
Kobzev , 1966

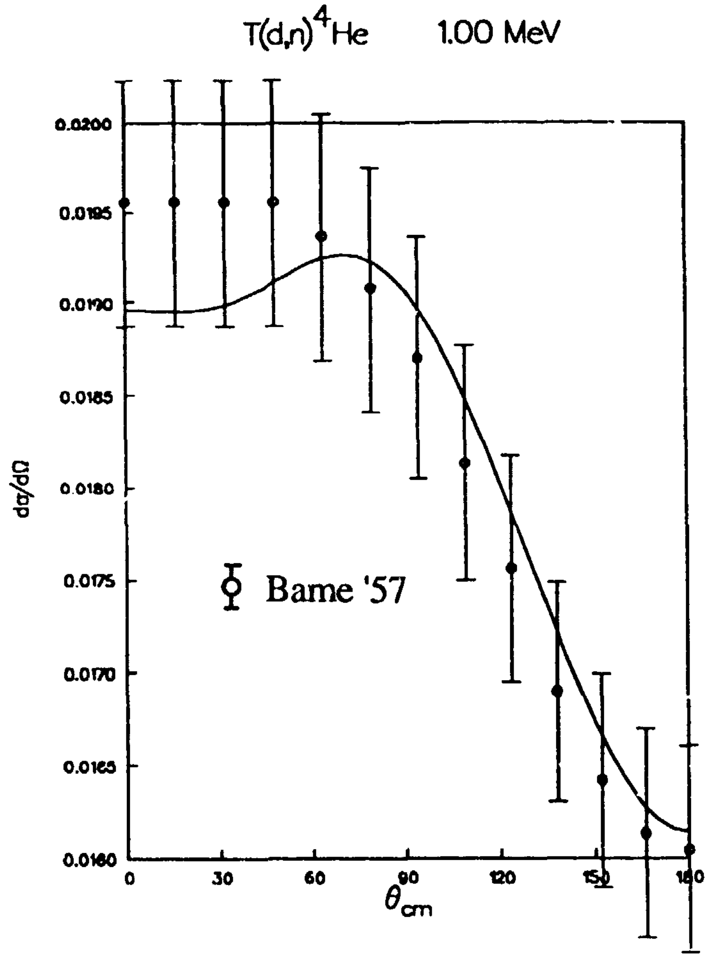


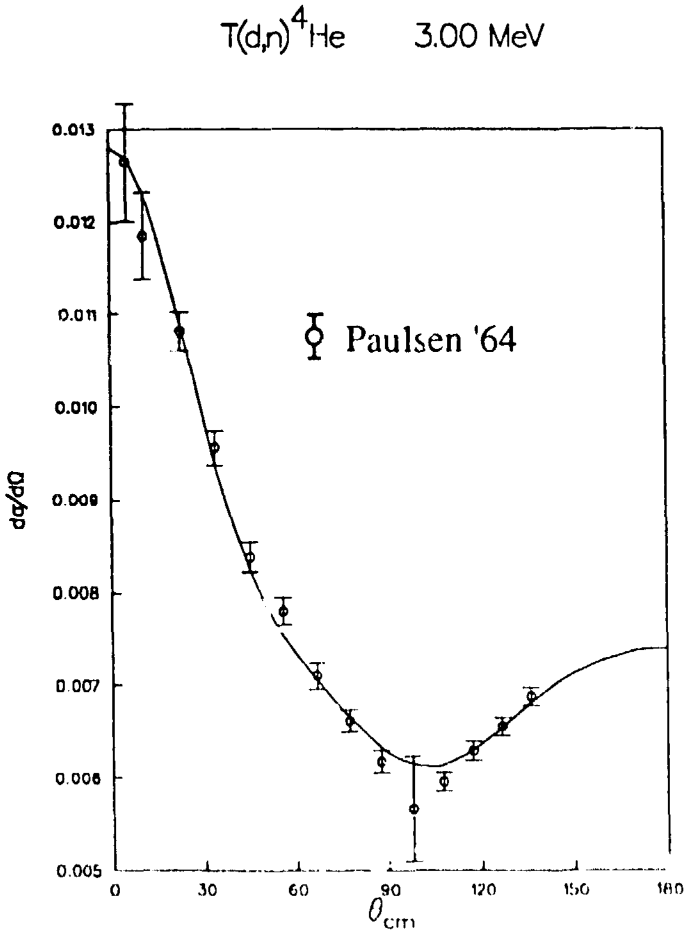
$^3H(d,n)^4He$ Cross Section
CROSS SECTION (b)
0.14
0.12
0.10
0.08
0.06
0.04
Bame , 1957
Magiera , 1975
Drosg . 1978
Goldberg , 1961
McDaniels , 1973
Stratton , 1952
Galonsky , 1956
ENDF/B-VI
Los Alamos
2.0
3.0
4.0
5.0
6.0
7.0
8.0
DEUTERON ENERGY (MeV)

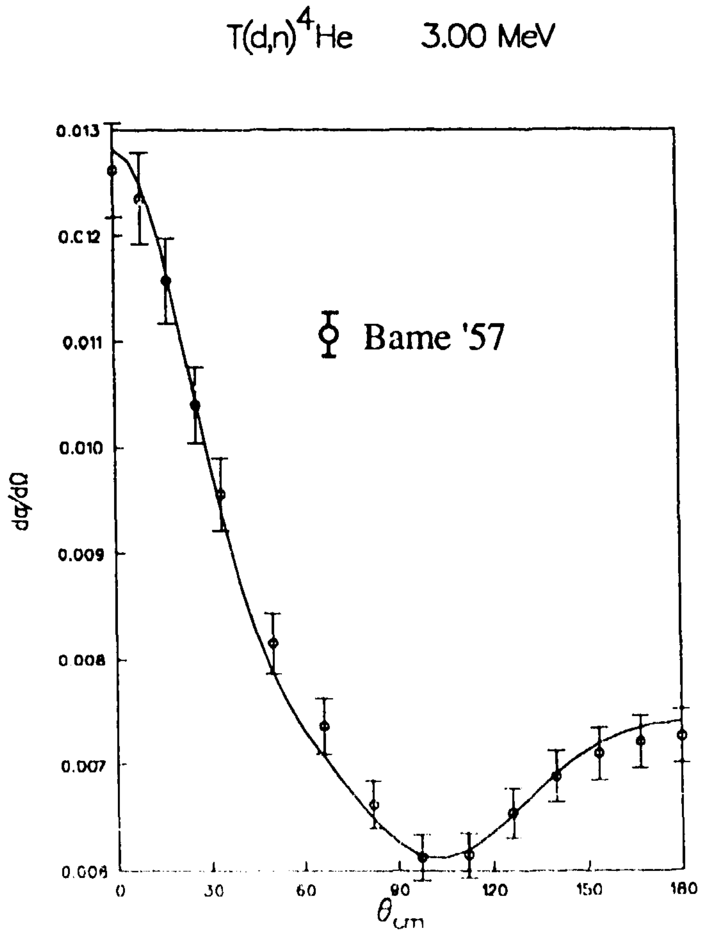


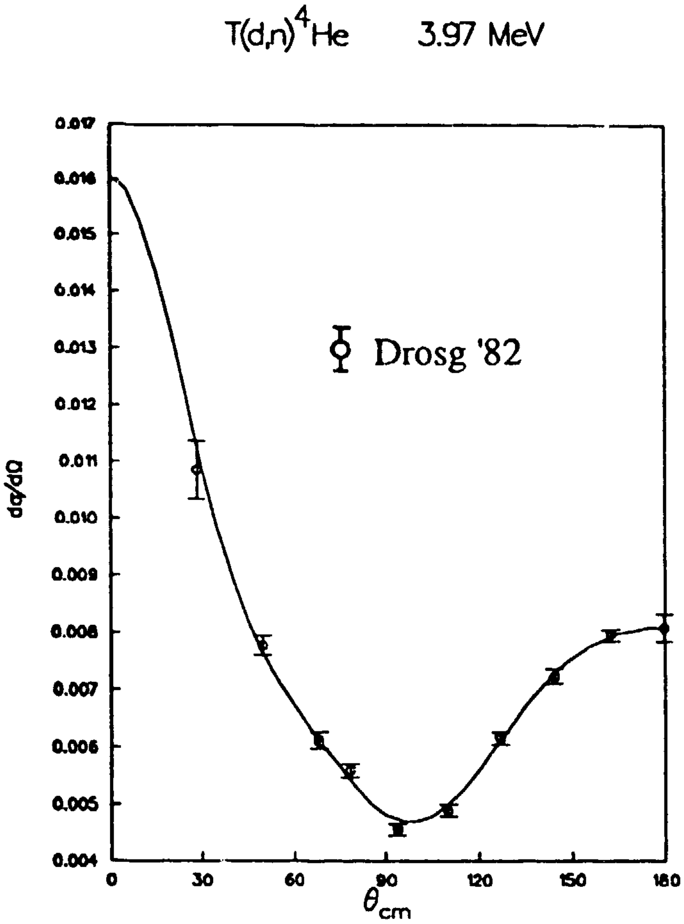
T(d,n)⁴He 0.75 MeV
Bame '57
dσ/dΩ
θcm
T(d,n)⁴He 2.50 MeV
Bame '57
dσ/dΩ
θcm
T(d,n)⁴He 4.00 MeV
Bame '57
dσ/dΩ
θcm
T(d,n)⁴He 6.00 MeV
Bame '57
dσ/dΩ
θcm

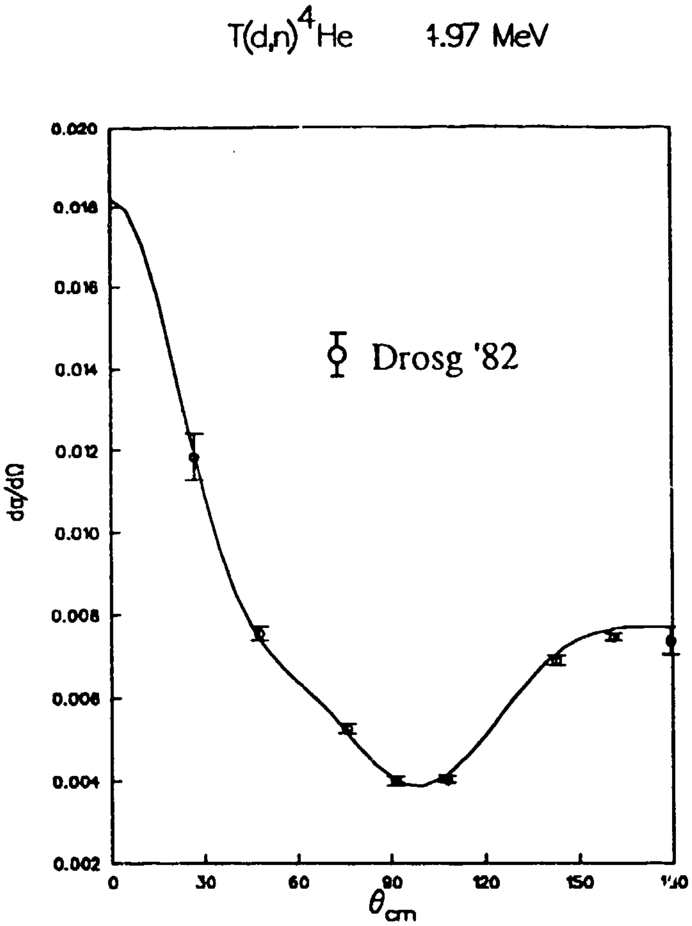

T(d,n)4He 1.00 MeV
dσ/dΩ
Paulsen '64
θcm
0.0200
0.0195
0.0190
0.0185
0.0180
0.0175
0.0170
0.0165
0.0160
0
30
60
90
120
150
180

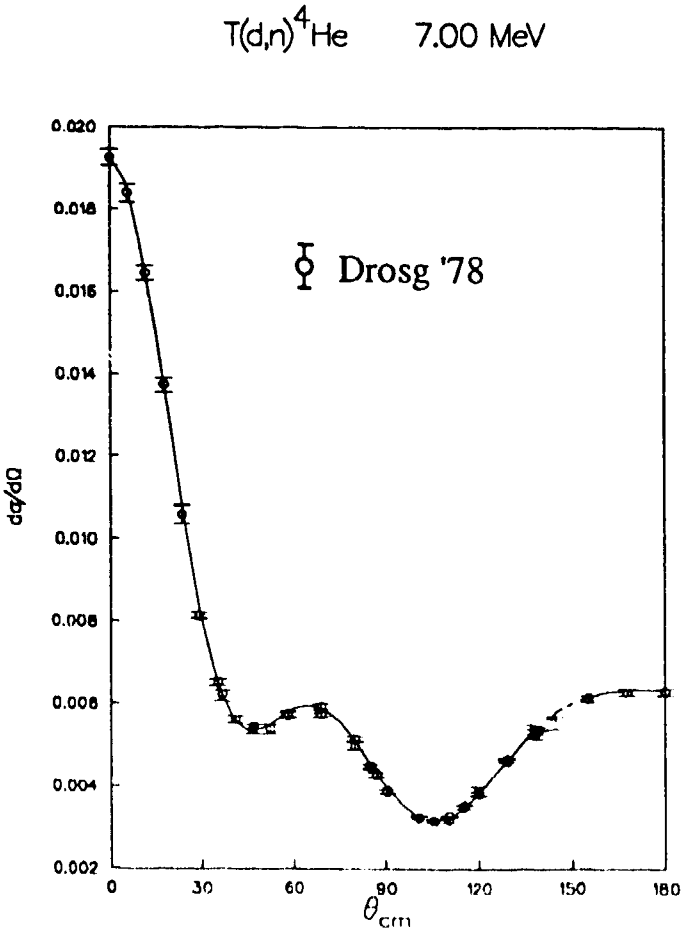

T(d,n)4He 1.00 MeV
dσ/dΩ
Bame '57
θcm
0.0200
0.0195
0.0190
0.0185
0.0180
0.0175
0.0170
0.0165
0.0160
0
30
60
90
120
150
180

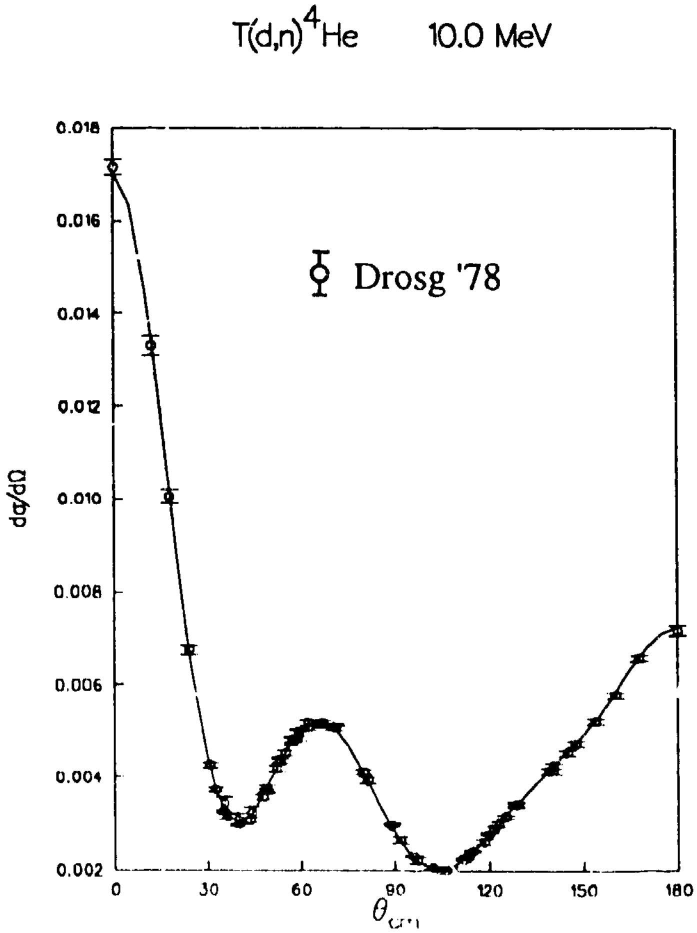

T(d,n)4He 3.00 MeV
dσ/dΩ
Paulsen '64
θcm
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0
30
60
90
120
150
180

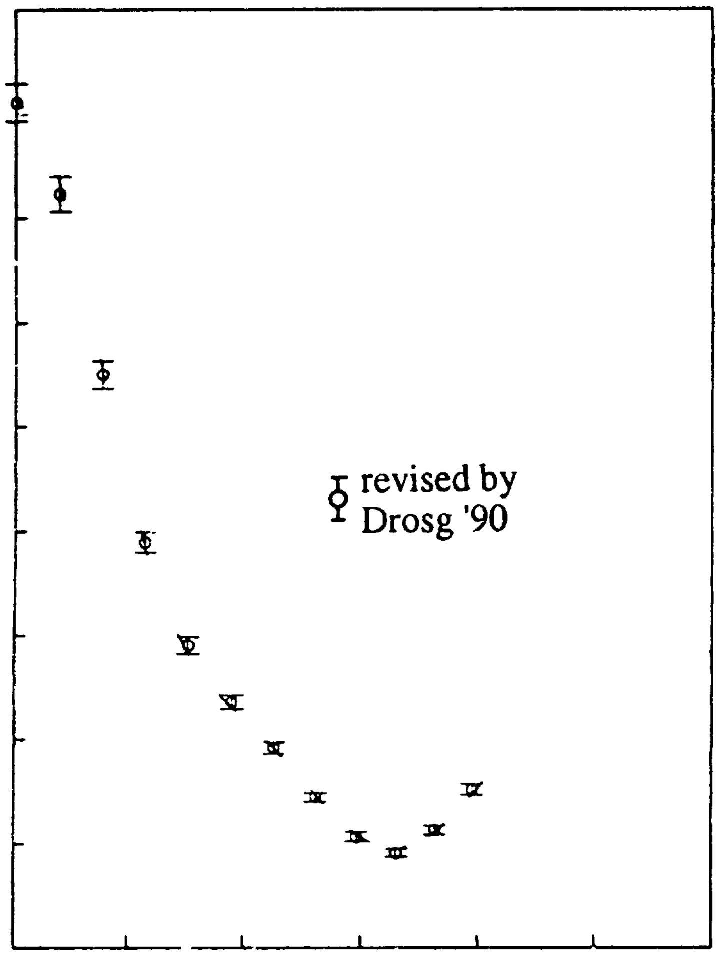

T(d,n)4He 3.00 MeV
dσ/dΩ
Bame '57
θcm
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0
30
60
90
120
150
180

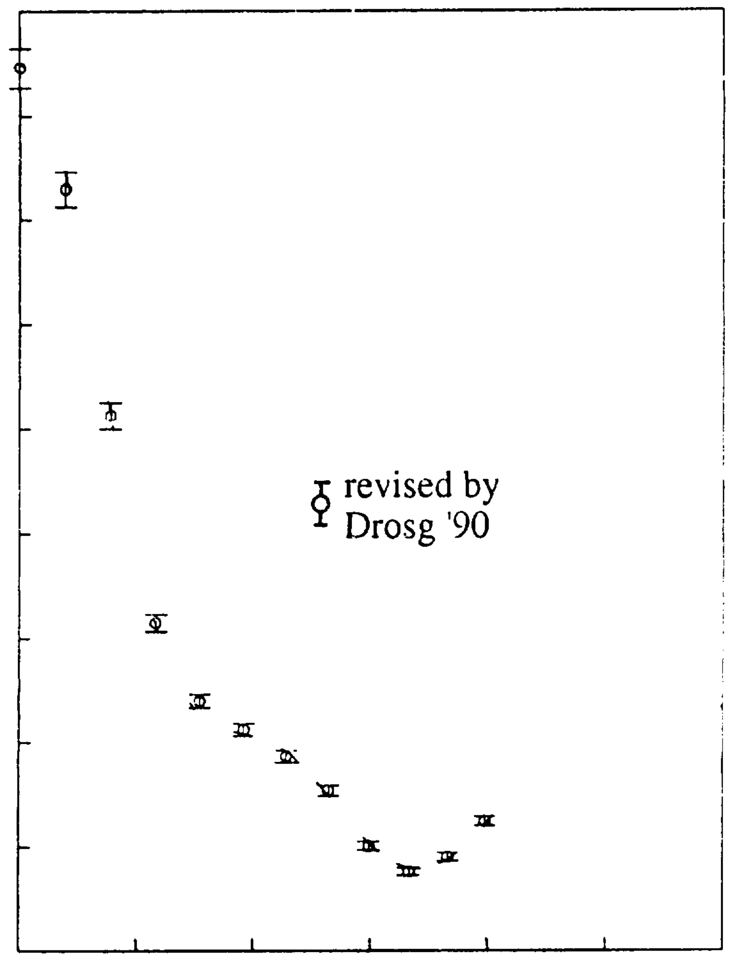

T(d,n)4He 3.97 MeV
Drosg '82
dσ/dΩ
θcm
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0
30
60
90
120
150
180

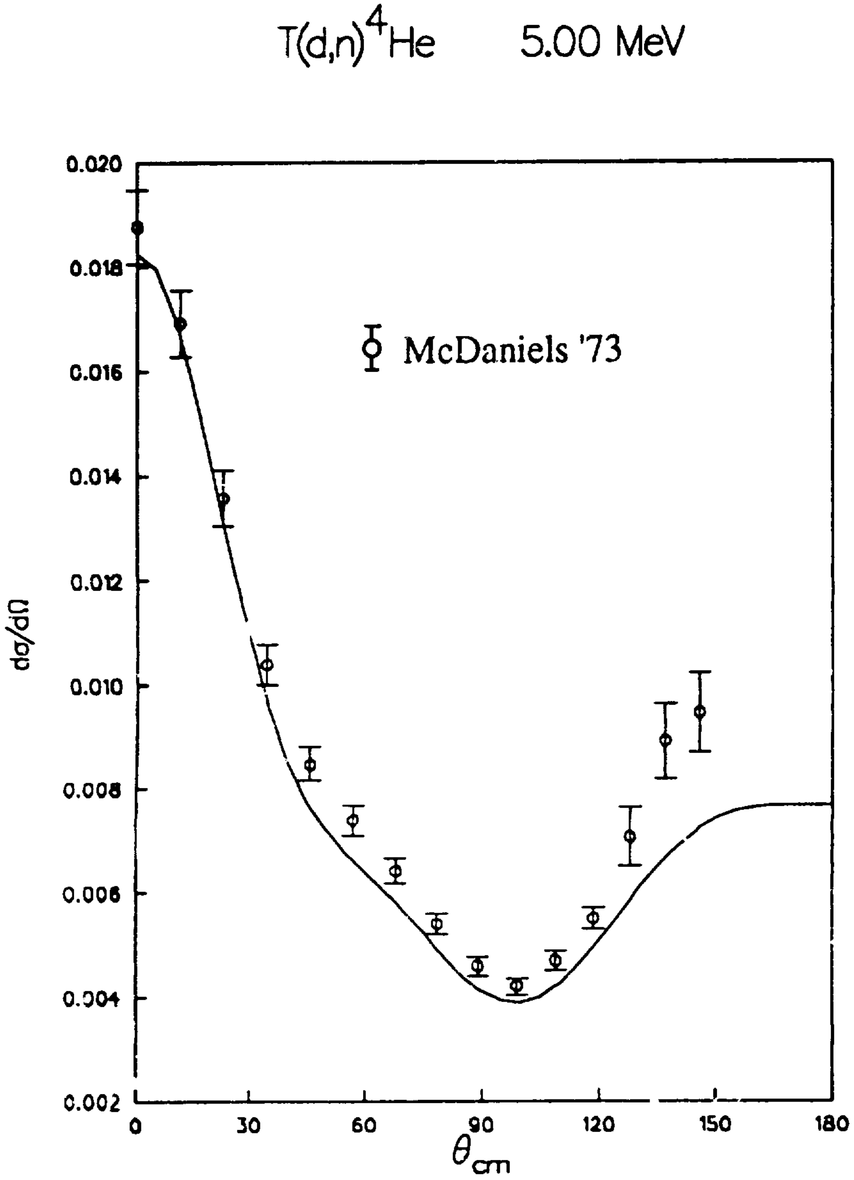

T(d,n)4He 4.97 MeV
Drosg '82
dσ/dΩ
θcm
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
30
60
90
120
150

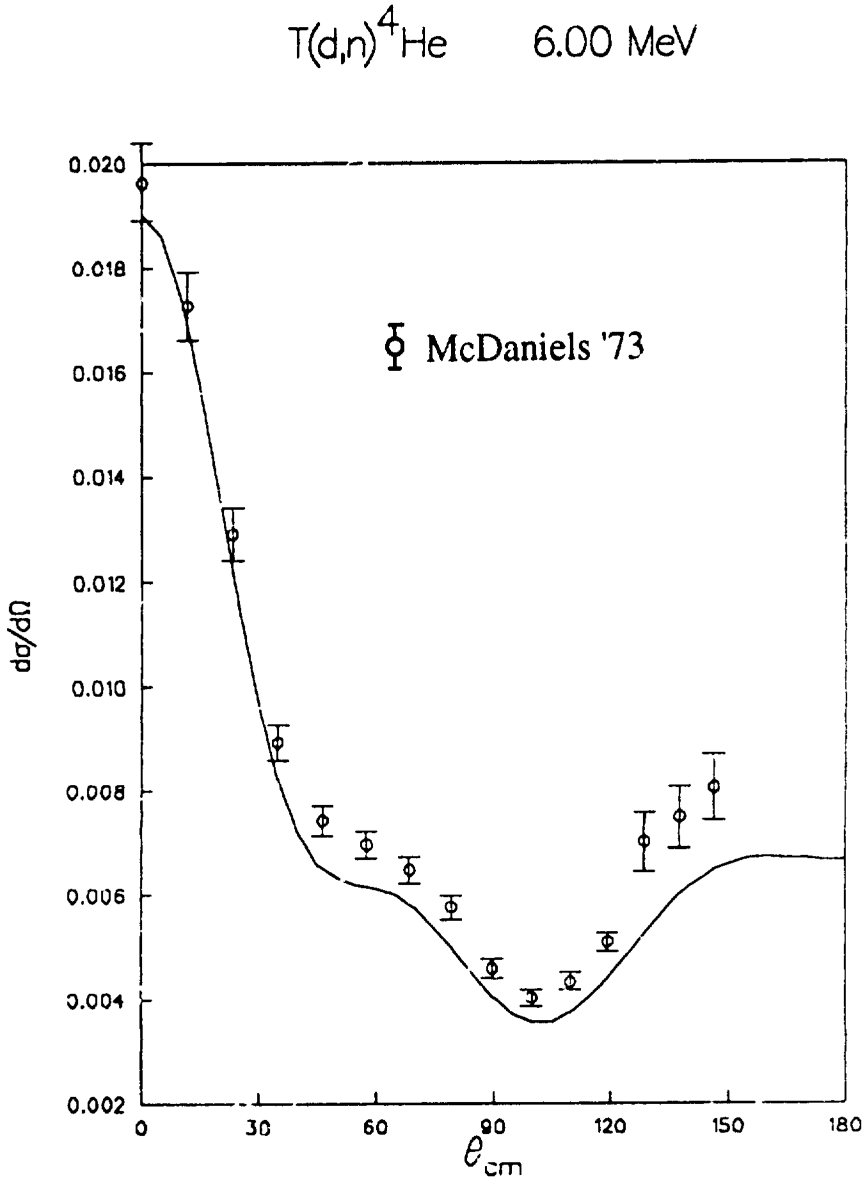

T(d,n)4He 7.00 MeV
Drosg '78
dσ/dΩ
θcm
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
30
60
90
120
150
180


T(d,n)4He 10.0 MeV
Drosg '78
dσ/dΩ
θcm
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

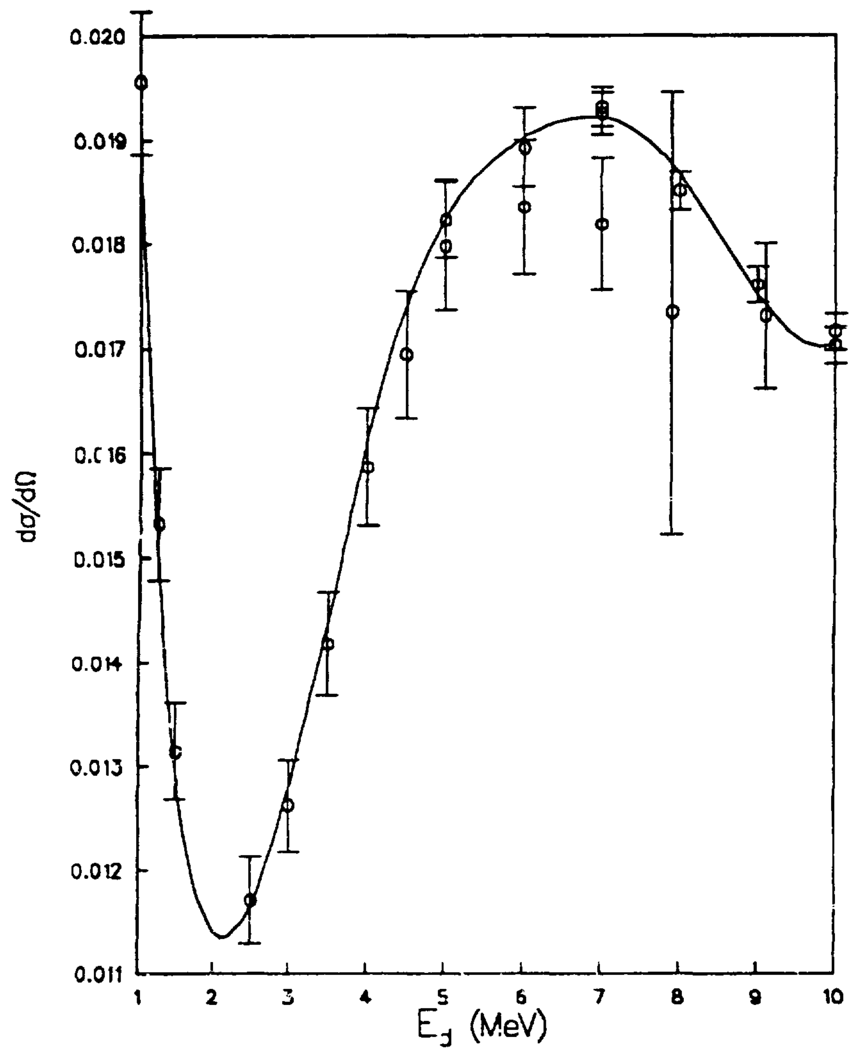

revised by
Drosg '90


revised by
Drosg '90

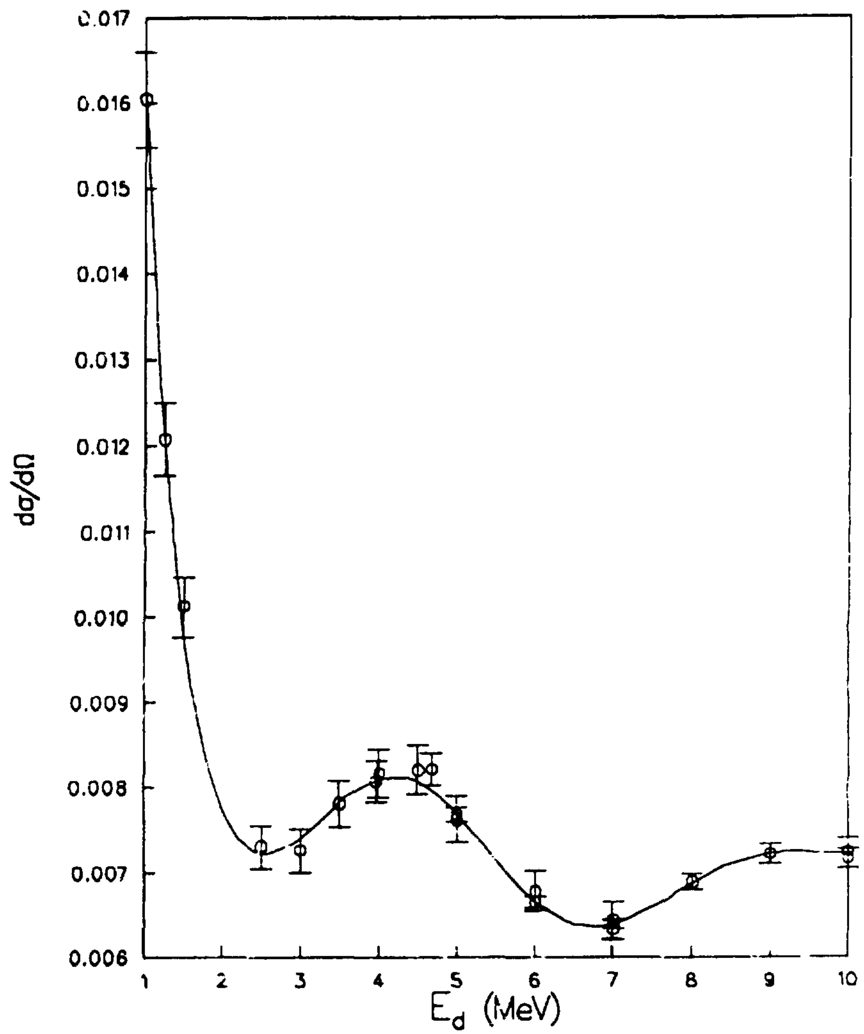

T(d,n)^{4}He 5.00 MeV
McDaniels '73
dσ/dΩ
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
30
60
90
120
150
180
θ_{cm}

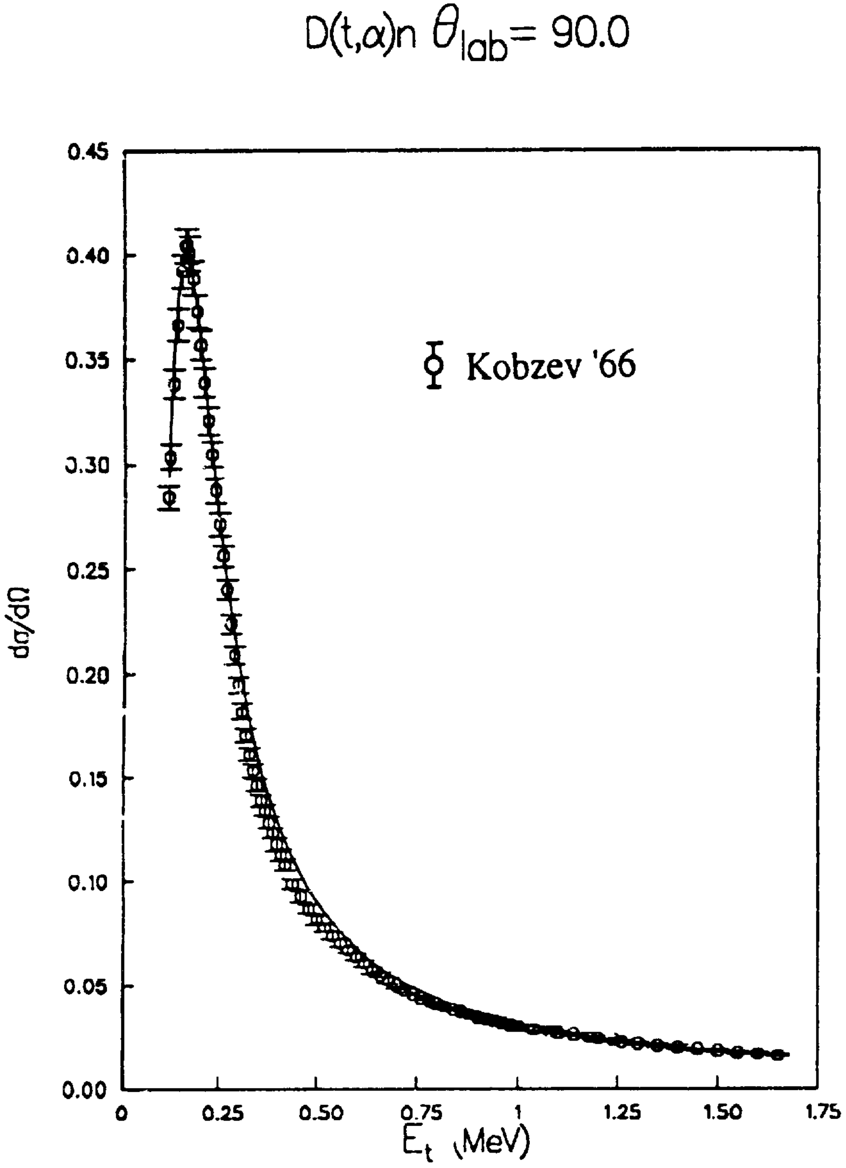

T(d,n)^{4}He 6.00 MeV
McDaniels '73
dσ/dΩ
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
30
60
90
120
150
180
θ_{cm}

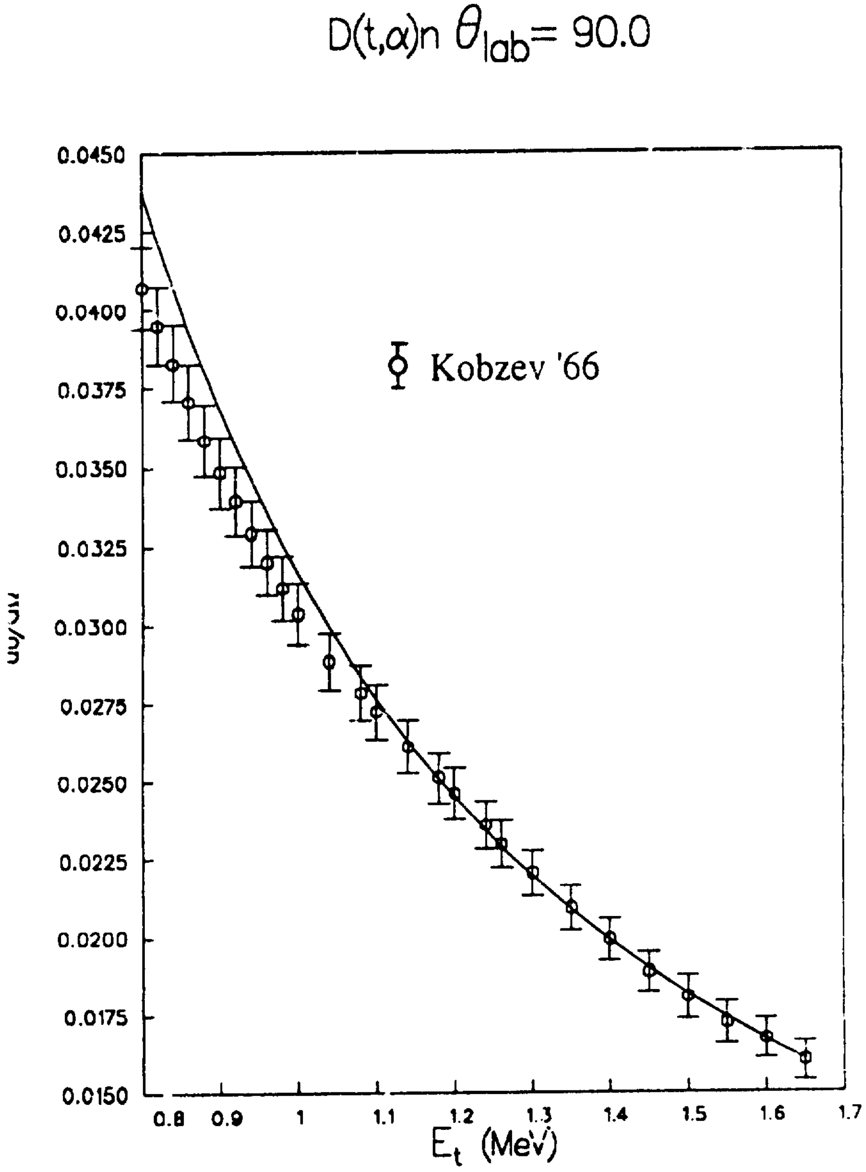
T(d,n)^{4}He θ_{cm} = 0.0



T(d,n)^{4}He θ_{cm} =180.0




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


D(t,α)n θlab= 90.0
Kobzev '66
Et (MeV)
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
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7

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.