Appendix A

Analysis and Results

A.1 Generating Clover PPAC Time Difference Spectrum

1. Reject multi-hit events in PPAC
2. Reject zero events in Clover 2 TAC
3. Generate Clover-2 add-back energy spectrum (with energy gate?)
4. Copy ADC42 to ADC16 (to put Clover time before PPAC time)
5. Define TDC command between ADC16-36
6. **New* TAC is between Clover-2 (any segment) any of the PPAC detectors (ADC17-36)
7. Project this TAC with different Clover-2 energies

$\star$ For getting the best time resolution, the centroids for each of the gamma-PPAC spectra are first matched for instrumental delays. To avoid variations in the timings for individual clover segments, TAC spectra were gated by individual Clover segments. The timing spreads between individual Clover segments were ns for 1 MeV gamma rays To simplify centroid matching, a condition of non-zero delayline signal was incorporated to eliminate the left-side peak associated with the detection of Sn-particles.

A.2 Nuclear Structure Data

Isotope	I^π E (MeV)	$I_i \rightarrow I_f$ B(E2;$I_i \rightarrow I_f$) (e^2b^2)	$\langle I_f \| M(E2) \| I_i \rangle$ (eb)	τ (ps)
^{112}Sn	2_1^+ 1.257	$0_1^+ \rightarrow 2_1^+$ 0.240(14)	0.490 (14)	0.542 (52)
	2_2^+ 2.151	$0_1^+ \rightarrow 2_2^+$ 0.0007(2)	0.026 (4)	
		$2_1^+ \rightarrow 2_2^+$ 0.037(15)	0.430 (80)	
	0_2^+ 2.191			
	4_1^+ 2.248	$2_1^+ \rightarrow 4_1^+$ 0.032(5)	0.403 (32)	
^{114}Sn	2_1^+ 1.299	$0_1^+ \rightarrow 2_1^+$ 0.232(8)	0.481(9)	0.48(2)
	0_2^+ 1.953	$0_2^+ \rightarrow 2_1^+$ 0.07(3))	0.27(4)	6.5(23)
	0_3^+ 2.156	$0_3^+ \rightarrow 2_1^+$ 0.016		7.6
	4_1^+ 2.187	$2_1^+ \rightarrow 4_1^+$ 0.035(3)	0.42(2)	5.3(4)
	2_2^+ 2.239			
^{116}Sn	2_1^+ 1.294	$0_1^+ \rightarrow 2_1^+$ 0.209(6)	0.457 (7)	0.538 (15)
	0_2^+ 1.757	$0_2^+ \rightarrow 2_2^+$ 0.44(17)	0.66 (12)	
	2_2^+ 2.112	$0_1^+ \rightarrow 2_2^+$ 0.0011(4)	0.032 (6)	
		$2_1^+ \rightarrow 2_2^+$ 0.013(5)	0.255 (45)	
	4_1^+ 2.391	$2_1^+ \rightarrow 4_1^+$ 0.137(25)	0.827 (73)	
		$2_2^+ \rightarrow 4_1^+$ 0.360(72)	1.342 (128)	
^{58}Ni	2_1^+ 1.454	$0_1^+ \rightarrow 2_1^+$ 0.0705(18)	0.266 (3)	0.891 (22)
		$0_1^+ \rightarrow 2_1^+$ 0.0493(18)	0.222 (4)	
	4_1^+ 2.459	$2_1^+ \rightarrow 4_1^+$ 0.0264(24)	0.363 (17)	

see: NNDC & N.-G Johnson et al. Nucl. Phys. A371(1981), 333

Isotope	I^π E (MeV)	$I_i \rightarrow I_f$ B(E3;$I_i \rightarrow I_f$) (e^2b^2)	$\langle I_f \| M(E3) \| I_i$ (eb)
^{112}Sn	3_1^- 2.355	$0_1^+ \rightarrow 3_1^-$ 0.087(12)	0.295 (20)
^{114}Sn	3_1^- 2.275		
^{116}Sn	3_1^- 2.266	$0_1^+ \rightarrow 3_1^-$ 0.127(17)	0.356 (24)

A.3 Doppler Correction

A.3.1 Details of ^{58}Ni measured with PPAC, ^{58}Ni excited

$^{58}Ni \rightarrow {}^{112}Sn$, E=175MeV, ϑ_p=32.3°, ϑ_γ=147°, φ_γ=143.2°

$$v_{cm} = 0.04634 \cdot \left(1 + \frac{A_2}{A_1}\right)^{-1} \sqrt{\frac{E_{lab}}{A_1}}$$

$$v_{cm} = 0.02746$$

$$\theta_{cm} = \vartheta_1 + arcsin\left(\frac{A_1}{A_2} \cdot sin\vartheta_1\right) = 48.4°$$

$$v_1 = v_{cm} \cdot \left[1 + \left(\frac{A_2}{A_1}\right)^2 + 2 \cdot \left(\frac{A_2}{A_1}\right) \cdot cos\theta_{cm}\right]^{\frac{1}{2}}$$

$$v_1 = 0.07417$$

$$cos\vartheta_{\gamma 1} = cos\vartheta_\gamma \cdot cos\vartheta_1 + sin\vartheta_\gamma \cdot sin\vartheta_1 \cdot cos(\varphi_\gamma - \varphi_1)$$

$$cos(\varphi_\gamma - \varphi_1) = cos\varphi_\gamma \cdot cos\varphi_1 + sin\varphi_\gamma \cdot sin\varphi_1$$

$$\frac{E_{\gamma 0}}{E_\gamma} = \frac{1 - v_1 \cdot cos\vartheta_{\gamma 1}}{\sqrt{1 - v_1^2}}$$

φ_1[°]	cos$\vartheta_{\gamma 1}$	E_γ=E_γ^{min}[keV]
9	-0.9118	1358
27	-0.8374	1365
45	-0.7504	1374
63	-0.6594	1382
81	-0.5732	1391
99	-0.5003	1398
117	-0.4478	1403
135	-0.4208	1406
153	-0.4221	1406
171	-0.4515	1403
189	-0.5060	1398
207	-0.5804	1390
225	-0.6674	1382
243	-0.7584	1373
261	-0.8446	1365
279	-0.9175	1358
297	-0.9700	1353
315	-0.9969	1350
333	-0.9957	1350
351	-0.9663	1353

A.3.2 Details of ^{112}Sn measured with PPAC, ^{58}Ni excited

$^{58}Ni \rightarrow {}^{112}Sn$, E=175MeV, ϑ_p=32.3°, ϑ_γ=147°, φ_γ=143.2°

$$v_{cm} = 0.04634 \cdot \left(1 + \frac{A_2}{A_1}\right)^{-1} \sqrt{\frac{E_{lab}}{A_1}}$$

$$v_{cm} = 0.02746$$

$$cos\vartheta_1 = \frac{v_{cm}}{v_1}\left(1 + \frac{A_2}{A_1} \cdot cos\theta_{cm}\right)$$

$$with\ \theta_{cm} = 180° - 2 \cdot \vartheta_2 = 115.4°$$

$$v_1 = v_{cm} \cdot \left[1 + \left(\frac{A_2}{A_1}\right)^2 + 2 \cdot \left(\frac{A_2}{A_1}\right) \cdot cos\theta_{cm}\right]^{\frac{1}{2}}$$

$$v_1 = 0.04814$$

$$cos\vartheta_{\gamma 1} = cos\vartheta_\gamma \cdot cos\vartheta_1 - sin\vartheta_\gamma \cdot sin\vartheta_1 \cdot cos(\varphi_\gamma - \varphi_2)$$

$$with\ \vartheta_1 = 84.4°$$

$$cos(\varphi_\gamma - \varphi_2) = cos\varphi_\gamma \cdot cos\varphi_2 + sin\varphi_\gamma \cdot sin\varphi_2$$

$$\frac{E_{\gamma 0}}{E_\gamma} = \frac{1 - v_1 \cdot cos\vartheta_{\gamma 1}}{\sqrt{1 - v_1^2}}$$

$\varphi_2(\varphi_1)$[°]	$cos\vartheta_{\gamma 1}$	E_γ=E_γ^{max}[keV]
9(189)	-0.4597	1421
27(207)	-0.3212	1430
45(225)	-0.1592	1441
63(243)	0.0104	1453
81(261)	0.1710	1464
99(279)	0.3068	1474
117(297)	0.4045	1481
135(315)	0.4547	1485
153(333)	0.4523	1485
171(351)	0.3976	1481
189(9)	0.2961	1473
207(27)	0.1575	1463
225(45)	-0.0045	1452
243(63)	-0.1741	1440
261(81)	-0.2246	1429
279(99)	-0.4704	1420
297(117)	-0.5682	1414
315(135)	-0.6183	1410
333(153)	-0.6160	1410
351(171)	-0.5613	1414

A.3.3 Details of ^{112}Sn measured with PPAC, ^{112}Sn excited

$^{58}Ni \rightarrow {}^{112}Sn$, E=175MeV, ϑ_p=32.3°, ϑ_γ=147°, φ_γ=143.2°

$$v_{cm} = 0.04634 \cdot \left(1 + \frac{A_2}{A_1}\right)^{-1} \sqrt{\frac{E_{lab}}{A_1}}$$

$$v_{cm} = 0.02746$$

$$v_2 = 2 \cdot v_{cm} \cdot cos\vartheta_2 = 0.04643$$

$$cos\vartheta_{\gamma 2} = cos\vartheta_\gamma \cdot cos\vartheta_2 + sin\vartheta_\gamma \cdot sin\vartheta_2 \cdot cos(\varphi_\gamma - \varphi_2)$$

$$cos(\varphi_\gamma - \varphi_2) = cos\varphi_\gamma \cdot cos\varphi_2 + sin\varphi_\gamma \cdot sin\varphi_2$$

$$\frac{E_{\gamma 0}}{E_\gamma} = \frac{1 - v_2 \cdot cos\vartheta_{\gamma 2}}{\sqrt{1 - v_2^2}}$$

φ_2[°]	cos$\vartheta_{\gamma 2}$	E_γ=E_γ^{min}[keV]
9	-0.9118	1205
27	-0.8374	1209
45	-0.7504	1213
63	-0.6594	1218
81	-0.5732	1223
99	-0.5003	1227
117	-0.4478	1230
135	-0.4208	1232
153	-0.4221	1232
171	-0.4515	1230
189	-0.5060	1227
207	-0.5804	1223
225	-0.6674	1218
243	-0.7584	1213
261	-0.8446	1208
279	-0.9175	1204
297	-0.9700	1202
315	-0.9969	1200
333	-0.9957	1200
351	-0.9663	1202

A.3.4 Details of ^{58}Ni measured with PPAC, ^{112}Sn excited

$^{58}Ni \rightarrow {}^{112}Sn$, E=175MeV, ϑ_p=32.3°, ϑ_γ=147°, φ_γ=143.2°

$$\mathrm{v}_{cm} = 0.04634 \cdot \left(1 + \frac{A_2}{A_1}\right)^{-1} \sqrt{\frac{E_{lab}}{A_1}}$$

$$v_{cm} = 0.02746$$

$$\vartheta_2 = 0.5 \cdot (180° - \theta_{cm})$$

$$with\ \theta_{cm} = \vartheta_1 + arcsin\left(\frac{A_1}{A_2} \cdot sin\vartheta_1\right) = 48.4°$$

$$v_2 = 2 \cdot v_{cm} \cdot cos\vartheta_2 = 0.02250$$

$$with\ \vartheta_2 = 65.8°$$

$$cos\vartheta_{\gamma 2} = cos\vartheta_\gamma \cdot cos\vartheta_2 - sin\vartheta_\gamma \cdot sin\vartheta_2 \cdot cos(\varphi_\gamma - \varphi_1)$$

$$cos(\varphi_\gamma - \varphi_2) = cos\varphi_\gamma \cdot cos\varphi_2 + sin\varphi_\gamma \cdot sin\varphi_1$$

$$\frac{E_{\gamma 0}}{E_\gamma} = \frac{1 - v_2 \cdot cos\vartheta_{\gamma 2}}{\sqrt{1 - v_2^2}}$$

$\varphi_1(\varphi_2)$[°]	cos$\vartheta_{\gamma 2}$	E_γ=E_γ^{max}[keV]
9(189)	0.0025	1257
27(207)	-0.1245	1253
45(225)	-0.2729	1249
63(243)	-0.4283	1245
81(261)	-0.5755	1241
99(279)	-0.6999	1237
117(297)	-0.7895	1235
135(315)	-0.8355	1233
153(333)	-0.8333	1234
171(351)	-0.7832	1235
189(9)	-0.6901	1237
207(27)	-0.5631	1241
225(45)	-0.4146	1245
243(63)	-0.2592	1249
261(81)	-0.1121	1254
279(99)	0.0124	1257
297(117)	0.1019	1260
315(135)	0.1479	1261
333(153)	0.1457	1261
351(171)	0.0956	1259

A.4 Range Energy Table for Sn on Sn

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Calculation using SRIM-2006 SRIM version — SRIM-2008.04
Calc. date — March 14, 2009

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Disk File = SRIM Outputs (Tin in Tin) Ion = Tin [50] , Mass = 119.902 amu
Target Density = 7.2816E+00 g/cm^3 = 3.6939E+22 atoms/cm^3
=============Target Composition========
AtomName =Sn AtomNumber=50 Atomic Percent=100.00 Mass Percent=100
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Bragg Correction = 0.00% Stopping Units = MeV /(mg/cm^2)
See bottom of Table for other Stopping units

Ion *Energy*	dE/dx *Elec.*	dE/dx *Nuclear*	Projected *Range*	Longitudinal *Straggling*	Lateral *Straggling*
1.00 MeV	1.118E+00	3.234E+00	2357 Å	1001 Å	698 Å
1.10 MeV	1.182E+00	3.151E+00	2600 Å	1088 Å	761 Å
1.20 MeV	1.242E+00	3.071E+00	2846 Å	1173 Å	823 Å
1.30 MeV	1.297E+00	2.996E+00	3095 Å	1258 Å	886 Å
1.40 MeV	1.348E+00	2.924E+00	3347 Å	1342 Å	949 Å
1.50 MeV	1.397E+00	2.857E+00	3601 Å	1425 Å	1011 Å
1.60 MeV	1.442E+00	2.792E+00	3857 Å	1507 Å	1074 Å
1.70 MeV	1.486E+00	2.731E+00	4116 Å	1589 Å	1137 Å
1.80 MeV	1.529E+00	2.673E+00	4376 Å	1670 Å	1200 Å
2.00 MeV	1.611E+00	2.565E+00	4904 Å	1830 Å	1326 Å
2.25 MeV	1.709E+00	2.444E+00	5572 Å	2025 Å	1485 Å
2.50 MeV	1.807E+00	2.335E+00	6249 Å	2216 Å	1644 Å
2.75 MeV	1.906E+00	2.237E+00	6931 Å	2401 Å	1802 Å
3.00 MeV	2.005E+00	2.149E+00	7616 Å	2580 Å	1961 Å
3.25 MeV	2.107E+00	2.068E+00	8302 Å	2754 Å	2118 Å
3.50 MeV	2.211E+00	1.994E+00	8988 Å	2922 Å	2273 Å
3.75 MeV	2.317E+00	1.926E+00	9672 Å	3084 Å	2427 Å
4.00 MeV	2.426E+00	1.863E+00	1.04 um	3239 Å	2579 Å
4.50 MeV	2.650E+00	1.751E+00	1.17 um	3533 Å	2876 Å
5.00 MeV	2.881E+00	1.654E+00	1.30 um	3804 Å	3162 Å

Ion *Energy*	dE/dx *Elec.*	dE/dx *Nuclear*	Projected *Range*	Longitudinal *Straggling*	Lateral *Straggling*
5.50 MeV	3.118E+00	1.569E+00	1.43 um	4053 Å	3435 Å
6.00 MeV	3.361E+00	1.493E+00	1.56 um	4282 Å	3695 Å
6.50 MeV	3.606E+00	1.425E+00	1.68 um	4491 Å	3942 Å
7.00 MeV	3.854E+00	1.364E+00	1.80 um	4683 Å	4175 Å
8.00 MeV	4.352E+00	1.259E+00	2.02 um	5026 Å	4605 Å
9.00 MeV	4.847E+00	1.171E+00	2.23 um	5317 Å	4990 Å
10.00 MeV	5.334E+00	1.096E+00	2.43 um	5566 Å	5333 Å
11.00 MeV	5.809E+00	1.031E+00	2.62 um	5782 Å	5642 Å
12.00 MeV	6.270E+00	9.741E-01	2.80 um	5971 Å	5921 Å
13.00 MeV	6.715E+00	9.242E-01	2.97 um	6137 Å	6174 Å
14.00 MeV	7.144E+00	8.797E-01	3.13 um	6285 Å	6405 Å
15.00 MeV	7.556E+00	8.399E-01	3.29 um	6417 Å	6616 Å
16.00 MeV	7.953E+00	8.040E-01	3.44 um	6536 Å	6810 Å
17.00 MeV	8.334E+00	7.714E-01	3.58 um	6643 Å	6990 Å
18.00 MeV	8.700E+00	7.416E-01	3.72 um	6742 Å	7157 Å
20.00 MeV	9.391E+00	6.893E-01	3.99 um	6919 Å	7458 Å
22.50 MeV	1.018E+01	6.345E-01	4.30 um	7108 Å	7785 Å
25.00 MeV	1.091E+01	5.886E-01	4.60 um	7267 Å	8068 Å
27.50 MeV	1.158E+01	5.496E-01	4.88 um	7404 Å	8317 Å
30.00 MeV	1.220E+01	5.160E-01	5.15 um	7523 Å	8540 Å
32.50 MeV	1.278E+01	4.866E-01	5.40 um	7628 Å	8740 Å
35.00 MeV	1.333E+01	4.608E-01	5.65 um	7721 Å	8921 Å
37.50 MeV	1.385E+01	4.378E-01	5.89 um	7805 Å	9087 Å
40.00 MeV	1.435E+01	4.173E-01	6.12 um	7881 Å	9240 Å

Multiply Stopping by	for Stopping Units
7.2814E+01	eV / Angstrom
7.2814E+02	keV / micron
7.2814E+02	MeV / mm
1.0000E+00	keV / (ug/cm2)
1.0000E+00	MeV / (mg/cm2)
1.0000E+03	keV / (mg/cm2)
1.9712E+02	eV / (1E15 atoms/cm2)
9.6617E-02	L.S.S. reduced units

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A.5 Input for Coulomb Excitation (lell30e1.f)

datacard#	parameter	input description
1	NMAX	number of nuclear states
2	NCM	index of level for which the lab-transformation is done
3	NTIME	-
4	XIMAX	largest number for ξ-parameter
5	EMMAXI	largest magnetic quantum number considered
6	ACCUR	absolute accuracy to which the final probabilities should be computed
	QPAR	effect of the giant dipole resonance
7	OUXI	print-out of ξ-matrix
8	OUPSI	print-out of ψ-matrix
9	OUAMP	print-out of excitation amplitudes
10	OUPROW	print-out of excitation probability during integration
11	OUANG0	print-out of angular distribution coefficients α^0
12	OUANG1	print-out of angular distribution coefficients α^1
13	OUANG2	print-out of angular distribution coefficients α^2
14	OUANG3	print-out of angular distribution coefficients α^3
15	NCORR	
16	INTERV	number of integration steps
17	Z1	charge number of the projectile
	A1	mass of projectile [amu]
18	Z2	charge number of the target nucleus
	A2	mass of target nucleus [amu]
19	EP	laboratory energy of projectile [MeV]
20	TLBDG	deflection angle [degree] in the lab-system
21	THETA	deflection angle [degree] in the cm-system
22	N	index of level

datacard#	parameter	input description
	SPIN(N)	spin quantum number of the Nth nuclear state
	EN(N)	excitation energy of the Nth nuclear state
	IPAR(N)	parity (-1 neg, 1 pos) of the Nth nuclear state
23	N	index of level
	M	index of level (M≥N)
	ME(N,M,LA)	electric matrix element
	LA	multipolarity (1≤LA≤6)
0		starts the calculation
500		stops the calculation

A.6 Input for Angular Distribution (anggro.f)

datacard#	parameter	input description
1	I11	output of the conversion coefficients (E2,M1,E1,E3)
	I12	possible decays of a state
	I13	HN (lifetime of the state)
	I14	G_K(N,M)
	I15	F_K(N,M)
	I16	α^3(k,κ)+feeding
	I17	Spin(N),Spin(M),W(N,K)
	I18	Spin(N),Spin(M),DS(N,K)
	I19	γ-ray angular distribution θ_γ=0°,180°,5°,ϕ_γ=0° and 180°
	I20	-
	I21	excitation probabilities, cross sections, α^3(k,κ)
	I22	1 ≡ solid angle correction, 2 ≡ +deorientation, 3 ≡ +SB
	I23	input M1-matrix element + M1 conversion coefficient
	I24	1 ≡ calc. in rest system, 1 input of θ_γ, ϕ_γ in rest system
	I25	projectile excitation

datacard#	parameter	input description
2	NCCK	number of values given for K-conversion
	NCCL	number of values given for L-conversion
	NCCM	number of values given for M-conversion
3-5	CCE1	lowest tabulated energy to be interpolated, -1.0 for L,M
	CCE2	lowest tabulated energy of the K, L2, M5 subshell
	CCMIN	min. energy given in the conversion table
	CCMAX	max. energy given in the conversion table
6_{1-}	α_K,I=1,NCCK	conversion coefficients (K-shell)
7_{1-}	α_L,I=1,NCCL	conversion coefficients (L-shell)
8_{1-}	α_M,I=1,NCCM	conversion coefficients (M-shell)
9	IXYZ	I23=1 IXYZ=initial state
	JXYZ	I23=1 JXYZ=final state
	MM1(1XYZ,JXYZ)	I23=1 M1-matrix element (IXYZJXYZ)
10	TT	θ_γ
	VGAMMA	ϕ_γ
	VI1	ϕ_1
	VI2	ϕ_γ
	K1LAB	state for cm to lab transformation
11	Q_0, Q_2, Q_4	I22=1 solid angle correction for Ge-detector
		I22=2, I22=3, I22=4, I22=5 (see program)
12	MZahl	number of theta integrations
	NORM	normalization, neg. value Rutherford
13	XA	initial scattering angle in cm system for integration
	XE	final scattering angle in cm system for integration

A.7 Important Formulas

nuclear lifetime:

$$\tau[S] = \left\{ \sum_M \sum_L \delta^2_{N\to M}(L) \cdot [1 + \alpha_{N\to M}(L)] \right\}^{-1} \tag{A.1}$$

with

$$\delta^2_{N\to M}(E2)[s^{-1}] = 1.225 \cdot 10^{13} \cdot E_\gamma[MeV]^5 \cdot B(E2; I_N \to I_M)[e^2b^2] \tag{A.2}$$

$$\delta^2_{N\to M}(M1)[s^{-1}] = 1.758 \cdot 10^{13} \cdot E_\gamma[MeV]^3 \cdot B(M1; I_N \to I_M)\left[\frac{e\hbar}{2m_pc}\right]^2 \tag{A.3}$$

$$\delta^2_{N\to M}(E1)[s^{-1}] = 1.590 \cdot 10^{17} \cdot E_\gamma[MeV]^3 \cdot B(E1; I_N \to I_M)[eb] \tag{A.4}$$

$$\delta^2_{N\to M}(E3)[s^{-1}] = 5.709 \cdot 10^{8} \cdot E_\gamma[MeV]^7 \cdot B(E3; I_N \to I_M)[e^3b^3] \tag{A.5}$$

relation between B(E2) values:

$$B(EL; I_N \to I_M) = \frac{2 \cdot I_M + 1}{2 \cdot I_N + 1} \cdot B(EL; I_M \to I_N) \tag{A.6}$$

reduced matrix element

$$B(EL; I_M \to I_N) = \frac{1}{2 \cdot I_M + 1} \cdot \langle I_N \| M(EL) \| I_M \rangle^2 \tag{A.7}$$

Coulomb excitation cross section (single state excitation):

$$\sigma_{E2} = 4.819 \cdot \left(1 + \frac{A_1}{A_2}\right)^{-2} \cdot \frac{A_1}{Z_2^2} \cdot \left(E_{MeV} - \left(1 + \frac{A_1}{A_2}\right) \cdot \triangle E_{MeV}\right) \cdot B(E2; 0^+ \to 2^+) \cdot f_{E2}(\xi) \tag{A.8}$$

with

$$\xi = \frac{Z_1 \cdot Z_2 \cdot A_1{}^{\frac{1}{2}} \cdot \triangle E'_{MeV}}{12.65 \cdot (E_{MeV} - 0.5 \cdot \triangle E'_{MeV})^{\frac{3}{2}}} with \triangle E'_{MeV} = \left(1 + \frac{A_1}{A_2}\right) . \triangle E_{MeV} \tag{A.9}$$