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Resurgence of beta spectrometry in a metrological context

Outlines

- Context and current situation
- The BetaShape code
- High precision study of atomic effects
- Outlook

The BetaShape program is available at http://www.nucleide.org/logiciels.htm



TU Dresden 2017 | X. Mougeot





Oriented research

Fundamental research

Nuclear physics

Particle physics

Radiotoxicology





Laboratoire National Henri Becquerel

lonizing radiation metrology

Radiochemistry

Bq, Gy and Sv units Activity standards ~ 0.1% Atomic and nuclear data



Applied research Industries Nuclear medicine Nuclear energy

Instrumentation

Laboratoire National LABORA Henri Becquerel





Importance of beta decays



Scientific research

- Nuclear astrophysics (r-process)
- Standard Model (CKM matrix unitarity, weak magnetism)
- Beyond Standard Model (Fierz interference, sterile neutrino)
- Neutrino physics (reactor monitoring, non-proliferation)
- New detectors (BrLa₃)



Ionizing radiation metrology

Activity measurements by Liquid Scintillation Counting

Better knowledge of the beta spectra \rightarrow better uncertainties



Atomic and nuclear data

- NNDC (Brookhaven),
 - \rightarrow **ENSDF** nuclear decay data
- **DDEP** (International collaboration)

Decay Data Evaluation Project Atomic and nuclear decay data recommended by the BIPM





Medical uses

Micro-dosimetry, internal radiotherapy



Nuclear fuel cycle Decay heat, nuclear waste





Beta spectrum measurement is old-fashioned

Parent	Mode	E_0	Experimental shape factor	Ref.	Range	$\% E_0$	$ar{E}_{ m sf}$	\bar{E}_{calc}	
Second	forbidd	en unique							
10 Be	β^-	556	$q^4 + (10/3)q^2p^2 + p^4$	[79]	100-500	71.9	252.33	252.00	
²² Na	eta^+	1821.02	$q^4 + (10/3)\lambda_2 q^2 p^2 + \lambda_3 p^4$	[80]	660–1660	54.9	835.83	833.00	
⁶⁰ Co	β^{-}	1490.56	$q^4 + (10/3)\lambda_2 q^2 p^2 + \lambda_3 p^4$	[<mark>81</mark>]	1350-1450	6.7	624.50	623.47	X. Mougeot, Phys. Rev.
¹³⁸ La	β^{-}	258	1+407.71W - 50.695/W -583.794 W^2 +246.279 W^3	[<mark>63</mark>]	2.5–255	97.9	90.48	95.55	C 91, 055504 (2015)
Third f	orbidder	n unique							
⁴⁰ K	β^{-}	1311.07	$\frac{1.05q^6 + 6.3q^4p^2}{+6.25q^2p^4 + 0.95p^6}$	[82]	100-1100	76.3	583.98	583.27	

Created database of 130 experimental shape factors

- Allowed: 36
- Forbidden unique: 25 (1st), 4 (2nd), 1 (3rd)
- Forbidden non-unique: 53 (1st), 9 (2nd), 1 (3rd), 1 (4th)
- \rightarrow Few measurements below 50 keV
- \rightarrow Very few high order forbidden transitions
- \rightarrow 11 published shape factors since 1976!

New precise measurements are needed to test the theoretical predictions



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If no experimental data \rightarrow Theoretical estimates

The LogFT program is widely used in nuclear data evaluations

- Handles β and ε transitions
- Provides mean energies of β spectra, log *ft* values, β^+ and ε probabilities
- Propagates uncertainties from input parameters
- Reads and writes ENSDF files (*Evaluated Nuclear Structure Data File*)

However

- Too simple analytical models \rightarrow lack of accuracy
- Forbiddenness limitation (allowed, first- and second- forbidden unique)
- Users now require β spectra and correlated v spectra

Constraints for a new code

- Fast calculations
- Ease-of-use for both evaluators and users
- Should read and write ENSDF files



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Visit Purpose Visit Evaluation of the shapes State spectro State spectro







The BetaShape code





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Behrens and Bühring formalism

 $\langle \phi_i$

Similarly we obtain for the space components

$$\langle \boldsymbol{p} | \mathbf{V} + \mathbf{A} | \boldsymbol{n} \rangle = i u_{p}^{*} \underline{\gamma_{4}} \gamma_{\mu} (1 + \underline{\lambda \gamma_{5}}) u_{n} = \sqrt{\frac{(W_{n} + M_{n})}{2W_{n}}} \sqrt{\frac{(W_{p} + M_{p})}{2W_{p}}} \\ \begin{pmatrix} 0 & i \boldsymbol{\sigma} \\ i \boldsymbol{\sigma} & 0 \end{pmatrix} \lambda \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\ \times \left\{ \left(\frac{\boldsymbol{\sigma} \mathbf{p}}{W_{p} + M_{p}} \chi_{p}^{m'} \right)^{+} \boldsymbol{\sigma} \chi_{n}^{m} + (\chi_{p}^{m'})^{+} \boldsymbol{\sigma} \frac{\boldsymbol{\sigma} \mathbf{p}}{W_{n} + M_{n}} \chi_{n}^{m} - \lambda (\chi_{p}^{m'})^{+} \boldsymbol{\sigma} \chi_{n}^{m} \\ - \lambda \left[\left(\frac{\boldsymbol{\sigma} \mathbf{p}}{W_{p} + M_{p}} \chi_{p}^{m'} \right)^{+} \boldsymbol{\sigma} \frac{\boldsymbol{\sigma} \mathbf{p}}{W_{n} + M_{n}} \chi_{n}^{m} - \right] \right\}.$$
(6.38)

This equals to

(p

$$\mathbf{V} + \mathbf{A} | n \rangle = \sqrt{\frac{(W_n + M_n)}{2W_n}} \sqrt{\frac{(W_p + M_p)}{2W_p}} \left\{ (\chi_p^m)^+ \frac{\boldsymbol{\sigma} \mathbf{p}_p}{W_p + M_p} \boldsymbol{\sigma} \chi_n^m + (\chi_p^m)^+ \boldsymbol{\sigma} \frac{\boldsymbol{\sigma} \mathbf{p}_n}{W_n + M_n} \chi_n^m - \lambda (\chi_p^m)^+ \boldsymbol{\sigma} \chi_n^m + (\chi_p^m)^+ \boldsymbol{\sigma} \frac{\boldsymbol{\sigma} \mathbf{p}_n}{W_n + M_n} - \lambda (\chi_p^m)^+ \boldsymbol{\sigma} \chi_n^m + (\chi_p^m)^+ \boldsymbol{\sigma} \chi_n^m + M_n + M$$

Finally we obtain for the space components

$$\begin{aligned} \left[\mathbf{v}(0) + \mathbf{A}(0) \mid n \right] &= \sqrt{\frac{(W_n + M_n)}{2W_n}} \sqrt{\frac{(W_p + M_p)}{2W_p}} \\ &\times \left\{ \left[\frac{\mathbf{p}_p}{W_p + M_p} + \frac{\mathbf{p}_n}{W_n + M_n} \right] (\chi_p^{m'})^+ \chi_n^m + (\chi_p^{m'})^+ \right. \\ &\times \left[\frac{i(\boldsymbol{\sigma} \times \mathbf{p}_p)}{W_p + M_p} - \frac{i(\boldsymbol{\sigma} \times \mathbf{p}_n)}{W_n + M_n} \right] \chi_p^m - \lambda (\chi_p^m')^+ \boldsymbol{\sigma} \chi_n^m \\ &+ \lambda \frac{\mathbf{p}_p \mathbf{p}_n}{(W_p + M_p)(W_n + M_n)} \left\{ (\chi_p^m)^+ \boldsymbol{\sigma} \chi_n^m \right\} + \lambda \frac{i(\mathbf{p}_p \times \mathbf{p}_n)}{(W_p + M_p)(W_n + M_n)} \\ &\times (\chi_p^{m'})^+ \chi_n^m - \lambda \left[(\chi_p^m')^+ \frac{(\boldsymbol{\sigma} \mathbf{p}_p) \mathbf{p}_n + \mathbf{p}_p (\boldsymbol{\sigma} \mathbf{p}_n)}{(W_p + M_p)(W_n + M_n)} \chi_n^m \right] \right\}. \end{aligned}$$
(6.40)

$$-\frac{i}{2M_{A}}F_{M}(q^{2})(\mathbf{P}\times\mathbf{q})\boldsymbol{\sigma}-F_{S}(q^{2})q_{0}+\frac{1}{4(2M_{A})^{2}}F_{S}(q^{2})q_{0}(\mathbf{P}^{2}-\mathbf{q}^{2})$$

$$-\frac{i}{2}\frac{1}{(2M_{A})^{2}}F_{S}(q^{2})q_{0}(\mathbf{P}\times\mathbf{q})\boldsymbol{\sigma}\Big]\chi^{M_{1}} (9.15)$$

$$b_{I}(p_{I})|A_{0}(0)|\phi_{I}(p_{I})\rangle = N(\chi^{M_{I}})^{+}\Big\{-\frac{1}{2M_{A}}F_{A}(q^{2})(\mathbf{P}\boldsymbol{\sigma})$$

$$-\frac{q_{0}}{2M_{A}}F_{P}(q^{2})(\mathbf{q}\boldsymbol{\sigma})-F_{T}(q^{2})(\mathbf{q}\boldsymbol{\sigma})+\frac{1}{4}\frac{1}{(2M_{A})^{2}}F_{T}(q^{2})$$

$$\times[(\mathbf{P}\mathbf{q})(\boldsymbol{\sigma}\mathbf{P}+\boldsymbol{\sigma}\mathbf{q})-(\boldsymbol{\sigma}\mathbf{q})(\mathbf{P}^{2}+\mathbf{q}^{2})]\Big\}\chi^{M_{1}} (9.16)$$

$$i(p_{I})|\mathbf{V}(0)|\phi_{I}(p_{I})\rangle = N(\chi^{M_{I}})^{+}\Big\{\frac{1}{2M_{A}}F_{V}(q^{2})\mathbf{P}+\frac{i}{2M_{A}}F_{V}(q^{2})(\boldsymbol{\sigma}\times\mathbf{q})$$

$$+iF_{M}(q^{2})(\boldsymbol{\sigma}\times\mathbf{q})-\frac{1}{2M_{A}}F_{M}(q^{2})q_{0}\mathbf{q}-\frac{i}{4M_{A}}F_{M}(q^{2})q_{0}(\boldsymbol{\sigma}\times\mathbf{P})$$

$$-F_{S}(q^{2})\mathbf{q}+\frac{1}{4(2M_{A})^{2}}F_{S}(q^{2})\mathbf{q}(\mathbf{P}^{2}-\mathbf{q}^{2})-\frac{i}{2(2M_{A})^{2}}F_{S}(q^{2})\mathbf{q}$$

$$\times((\mathbf{P}\times\mathbf{q})\boldsymbol{\sigma})-\frac{i}{2(2M_{A})^{2}}F_{M}(q^{2})\mathbf{P}((\mathbf{P}\times\mathbf{q})\boldsymbol{\sigma})-\frac{i}{4(2M_{A})^{2}}$$

$$\timesF_{M}(q^{2})(\mathbf{P}^{2}+\mathbf{q}^{2})(\boldsymbol{\sigma}\times\mathbf{q})+\frac{i}{2(2M_{A})^{2}}F_{M}(q^{2})(\mathbf{P}\mathbf{q})(\boldsymbol{\sigma}\times\mathbf{P})\Big\}\chi^{M_{1}} (9.17)$$

$$(\phi_{I}(p_{I})|\mathbf{A}(0)|\phi_{I}(p_{I})\rangle = N(\chi^{M_{I}})^{+}\Big\{-F_{A}(q^{2})\boldsymbol{\sigma}+\frac{1}{2(2M_{A})^{2}}$$

$$\times F_{A}(q^{2})(\mathbf{P}^{2}-\frac{1}{4(2M_{A})^{2}}F_{A}(q^{2})(\mathbf{P}^{2}+\mathbf{q}^{2})\boldsymbol{\sigma}-\frac{i}{2(2M_{A})^{2}}$$

$$\times F_{A}(q^{2})(\mathbf{P}\times\mathbf{q})-\frac{1}{2(2M_{A})^{2}}F_{A}(q^{2})(\mathbf{P}^{2}+\mathbf{q}^{2})\boldsymbol{\sigma}-\frac{i}{2(2M_{A})^{2}}$$

$$\times F_{A}(q^{2})(\mathbf{P}\times\mathbf{q})-\frac{1}{2(2M_{A})^{2}}F_{A}(q^{2})[(\boldsymbol{\sigma}\mathbf{P})\mathbf{P}-(\boldsymbol{\sigma}\mathbf{q})\mathbf{q}]$$

$$+\frac{1}{2M_{A}}F_{T}(q^{2})(q_{0}\mathbf{P}^{2}\boldsymbol{\sigma}-\frac{1}{4(2M_{A})^{2}}F_{T}(q^{2})q_{0}(\mathbf{P}^{2}+\mathbf{q}^{2})\boldsymbol{\sigma}$$

$$-\frac{i}{2(2M_{A})^{2}}F_{T}(q^{2})q_{0}(\mathbf{P}\times\mathbf{q})-\frac{1}{2(2M_{A})^{2}}F_{T}(q^{2})q_{0}(\mathbf{P})\mathbf{P}$$

$$-(\boldsymbol{\sigma}\mathbf{q})\mathbf{q}]-\frac{1}{2M_{A}}F_{P}(q^{2})(\boldsymbol{\sigma}\mathbf{q})\mathbf{q}\Big\}\chi^{M_{I}}. (9.18)$$

 $+\sqrt{2}\left(\left[rI'(r)\beta\gamma_5T_{121}\right]\right)$ $\mp \frac{f_{\rm P}}{R} (W_0 R \pm \frac{6}{5} \alpha Z)^{\rm D} \mathfrak{N}_{110}^{(0)}(1, 1, 1, 1)$ (14.101) ${}^{A}F_{121}^{(0)} = \mp \lambda \ {}^{A}\mathfrak{M}_{121}^{(0)} - \frac{f_{\mathrm{T}}}{R} \left[\frac{5}{\sqrt{3}} \, {}^{C}\mathfrak{M}_{111}^{(0)} - (W_{0}R \pm \frac{6}{3}\alpha Z) \ {}^{A}\mathfrak{M}_{121}^{(0)} \right] \mp \frac{f_{P}}{R} 5 \sqrt{3} \ {}^{D}\mathfrak{M}_{110}^{(0)}$ (14.102) ${}^{A}F_{121}^{(0)}(1, 1, 1, 1) = \mp \lambda \,{}^{A}\mathfrak{M}_{121}^{(0)}(1, 1, 1, 1)$ $-\frac{f_{\mathrm{T}}}{R}\left\{\sqrt{\frac{3}{3}}\left(\int\left(\frac{r}{R}\right)[5I(r)+rI'(r)]\beta T_{111}\right)\right.$ $-(W_0R\pm\frac{6}{5}\alpha Z)^{\wedge}\mathfrak{M}^{(0)}_{121}(1,1,1,1)$ $\mp \frac{f_{\rm P}}{R} \sqrt{\frac{2}{3}} \left(\int \left(\frac{r}{R} \right) [5I(r) + rI'(r)] \beta \gamma_5 T_{110} \right)$ (14.103) ${}^{\vee}F^{(0)}_{\alpha\beta\gamma} = -{}^{\vee}\mathfrak{M}^{(0)}_{\alpha\beta\gamma} - \frac{f_{M}}{f_{M}}(W_{\alpha}R \pm \frac{6}{2}\alpha Z) {}^{C}\mathfrak{M}^{(0)}_{\alpha\beta\gamma}$

SPECIAL FORMULAE

$${}^{\vee}F_{220}^{(0)} = {}^{\vee}\mathfrak{M}_{220}^{(0)} + \frac{f_{M}}{R}\sqrt{(10)} \,{}^{c}\mathfrak{M}_{211}^{(0)} \pm \frac{f_{S}}{R} \left(W_{0}R \pm \frac{6}{3}\alpha Z\right) \,{}^{\vee}\mathfrak{M}_{220}^{(0)}$$
(14.105)

 $(14\ 104)$

(14.108)

$$\begin{aligned} \mathbf{y}_{1,1} &= {}^{\vee}\mathfrak{M}_{220}^{(0)}(1,1,1,1) \\ &+ \frac{f_{M}}{R} \left\{ \sqrt{\frac{2}{3}} \left(\int \left(\frac{r}{R} \right) [5I(r) + rI'(r)] \beta T_{211} \right) \right. \\ &+ \sqrt{\frac{2}{3}} \left(\int \left(\frac{l}{R} \right) rI'(r) \beta T_{231} \right) \right\} \\ &+ \frac{f_{S}}{R} \left(W_{0}R \pm \frac{6}{3} \alpha Z \right) {}^{\vee}\mathfrak{M}_{220}^{(0)}(1,1,1,1) \end{aligned}$$
(14.106)

$${}^{A}F_{221}^{(0)} = \pm \lambda \,^{A}\mathfrak{M}_{221}^{(0)} + \frac{f_{\mathrm{T}}}{R} \left[\sqrt{(15)} \,^{C}\mathfrak{M}_{211}^{(0)} - (W_{0}R \pm \frac{6}{5}\alpha Z) \,^{A}\mathfrak{M}_{221}^{(0)} \right] \quad (14.107)$$

$$+ \frac{f_{\rm T}}{R} \left\{ \sqrt{\frac{2}{3}} \left(\int \left(\frac{r}{R} \right) [5I(r) + rI'(r)] \beta T_{211} \right) - \sqrt{\frac{2}{3}} \left(\int \left(\frac{r}{R} \right) rI'(r) \beta T_{231} \right) - (W_0 R \pm \frac{6}{3} \alpha Z) \wedge \mathfrak{M}_{221}^{(0)}(1, 1, 1, 1) \right\}$$

More than 600 pages!



H. Behrens and W. Bühring, Electron Radial Wave functions and Nuclear Beta Decay, Oxford Science Publications (1982)

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17)

 $VF_{220}^{(0)}(1, 1)$

AF(0



Basics of beta decay



Electroweak interaction

 $\left. \begin{array}{l} M_{W+,W-,Z0} \sim 80 \; \mathrm{GeV} \\ E_{\mathrm{max}}(\beta) \lesssim 50 \; \mathrm{MeV} \end{array} \right\}$

Fermi: 4 particles interacting at one vertex

ΔJ	$\pi_i \pi_f$	Classification
0,1	1	Allowed
0,1	-1	1 st fnu
>1	$(-1)^{ \Delta J }$	$ \Delta J ^{\text{th}}$ fnu
>1	$(-1)^{ \Delta J -1}$	$(\Delta J - 1)^{\text{th}}$ fu

 $\Delta J = \left| J_f - J_i \right|$

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fnu: forbidden non-unique *fu*: forbidden unique

Free neutron decay

$$\begin{split} H_{\beta} &= \frac{G_{\beta}}{\sqrt{2}} \quad \left[\begin{array}{cc} \overline{\psi}_p \gamma_{\mu} (1 + \lambda \gamma_5) \psi_n & \text{Hadron current} \\ & \times \overline{\psi}_e \gamma_{\mu} (1 + \gamma_5) \psi_{\nu} + \text{h.c.} \end{array} \right] \text{ Lepton current} \end{split}$$

Neutrino

 $m_{\overline{\nu}} \sim \mathbf{0} \rightarrow \beta$ spectrum very poorly modified, in the endpoint region

Nucleus

- Point charge, spherical symmetry
 → no deformation of the nucleus
- $M_{\text{nucleus}} \sim \infty \rightarrow E_{\text{recoil}} \sim 0$



Physics modelling in BetaShape



Nuclear current can be factored out for allowed and forbidden unique transitions

$$C(W) = (2L-1)! \sum_{k=1}^{L} \lambda_k \frac{p^{2(k-1)} q^{2(L-k)}}{(2k-1)![2(L-k)+1]!}$$

L = 1 if $\Delta J = 0$ $L = \Delta J$ otherwise

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$$F_0 L_0 = \frac{\alpha_{-1}^2 + \alpha_1^2}{2p^2} \qquad \lambda_k = \frac{\alpha_{-k}^2 + \alpha_k^2}{\alpha_{-1}^2 + \alpha_1^2} = 1?$$

 \rightarrow Solving the Dirac equation for the leptons is sufficient with these assumptions

Forbidden **non-unique** transitions calculated according to the ξ approximation

if
$$2\xi = \alpha Z/R \gg E_{max}$$

1st fnu \rightarrow allowed
applied to 2nd, 3rd, etc.

$\textbf{Assumptions} \rightarrow \textbf{Corrections}$

- Analytical screening corrections
- Radiative corrections

Propagation of uncertainty on E_{max}

X. Mougeot, Phys. Rev. C 91, 055504 (2015)





Electron wave function \rightarrow spherical symmetry

Dirac equation \rightarrow coupled differential equations

Analytical solutions (approximate)

M.E. Rose, *Relativistic Electron Theory*, Wiley and Sons (1961)

nucleus = point charge + very approximate correction for its spatial extension

LogFT treatment

Power series expansion (exact solutions)

nucleus = uniformly charged sphere \rightarrow fast computation of the solutions

$${f(r) \atop g(r)} = \frac{(pr)^{k-1}}{(2k-1)!!} \sum_{n=0}^{\infty} {a_n \\ b_n} r^n$$

H. Behrens, W. Bühring, *Electron Radial Wave functions and Nuclear Beta Decay*, Oxford Science Publications (1982) BetaShape treatment





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Analytical screening corrections









Radiative corrections

Electrons
$$\rightarrow \times [1 + \delta_R(W, Z)]$$

 $\delta_R(W, Z) = \delta_1(W) + \delta_2(Z) + \delta_3(Z) + \delta_4(Z)$
 $\delta_1(W) = \frac{\alpha}{2\pi} g(W, q)$
 $g(W,q) = 3 \ln \left(\frac{m_p}{m_e}\right) - \frac{3}{4} + \frac{4}{\beta} L\left(\frac{2\beta}{1+\beta}\right)$
 $+ 4\left(\frac{\tanh^{-1}\beta}{\beta} - 1\right) \left[\frac{q}{3W} - \frac{3}{2} + \ln(2q)\right]$
 $+ \frac{\tanh^{-1}\beta}{\beta} \left[(1 + \beta^2)\frac{q^2}{3W^2} - 4\tanh^{-1}\beta\right]$
 $\delta_2(Z) = 1.1 |Z| \alpha^2 \frac{m_p}{m_e}$
 $\delta_3(Z) = \frac{Z^2 \alpha^3}{\pi} \left(3 \ln 2 - \frac{3}{2} + \frac{\pi^2}{3}\right) \frac{m_p}{m_e}$
 $\delta_4(Z) = \frac{|Z| \alpha^3}{2\pi} \frac{m_p}{m_e}$
A. Sirlin, Phys. Rev. 164, 1767 (1967)
W. Jaus, Phys. Lett. 40, 616 (1972)

Virtual photons, internal bremsstrahlung.

Only **outer** radiative corrections influence the energy dependence of the β spectrum. **Analytical** solutions from QED for **allowed**

Neutrinos $\rightarrow \times [1 + \delta_{\nu}(q)]$ $\delta_{\nu}(q) = \frac{\alpha}{2\pi}h(W)$ $h(W) = 3\ln\left(\frac{m_p}{m_e}\right) + \frac{23}{4} + \frac{8}{\beta}L\left(\frac{2\beta}{1+\beta}\right)$ $+ 8\left(\frac{\tanh^{-1}\beta}{\beta} - 1\right)\ln(2W\beta)$ $+ 4\frac{\tanh^{-1}\beta}{\beta}\left(\frac{7+3\beta^2}{8} - 2\tanh^{-1}\beta\right)$ A. Sirlin, Phys. Rev. D 84, 014021 (2011)

 $\beta = p/W$ Spence function $L(x) = \int_0^x \frac{\ln(1-t)}{t} dt$

universite



transitions.



- Experimental shape factors (database of 130 elements)
- Mean energy $\overline{E} = \int_0^{E_0} E \cdot N(E) dE / \int_0^{E_0} N(E) dE$
- Log ft value

$$\begin{array}{c|c} \mathbf{W} & \mathbf{f}_{\beta^{-}} = \int_{1}^{W_{0}} N(W) dW \\ \mathbf{W} & \mathbf{f}_{\varepsilon/\beta^{+}} = \mathbf{f}_{\varepsilon} + \mathbf{f}_{\beta^{+}} \end{array} \end{array} \end{array}$$
 Partial half-life: $t_{i} = T_{1/2}/I_{\beta} \longrightarrow \log ft$

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provided that
$$f_{\beta^+} \neq 0$$
 $\rightarrow \log ft = \log\left(\frac{f_{\beta^+}}{I_{\beta^+}}T_{1/2}\right) + \log\left(\frac{1+f_{\varepsilon}/f_{\beta^+}}{1+I_{\varepsilon}/I_{\beta^+}}\right)$

However

$$\frac{I_{\varepsilon}}{I_{\beta^+}} = \frac{\lambda_{\varepsilon}}{\lambda_{\beta^+}} = \frac{K_{\text{nuc}} \sum_{x} n_x C_x f_x}{K_{\text{nuc}} \int_1^{W_0} N(W) dW} \approx \frac{f_{\varepsilon}}{f_{\beta^+}}$$

 C_{x} : lepton dynamics

 K_{nuc} : nuclear structure (allowed, forbidden unique) n_x : relative occupation number of the orbital, not accounted for in the LogFT program For allowed and forbidden unique electron capture transitions, one has

$$\rightarrow \log ft \approx \log \left(\frac{f_{\beta^+}}{I_{\beta^+}} T_{1/2} \right)$$







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Output file

Transition parameters and options for calculation

Experimental shape factor

Mean energies, log *ft* values, analysis parameters

 β and ν spectra

Authers V	Mougaot (used)	10/06/2016)					<u>ns</u>	
CEA, LIST	. mougeot (xavie , Laboratoire Na	r.mougeotgcea.fr) tional Henri Becc	nuerel (LNHB), Gif	-sur-Yvette F-911	91, France			
Please ci	te: X. Mougeot,	Physical Review C	5 91, 055504; Erra	atum Phys. Rev. C	92, 059902 (2015)		sinale	trans
							enigio	ti ai ie
Parent nu Calculatio	cleus: 18-Ar-41 on of the 1st fo:	[7/2*] g.s> rbidden unique tr	Daughter nucleus ransition from the	: 19-K-41 [3/2+] beta - decay of	g.s. Ar-41			
Bühring's	screening corre	ction is consider	ced.					
End-point	energy: 2491.60	(40) keV Ene	ergy step: 8 keV	Intensity: 0.0	0784 (19)			
An experi	mental shape fac	tor has been four	nd: (q^2 + 1_2*p^2	?)				
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Input mean	n energy: 1076.6	0 (20) keV	1072 92 (10)					
Mean energ Mean energ	gy from the calc gy from the expe	ulated spectrum: rimental shape fa	1072.92 (19) Kev actor: 1076.05 (19) keV				
Mean ener	gy from the calc	ulated spectrum i	lf lk=1: 1076.0 (3	3) keV				
Input log	ft value: 9.72							
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Agreement Correspond	of the experiment	ntal and calculat t: 1.75e-02 %	ed spectra in [13	330,2420] keV: 99.	98 %			
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Agreement Correspond Variation E(keV) 0	of the experiment ding disagreement of the mean ener dN/dE calc. 1.37491e-06	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10	ced spectra in [13 % dN/dE exp. 1.36282e-06	unc. 4.54479e-10	98 % dN/dE 1k=1 1.35951e-06	unc. 1.58534e-08		
Agreement Correspond Variation E(keV) 0 8	of the experime: ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41489e-06	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10	ed spectra in [13 % dN/dE exp. 1.36282e-06 1.40958e-06	unc. 4.54479e-10 4.67776e-10	dN/dE 1k=1 1.35951e-06 1.39901e-06	unc. 1.58534e-08 1.63497e-08		
Agreement Correspond Variation E (keV) 0 8 16	of the experimending disagreemen of the mean ener dN/dE calc. 1.37491e-06 1.41489e-06 1.46578e-06	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10	<pre>d spectra in [13 % dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06</pre>	unc. 4.54479e-10 4.83425e-10	dN/dE 1k=1 1.35951e-06 1.39901e-06 1.44933e-06	unc. 1.58534-08 1.63497e-08 1.69282e-08		
Agreement Correspond Variation E(keV) 0 8 16 24	of the experimen ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41499e-06 1.46578e-06 1.52758e-06	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10	dN/dE 1k=1 1.35951e-06 1.39901e-06 1.44933e-06 1.51049e-06	unc. 1.58534-08 1.63497e-08 1.69282e-08 1.75890e-08		
Agreement Correspond Variation E (keV) 0 8 16 24	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41489e-06 1.46578e-06 1.52758e-06	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10	dN/dE 1k=1 1.35951e=06 1.39901e=06 1.44933e=06 1.51049e=06	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08		
Agreement Correspond Variation E (keV) 0 8 16 24 2472	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.4489e-06 1.46578e-06 1.52758e-06 	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10	dN/dE 1k=1 1.35951e-06 1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10		
Agreement Correspond Variation E(keV) 0 8 16 24 2472 2480	of the experimen ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41499e-06 1.46578e-06 1.52758e-06 • • • • • • • •	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10	dN/dE 1k=1 1.35951e-06 1.359901e-06 1.51049e-06 .51049e-06	unc. 1.58534-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10		
Agreement Correspond Variation E (keV) 0 8 16 24 2472 2480 2488 2488	of the experiment ding disagreement of the mean ener dN/dE calc. 1.37491e-06 1.41499e-06 1.46578e-06 1.52758e-06 ••••••••••••••••••••••••••••••••••••	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.0000e:00	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11 0.00000-100	dN/dE 1k=1 1.35951e-06 1.359901e-06 1.41933e-06 1.51049e-06 	unc. 1.58534=-08 1.63497=-08 1.69282=-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000-00		
Agreement Correspon Variation E (keV) 0 8 16 24 2472 2480 2491.6	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41499e-06 1.46578e-06 1.46578e-06 0.9655e-09 2.15057e-09 2.07631e-10 0.00000e+00	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11 0.00000e+00	<pre>98 % dN/dE 1k=1 1.35951e-06 1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09 2.16118e-09 2.08648e-10 0.00000e+00</pre>	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00		
Agreement Correspon Variation E (keV) 0 8 16 24 2472 2480 2488 2491.6	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41499e-06 1.46578e-06 1.52758e-06 • • • • • • • • • • • • • • • • • • •	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11 0.00000e+00	dN/dE 1k=1 1.35951e-06 1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09 2.16118e-09 2.08648e-10 0.00000e+00	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00		
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Agreement Correspons Variation E (keV) 0 8 16 24 2472 2480 2488 2491.6	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41489e-06 1.46578e-06 1.52758e-06 .09655e-09 2.15057e-09 2.07631e-10 0.00000e+00	ntal and calculat t: 1.75e-02 % rgies: -2.91e-01 unc. 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.66465e-11 0.00000e+00	dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 	unc. 4.54479e-10 4.67776e-10 4.63425e-10 5.01425e-10 1.54856e-10 5.09102e-11 0.00000e+00	dN/dE 1k=1 1.35951e-06 1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09 2.16118e-09 2.06648e-10 0.00000e+00	unc. 1.58534=-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00		
Agreement Correspon Variation E (keV) 0 8 16 24 2472 2480 2491.6 Antineutr Mean ener	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.41489e-06 1.46578e-06 1.52758e-06 2.05655e-09 2.05631e-10 0.00000e+00 ino spectrum gy from the calc	unc. 4.56604=-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.6965e-11 0.00000e+00 ulated spectrum:	<pre>d spectra in [13 % dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.24064e-09 2.18157e-10 0.00000e+00 1416.48 (29) keV</pre>	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 1.54856e-10 5.09102e-11 0.00000e+00	<pre>98 % dN/dE 1k=1 1.35951e=06 1.39901e=06 1.44933e=06 1.51049e=06 6.12687e=09 2.06148e=10 0.00000e+00</pre>	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00		
Agreement Correspons Variation E (keV) 0 8 16 24 2472 2480 2491.6 Antineutr Mean ener Mean ener	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491e-06 1.4459e-06 1.46578e-06 1.52758e-06 2.15057e-09 2.07631e-10 0.00000e+00 ino spectrum gy from the calc gy from the calc	unc. 4.56604-10 4.67613e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00 ulated spectrum: rimental shape for	<pre>d spectra in [13 % dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00 1416.48 (29) keV actor: 1416.24 (2)</pre>	unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11 0.00000e+00 e) keV	dN/dE 1k=1 1.35951e-06 1.359901e-06 1.4993ae-06 1.51049e-06 6.12687e-09 2.16118e-09 2.08648e-10 0.00000e+00	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00		
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Agreement Correspon Variation E (keV) 0 8 16 24 2480 2480 2488 2491.6 	of the experime ding disagreemen of the mean ene dN/dE calc. 1.37491-06 1.41489-06 1.45578-06 1.45578-06 .00655e-09 2.15057e-09 2.07631e-10 0.00000e+00 .00000e+00 .00000e+00 dN/dE calc. 0.00000e+00	unc. 4.56604e-10 4.56604e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.66465e-11 0.00000e+00 ulated spectrum; rimental shape faulated spectrum i unc. 0.00000e+00	<pre>d spectra in [13 dN/dE exp. 1.36282e-06 1.40958e-06 1.40958e-06 1.52621e-06</pre>	<pre>unc. 4.54479e-10 4.67776e-10 4.63425e-10 5.01425e-10 1.54856e-10 5.09102e-11 0.00000e+00</pre>	<pre>98 % dN/dE 1k=1 1.35951e=06 1.39901e=06 1.44933e=06 1.51049e=06 6.12687e=09 2.16118e=09 2.0646e=10 0.00000e+00 dN/dE 1k=1 0.00000e+00</pre>	unc. 1.58534e-08 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00 unc. 0.00000e+00		
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CARNOT

CEA LIST

UNIVERSITE PARIS-SACLAY

list ^{Ceatech}	Output file	12 3 BetaShap 4 Analytic 5 Author: 6 CEA, LIS	e al version: 1.0 (X. Mougeot (xavie T. Laboratoire Na	(10/06/2016) er.mougeot@cea.fr) ttional Henri Becc) Juerel (LNHB), Gij	f-sur-Yvette F-911	91. France		.bs
Transition options fo	parameters and or calculation	7 Flease c 8 9 11 Parent n Calculat 14 Bühring' 15 16 End-poin 17 18 An exper 19 Energy r 20 From [19] 21	<pre>ite: X. Mougeot, uucleus: 18-Ar-41 ion of the 1st fo s screening corre- it energy: 2491.60 immental shape fac ange of the measu 61KA19] G.R. Kart</pre>	Physical Review ([7/2*] g.s> prbidden unique tr action is consider (40) keV Ener stor has been four rement: 1330 - 24 cashov, N.A. Burgo	Daughter nucleus Daughter nucleus cansition from the red. ergy step: 8 keV nd: (q^2 + 1_2*p^2 20 keV pov, A.V. Davydov,	atum Phys. Rev. C s: 19-K-41 [3/2+] a beta - decay of Intensity: 0.0 2) Izvest. Akad. Na	92, 059902 (2015) 	. 25, 189 (1961) or Colum	mbia Tech. Trans1. 25, 184 (1962
Parent 1	nucleus: 18-Ar-41	[7/2]	*] g.s.	>	Daughte	r nucle	us: 19-	K-41 [3/2+] g.s.
Calculat	tion of the 1st fo	orbido	den uni	que tra	nsition	from t	he beta	- decay of	f Ar-41
Bühring	's screening corr	ection	n is com	nsidere	d.				
Bühring	's screening corr	ection	n is co	nsidere	d.				
Bühring End-poir	's screening corront of the screening corron of the screening strength	ection 0 (40)	n is com) keV	nsidere Ener	d. gy step	: 8 keV	In	tensity: 0	.00784 (19)
Bühring End-poir	's screening corr nt energy: 2491.6	ection 0 (40)	n is com) keV	nsidere Ener 4.67613e-10	d. gy step	• 8 keV	In 1.39901e-06	tensity: 0	.00784 (19)
Bühring End-poir	's screening corr nt energy: 2491.6	ection 0 (40) ³⁸⁸ ⁸ ³⁹ ¹⁶ ¹⁶ ²⁴	n is com) keV 1.41489e-06 1.46578e-06 1.52758e-06	Ener 4.67613e-10 4.82021e-10 4.99830e-10	d. gy step 1.40958e-06 1.46404e-06 1.52621e-06	: 8 keV 4.67776e-10 4.83425e-10 5.01425e-10	I.39901e-06 1.44933e-06 1.51049e-06	tensity: 0	.00784 (19)
Bühring End-poir	's screening corr nt energy: 2491.6	ection 0 (40) 0 16 16 24	n is com) keV	Ener 4.67613e-10 4.82021e-10 4.99830e-10	d. gy step 1.40958-06 1.46404e-06 1.52621e-06	: 8 keV 4.67776e-10 4.83425e-10 5.01425e-10	In 1.39901e-06 1.44933e-06 1.51049e-06	tensity: 0 1.63497e-08 1.69282e-08 1.75890e-08	.00784 (19)
Bühring End-poin	's screening corr nt energy: 2491.6	ection 0 (40) 39 16 10 24 16 24 2472	n is col) keV 1.41489e-06 1.46578e-06 1.52758e-06 6.09655e-09 2.56572-00	4.67613e-10 4.62021e-10 4.99830e-10 2.46104e-10	d. gy step 1.40958e-06 1.46404e-06 1.52621e-06 	8 keV 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 2.54505e-10	1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09 2.16138e-00	tensity: 0 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.56055 10	.00784 (19)
Bühring End-poi	's screening corr nt energy: 2491.6	ection 0 (40) 89 16 10 24 80 24 86 2472 87 2480 88 2488	n is col) keV 1.41499e-06 1.46578e-06 1.52758e-06 .52758e-06 .52758e-09 2.15057e-09 2.15057e-09 2.07631e-10	4.67613e-10 4.62021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11	d. <u>gy step</u> 1.40958e-06 1.46404e-06 1.46404e-06 1.52621e-06 .224064e-09 2.24064e-09 2.28157e-10	4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11	1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09 2.16118e-09 2.08648e-10	tensity: 0 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11	.00784 (19)
Bühring End-poin	's screening corr nt energy: 2491.6	ection (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40) (40	n is col keV 1.41489e-06 1.46578e-06 1.52758e-06 .52758e-06 .52758e-09 2.15057e-09 2.15057e-09 2.07631e-10 0.00000e+00	A.67613e-10 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00	d. gy step 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00	: 8 keV 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11 0.00000e+00	1.39901e-06 1.41933e-06 1.51049e-06 6.12687e-09 2.16118e-09 2.08648e-10 0.00000e+00	tensity: 0 1.63497e-08 1.69282e-08 1.75890e-08 2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00	.00784 (19)
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Bühring End-poin	's screening corrent of the energy: 2491.6	2472 40 40 40 40 40 41 42 42 42 42 42 43 44 45 2488 2491.6 55 56 Mean ene 56 Mean ene 57 58 59 50 50 51 52 54 55 56 57 58 59 50 50 51 52 53 54 55 56 57 58 59 50 50 51 52	n is colored by keV 1.41489e-06 1.46578e-06 1.52758e-06 2.15057e-09 2.15057e-09 2.07631e-10 0.00000e+00 cripy from the calc cripy from the calc cripy from the calc dN/dE calc. 0.00000e+00 1.0000e+00 1.0000e+00	Ener 4.67613e-10 4.22021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00	d. gy step 1.40958e-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00 1416.48 (29) keV actor: 1416.24 (2) if 1k=1: 1413.4 (2) dN/dE exp. 0.00000e+00 1.07022 02	8 keV 4.67776e-10 4.83425e-10 5.01425e-10 2.54503e-10 1.54856e-10 5.09102e-11 0.00000e+00 9) keV 9) keV unc. 0.00000e+00 6.9340 keV	Lin 1.39901e-06 1.44933e-06 1.51049e-06 .51049e-06 .6.12687e-09 2.16118e-09 2.08645e-10 0.00000e+00 dN/dE 1k=1 0.00000e+00	<pre>unc. 0.00000e+00 5.7338e-12</pre>	.00784 (19)
Bühring End-poin	's screening corr nt energy: 2491.6	2472 2488 2491.6 24 24 24 33 46 2488 2491.6 55 66 27 2491.6 55 66 57 67 68 59 66 67 68 59 60 50 51 52 54 55 64 55 65 66 67 68 60 51 60 52 60 53 64	n is colored keV 1.41499-06 1.46578e-06 1.52758e-06 2.15057e-09 2.07631e-10 0.00000e+00 2.07631e-10 0.00000e+00 1.06916e-09 4.23052e-09	Ener 4.67613e-10 4.82021e-10 4.99830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00 5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5.	d. gy step 1.40958=-06 1.46404=-06 1.52621=-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00 1.416.48 (29) keV actor: 1416.24 (2) if lk=1: 1416.24 (2) if lk=1: 1416.24 (2) dN/dE exp. 0.00000e+00 1.07023e-09 4.23474e-09	 8 keV 4.67776e-10 4.83425e-10 5.01425e-10 5.4856e-10 5.09102e-11 0.00000e+00 9) keV 90 keV 91 keV 91 keV 	L1.39901e-06 1.44933e-06 1.51049e-06 .51049e-09 2.16118e-09 2.08648e-10 0.00000e+00 1.07440e-09 4.25140e-09	unc. 0.00000e+00 5.77388e-12 2.3738e-11	.00784 (19)
Bühring End-poir	's screening corrent of the energy: 2491.6	40 40 46 2472 47 2480 48 2491.6 53 Antineut 55 Mean ene 56 Mean ene 57 Mean ene 56 Mean ene 57 0 58 16 59 16	n is con . keV 	Ener 4.67613e-10 4.82021e-10 4.89830e-10 2.46104e-10 1.49183e-10 4.86465e-11 0.00000e+00 5.7713e-13 2.12127e-12 4.70705e-12	d. gy step 1.40958-06 1.46404e-06 1.52621e-06 6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00 1416.48 (29) keV actor: 1416.24 (2) if lk=1: 1416.24 (2) dN/dE exp. 0.00000e+00 1.07023e-09 4.23474e-09 9.42521e-09	8 keV 4.67776e-10 4.67776e-10 4.83425e-10 5.01425e-10 5.01425e-10 5.09102e-11 5.09102e-11 0.00000e+00 9) keV 34) keV unc. 0.00000e+00 5.37166e-13 2.11910e-12 4.70220e-12	LIN 1.39901e-06 1.44933e-06 1.51049e-06 6.12687e-09 2.16118e-09 2.08648e-10 0.00000e+00 0.00000e+00 1.07440e-09 4.25140e-09 9.46266e-09	unc. 0.00000e+00 0.0000e+00 0.00000e+00 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11 0.00000e+11	.00784 (19)



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Clatech	Output file	2 3 BetaShape 4 Analytical version: 1. 5 Author: X. Mougeot (xa 6 CEA, LIST, Laboratoire 7 Please cite: X. Mougeo 8 9 10 11 Parent nucleus: 18-Ar- 12 Calculation of the 1st 13 14 Bühring's screening co 15) (10/06/2016) //er.mougeot@cea.fr National Henri Bec , Physical Review) querel (LNHB), Gif C 91, 055504; Erra Daughter nucleus ransition from the red.	-sur-Yvette F-911 tum Phys. Rev. C 	91, France 92, 059902 (2015) g.s. Ar-41		. <mark>bs</mark> sing	le transit	tion
Experimen	ital shape factor	16 End-point energy: 2491 17 18 An experimental shape 19 Energy range of the me 20 From [1961KA19] G.R. K 21	.60 (40) keV En Eactor has been fou asurement: 1330 - 2 artashov, N.A. Burg	ergy step: 8 keV nd: (q^2 + 1_2*p^2 420 keV ov, A.V. Davydov,	Intensity: 0.0 ?) Izvest. Akad. Na	0784 (19) uk SSSR, Ser. Fiz	. 25, 189 (1961)	or Columbia Tech.	Transl. 25, 184	(1962)
An experiment Energy range From [1961KA1	tal shape factor has of the measurement: 19] G.R. Kartashov, 1	been found: (1330 - 2420 k N.A. Burgov, A	q^2 + 1_2* eV .V. Davydo	p^2) ov, Izves	st. Akad.	Nauk SSS	R, Ser.	Fiz. 25,	189 (196:	1)
		30 Log ft value from the 31 Agreement of the exper 32 Agreement of the exper 33 Corresponding disagrees 34 Variation of the mean 35 S 36 E (keV) 37 0 38 1.41489e=0 39 16 40 24 24 1.52758e=0	calculated spectrum imental and calcula ment: 1.75e-02 % energies: -2.91e-01 . unc. 6 4.56604e-10 5 4.67613e-10 5 4.82021e-10 5 4.89830e-10	<pre>if lk=1: log ft 9 ted spectra in [13 ted spectra in [13 ted spectra in [14 dN/dE exp. 1.36282e-06 1.40958e-06 1.46404e-06 1.52621e-06</pre>	<pre>0.740 (12) with 030,2420] keV: 99. unc. 4.54479e-10 4.67776e-10 4.83425e-10 5.01425e-10</pre>	<pre>component: log f 98 % dN/dE lk=1 1.35951e-06 1.39901e-06 1.4993e-06 1.51049e-06</pre>	unc. 1.58534e-08 1.63497e-08 1.63282e-08 1.75890e-08			
		346 2472 6.09655e-0 347 2480 2.15057e-0 348 2488 2.07631e-1 349 2491.6 0.00000e+0 350 351 352 354 354	9 2.46104e-10 9 1.49183e-10 0 4.86465e-11 0 0.00000e+00	6.32780e-09 2.24064e-09 2.18157e-10 0.00000e+00	2.54503e-10 1.54856e-10 5.09102e-11 0.00000e+00	6.12687e-09 2.16118e-09 2.08648e-10 0.00000e+00	2.71767e-10 1.54915e-10 4.76298e-11 0.00000e+00			
		356 Mean energy from the c 357 Mean energy from the c 358 Mean energy from the c 359 360 E(keV) 361 0 0.000000e+0 362 8 1.06916e-0 363 16 4.23052e-0 364 24 9.41583e-0	alculated spectrum: xperimental shape f alculated spectrum . unc. 0 0.00000e+00 9 5.37713e-13 9 2.12127e-12 9 4.70705e-12	1416.48 (29) keV actor: 1416.24 (2) if lk=1: 1413.4 (3 dN/dE exp. 0.00000e+00 1.07023e-09 4.23474e-09 9.42521e-09	<pre>3) keV unc. 0.00000e+00 5.37166e-13 2.11910e-12 4.70220e-12</pre>	dN/dE lk=1 0.00000e+00 1.07440e-09 4.25140e-09 9.46266e-09	unc. 0.00000e+00 5.77388e-12 2.30004e-11 5.15326e-11			





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Ceatech Out	put file	hape tical version: 1.0 (10/06/20) r: X. Mougeot (xavier.mougeo) LIST, Laboratoire National H e cite: X. Mougeot, Physical	16) 10cea.fr) enri Becquerel (LNHB), Gi Review C 91, 055504; Err	f-sur-Yvette F-91191, atum Phys. Rev. C 92,	France 059902 (2015)	<mark>.bs</mark> single transitior
Mean energies, log values, analysis parameters	100 11 Paren 12 Calcu 13 14 Bühri 15 16 End-p 17 18 An ex 19 Energ 20 From 21 12 19 Mean 24 Mean 25 Mean 26 29 Log f 30 Log f 30 Log f 31 Agree 33 Corre 34 Agree 34 Agree 35 Corre 34 Agree 35 Corre 36 Corre 37 Corre 38 Corre 39 Corre 30 Corre 30 Corre 30 Corre 30 Corre 31 Corre 33 Corre 34 Corre 35 Corre 36 Corre 37 Corre 38 Corre 39 Corre 30 Corre 30 Corre 30 Corre 30 Corre 31 Corre 31 Corre 32 Corre 33 Corre 34 Corre 35 Corre 36 Corre 36 Corre 37 Corre 38 Corre 39 Corre 30 Corre 30 Corre 30 Corre 30 Corre 30 Corre 30 Corre 30 Corre 31 Corre 31 Corre 31 Corre 31 Corre 32 Corre 33 Corre 34 Corre 35 Corre 36 Corre 36 Corre 37 Corre 38 Corre 3	t nucleus: 18-Ar-41 [7/2*] g. lation of the 1st forbidden u ng's screening correction is oint energy: 2491.60 (40) key perimental shape factor has h y range of the measurement: 1 [1961KA19] G.R. Kartashov, N mean energy: 1076.60 (20) ke energy from the calculated sp energy from the calculated sp log ft value: 9.72 t value from the calculated st t value from the calculated st t value from the calculated sp t value from the calculated sp energy from the calculated sp log ft value: 9.72 t value from the calculated sp t value f v	.s> Daughter nucleu unique transition from the considered. V Energy step: 8 keV been found: (q^2 + 1_2*p^. 1330 - 2420 keV .A. Burgov, A.V. Davydov, eV ev pectrum: 1072.92 (19) keV shape factor: 1076.05 (1 pectrum if 1k=1: 1076.0 () spectrum: log ft 9.735 (1 1 shape factor: log ft 9. spectrum if 1k=1: log ft 9. calculated spectra in [1: -02 % 2.91e-01 %	<pre>s: 19-K-41 [3/2+] g.s e beta - decay of Ar- Intensity: 0.0078: 2) Izvest. Akad. Nauk : 9) keV 33) keV 1) with components: 728 (11) with components: 9.740 (12) with components: 330,2420] keV: 99.98 ; </pre>	1 1 2 2 2 2 2 2 2 3 2 3 2 3 2 3 2 3 3 3 3	, 189 (1961) or Columbia Tech. Transl. 25, 184 (1962) and log partial T1/2 5.924 (11) 3 (42) 6 (5)
Input mean energy: 1076.60 Mean energy from the calcu Mean energy from the exper	(20) keV lated spectrum: 1072 imental shape factor	.92 (19) keV : 1076.05 (19) ke	•V			
Mean energy from the calcu	lated spectrum if lk	=1: 1076.0 (33) }	ceV			
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	363 1 364 2	6 4.23052e-09 2.1211 4 9.41583e-09 4.707	100020000 270-12 4.234740-09 050-12 9.425210-09	2.11910e-12 4.70220e-12	4.25140e-09 2 9.46266e-09 5	2.30004e-11 5.15326e-11





list ^{CE2tech}	Out	out file	BetaShape Analytical version: 1.0 (10 Author: X. Mougeot (xavier. CEA, LIST, Laboratoire Nati Please cite: X. Mougeot, Ph	-	. <mark>bs</mark> single transitior		
ſ	E (keV)	dN/dE calc.	unc.	dN/dE exp.	unc.	dN/dE lk=1	unc.
	8	1 41489e-06	4 67613e-10	1.30252e-06	4.67776e-10	1 39901e-06	1.53557E-08
	16	1.46578e-06	4.82021e-10	1.46404e-06	4.83425e-10	1.44933e-06	1.69282e-08
	24	1.52758e-06	4.99830e-10	1.52621e-06	5.01425e-10	1.51049e-06	1.75890e-08
	32	1.59207e-06	5.18314e-10	1.59014e-06	5.19795e-10	1.57433e-06	1.82615e-08
	_	23	Mean energy from the calcul	ated spectrum: 1072.92 (19) keV)) b ell		
	Mean energy Mean energy Mean energy E(keV) 0 8 16	dN/dE calc. 0.00000e+00 1.06916e-09 4.23052e-09	lated spectrum: imental shape fa lated spectrum s unc. 0.00000e+00 5.37713e-13 2.12127e-12	1416.48 (29) keV actor: 1416.24 (29 if lk=1: 1413.4 (3 dN/dE exp. 0.00000e+00 1.07023e-09 4.23474e-09	<pre>) keV 4) keV unc. 0.00000e+00 5.37166e-13 2.11910e-12</pre>	dN/dE 1k=1 0.00000e+00 1.07440e-09 4.25140e-09	unc. 0.00000e+00 5.77388e-12 2.30004e-11
β and v s	spectra	351 352 353 354 355 356 357 358 359 360 361 362 363 364	Antineutrino spectrum Mean energy from the calcul Mean energy from the experi Mean energy from the calcul E (keV) dN/dE calc. 0 0.00000e+00 8 1.06916e-09 16 4.23052e-09 24 9.41583e-09	ated spectrum: 1416.48 (29) keV mental shape factor: 1416.24 (2) ated spectrum if 1k=1: 1413.4 (3 unc. dN/dE exp. 0.00000e+00 0.00000e+00 5.37713e-13 1.07023e-09 2.12127e-12 4.23474e-09 4.70705e-12 9.42521e-09	<pre>9) keV 34) keV unc. dN/dE 1k=1 0.00000e+00 0.00000e+00 5.37166e-13 1.07440e-09 2.11910e-12 4.25140e-09 4.70220e-12 9.46266e-09</pre>	unc. 0.00000+00 5.77388=12 2.30004=11 5.15326=-11	
HB			TL	J Dresden 2017 X. M	ougeot – Beta spectroi	metry 20	CARNOT CEA LIST PARIS-SACLAY

LNHB Henri Becquerel





Examples of improved calculations



These two transitions are calculated as allowed by the LogFT program.



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Atomic effects





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Indirect magnetic coupling



System cooled down to 10 mK





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⁶³Ni and ²⁴¹Pu beta spectra



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Atomic exchange effect

- \rightarrow Indistinguishable from the direct decay to a final continuum state
- → Depends on the overlap of the continuum and bound electron wave functions
- → Allowed transitions: only the ns orbitals are reachable

 $\begin{aligned} \text{Spectrum correction factor} & \left[1 + \eta_{ex}^{T}(E)\right] \\ \text{Total exchange factor} & \eta_{ex}^{T}(E) = \sum_{n} \eta_{ex}^{ns}(E) + \sum_{\substack{m,n \ (m \neq n)}} \mu_{m} \mu_{n} \\ \text{Subshell contribution} & \eta_{ex}^{ns}(E) = f\left(\mu_{n}^{2} - 2\mu_{n}\right) \\ \text{with} & \mu_{n} = \langle Es' | ns \rangle \frac{g_{n,\kappa}^{b}(R)}{g_{e}^{c}(R)}, \quad f = \frac{g_{\kappa}^{c}(R)^{2}}{g_{\kappa}^{c}(R)^{2} + f_{c}^{c}(R)^{2}} \end{aligned}$





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A new screening correction



H. Behrens, W. Bühring, *Electron Radial Wave functions and Nuclear Beta Decay*, Oxford Science Publications (1982)

Screening

Generally corrected for using a constant Thomas-Fermi potential, which creates a **non physical discontinuity** in the spectrum.

Evaluating the wave functions at the nuclear surface cannot provide a good result because of the weakness of the screened potentials in this region.

- \rightarrow Implementation of a **new screening correction** which:
 - avoids complete calculation of lepton and nuclear matrix elements
 - · is available only for allowed transitions up-to-now

$$C_{sc} = 1 - \frac{\Delta R_{unsc}}{\Delta R_{sc}} \cdot \left(1 - \frac{f_{sc}}{f_{unsc}}\right)$$

exchange formalism $\rightarrow f$ factor

mean value \rightarrow spatial extension





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Coulomb potential for electron bound wave functions





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Numerical procedure

• For bound states, the **orbital energy** is **not known** in advance

→ iterative procedure

• **Orbital energy** \rightarrow Oscillation frequency of the wave functions

 \rightarrow Accuracy of the overlap

 \Rightarrow Adjustment of V_{ex} to reach the "good" energies in

J.P. Desclaux, At. Data Nucl. Data Tab. 12, 311 (1973)

Inspection

Useful tabulated parameters for β spectra, electron capture, electron polarization, β - γ angular correlation, etc.

Tabulated screened parameters $F_0L_0^*/F_0L_0$ and λ_2^*/λ_2 only, but for very few energies

H. Behrens, J. Jänecke, Landolt-Börnstein, New Series, Group I, vol. 4, Springer Verlag, Berlin (1969)

For both the continuum and bound wave functions,

Without screening: parameters perfectly reproduced

With screening: parameters in excellent agreement, despite different potentials









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Quality of the calculations



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Outlook





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The EMPIR project MetroBeta (2016-2019)

http://metrobeta-empir.eu/



8 partners from 6 countries

- France (LNHB)
- Germany (PTB Berlin and Braunschweig, Heidelberg University)
- Czech Republic (CMI)
- Poland (UMCS)
- Switzerland (IRA)
- The Netherlands (Gonitec)

Work packages

- WP1: Theoretical calculations of beta spectra
- WP2: High-resolution beta spectrometry based on Metallic Magnetic Calorimeters
- WP3: Measurements of beta spectra with other methods
- WP4: Comparison and validation of measurements
- WP5: Creating Impact

LNHB is highly involved

- Coordination of the project (Mark A. Kellett)
- Coordination of WP1 (X. Mougeot)
- Scientific work scheduled in WP1, WP2, WP4, WP5



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- BetaShape: ENSDF files, improved modelling, mean energies, log *ft* values, β^-/β^+ and correlated $\overline{v_e}/v_e$ spectra, multiple transitions, propagation of uncertainties.
- The BetaShape program is now the reference code for DDEP evaluations. Available at <u>http://www.nucleide.org/logiciels.htm</u>
- Metallic magnetic calorimetry has been demonstrated to have a great potential for high precision beta spectrometry.
- Exchange and screening effects have been demonstrated to have a great influence on the spectrum shape at low energy.

Unmentioned studies in progress

- Measurements with silicon detectors.
- Inclusion of the nuclear structure in the beta spectrum calculation.
- Improved modelling for electron capture transitions.







Street art from **C215** at CEA Saclay (<u>www.c215.fr</u>)

Thank you for your attention

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