Differential intensities of two-neutrino double beta-decay of selenium-82

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$$^{82}_{34}Se \rightarrow ^{82}_{36}Kr \quad + \quad 2e^{-}$$

$$^{82}_{34}Se \rightarrow ^{82}_{36}Kr \quad + \quad 2e^{-} \quad + \quad 2\overline{\nu}$$

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Evidence of Single State Dominance in the Two-Neutrino Double-β Decay of ^{82}Se with CUPID-0

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We report on the measurement of the two-neutrino double-β decay of ^{82}Se performed for the first time with cryogenic calorimeters, in the framework of the CUPID-0 experiment. With an exposure of 9.95 kg yr of Zn^{82}Se, we determine the two-neutrino double-β decay half-life of ^{82}Se with an unprecedented precision level, $T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat})\,^{+0.19}_{-0.13}(\text{syst})] \times 10^{19}$ yr. The very high signal-to-background ratio, along with the detailed reconstruction of the background sources allowed us to identify the single state dominance

the tracks originated from foils from enrichment run 1 or 2. Multiple isotopes listed on the same line indicates the assumption of secular equilibrium

% of Total		$2.6\,\text{MeV} < E_{tot} < 3.2\,\text{MeV}$	
		Expected events	% of Total
Run 1	Run 2	Run 1 & Run 2	Run 1 & Run 2
2.4	1.9	4.1 ± 0.1	34
1.3	1.4	3.1 ± 0.1	25
7.9	23.0	< 0.1	
3.5	2.8	< 0.1	
2.0	1.6	3.0 ± 0.1	25
3.1	2.7	0.1 ± 0.1	1
20.1	33.4	10.3 ± 0.1	84
79.9	66.6	1.9 ± 0.1	16
100.0	100.0	12.2 ± 0.2	100
N/A	N/A	15	N/A

5.1 Higher-state vs single-state dominated transitions

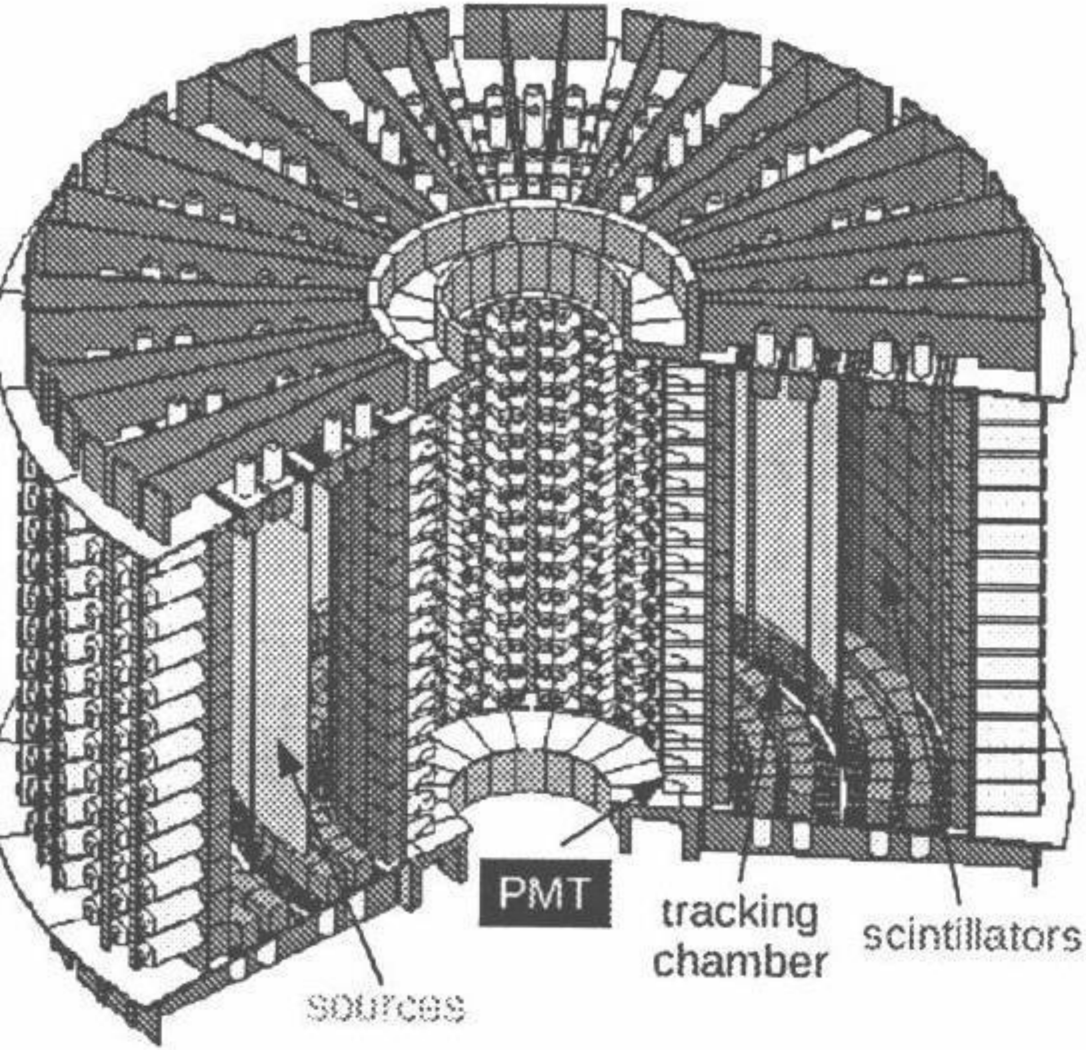
For the purpose of the nuclear matrix element calculation, the decay of ^{82}Se to ^{82}Kr is modelled as two virtual β transitions: one between the ground state of ^{82}Se and the 1^+ states of the intermediate nucleus of ^{82}Br, and one between the 1^+ states of ^{82}Br and the ground state of ^{82}Kr. If one single intermediate 1^+ state dominates the transition, then the process is said to be single-state dominated (SSD). Alternatively, if the process proceeds through many higher intermediate excited states, it is said to be higher-state dominated (HSD). Previously, it has been assumed that ^{82}Se

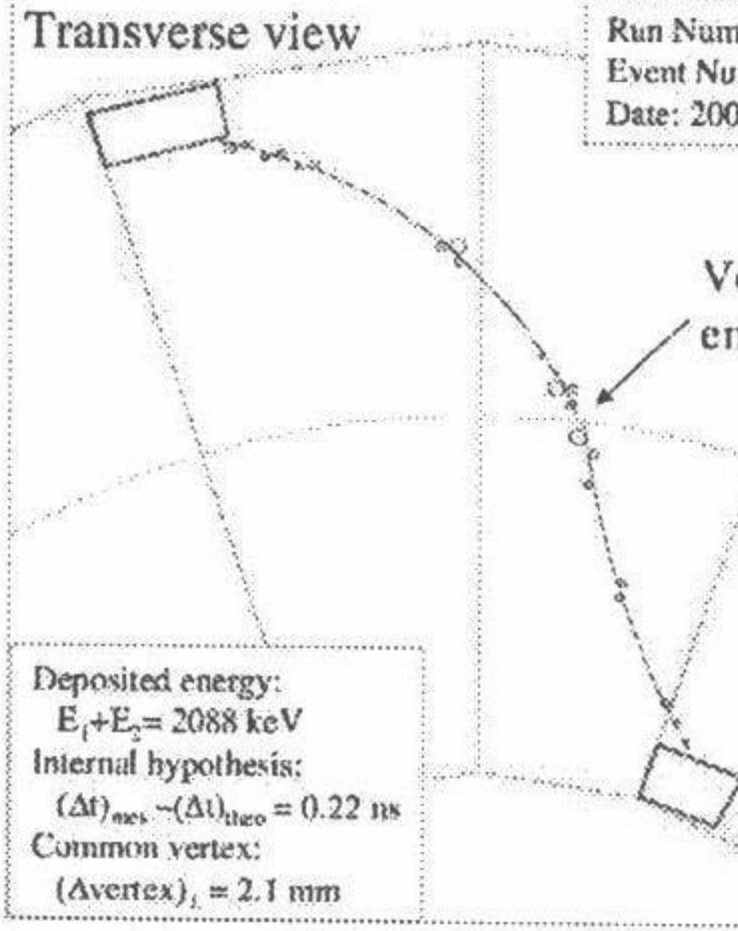
Single State Dominance mechanism

Investigation on the base of differential intensities measurement

Semenov S.V., Šimkovic F., Khruschev V.V., Domin P. , Phys. Atom. Nucl. 2000, V.63, P. 1196;

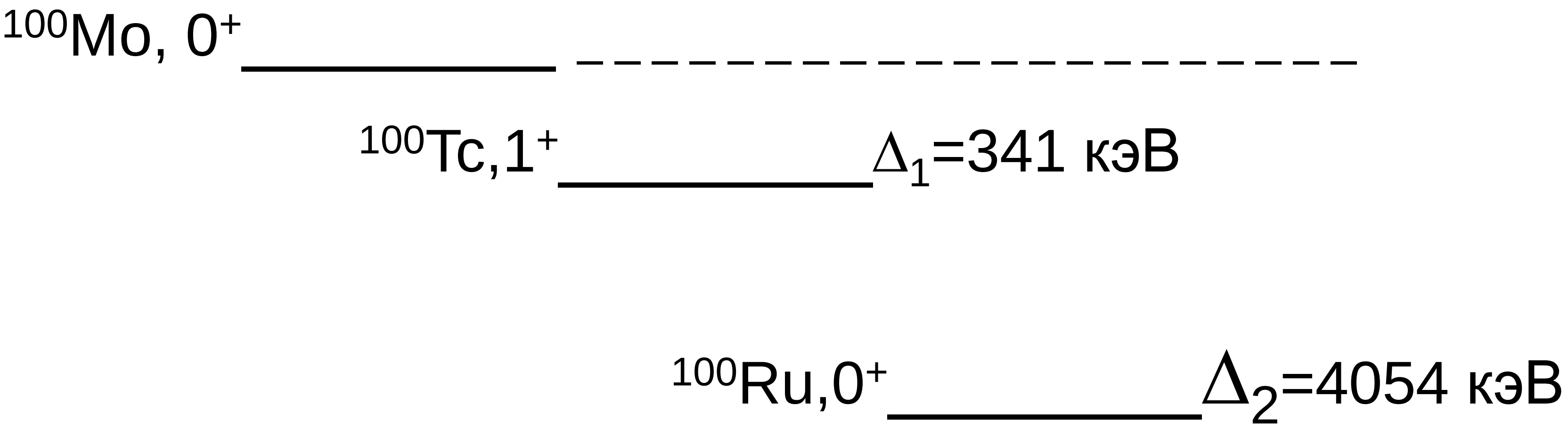
Šimkovic, F., Domin, P., Semenov S.V., J. Phys. G. 2001, V. 27, P. 2233


PMT
tracking chamber
scintillators
sources


Transverse view
Run Num
Event Nu
Date: 200
V
en
Deposited energy:
E_1+E_2= 2088 keV
Internal hypothesis:
$(\Delta t)_{mes}-(\Delta t)_{theo}$ = 0.22 ns
Common vertex:
$(\Delta vertex)_\perp$ = 2.1 mm

$$^{100}Mo \rightarrow {}^{100}Ru + 2e^{-} + 2\bar{\nu}_{e} \quad \Delta L = 0$$

$$^{100}Mo \rightarrow {}^{100}Ru + 2e^{-} \quad \Delta L = 2$$



^{100}Mo, 0^{+}

^{100}Tc, 1^{+} Δ_1=341 кэВ

^{100}Ru, 0^{+} Δ_2=4054 кэВ

$$\left[T_{1/2}^{2\nu 2\beta}\left(0_i^+ \to 0_f^+\right)\right]^{-1} = \frac{G_\beta^4 g_A^4}{32\pi^7 \ln 2} \int_{m_e}^{T+m_e} de_1 \int_{m_e}^{T+2m_e-\varepsilon_1} d\varepsilon_2 \int_{0}^{T+2m_e-\varepsilon_1-\varepsilon_2} d\omega_1 \times$$

$$\times F(Z_f,\varepsilon_1)F(Z_f,\varepsilon_2)\,p_1\varepsilon_1 p_2\varepsilon_2\,\omega_1^2\omega_2^2 A_{0_f^+}$$

$$4\mathrm{A}_{0_f^+} = \left|\sum_N \left\langle 0_f^+ \left\| \hat{\beta}^- \right\| 1_N^+ \right\rangle \left\langle 1_N^+ \left\| \hat{\beta}^- \right\| 0_i^+ \right\rangle (K_N + L_N)\right|^2 + \frac{1}{3}\left|\sum_N \left\langle 0_f^+ \left\| \hat{\beta}^- \right\| 1_N^+ \right\rangle \left\langle 1_N^+ \left\| \hat{\beta}^- \right\| 0_i^+ \right\rangle (K_N - L_N)\right|^2 \tag{2}$$

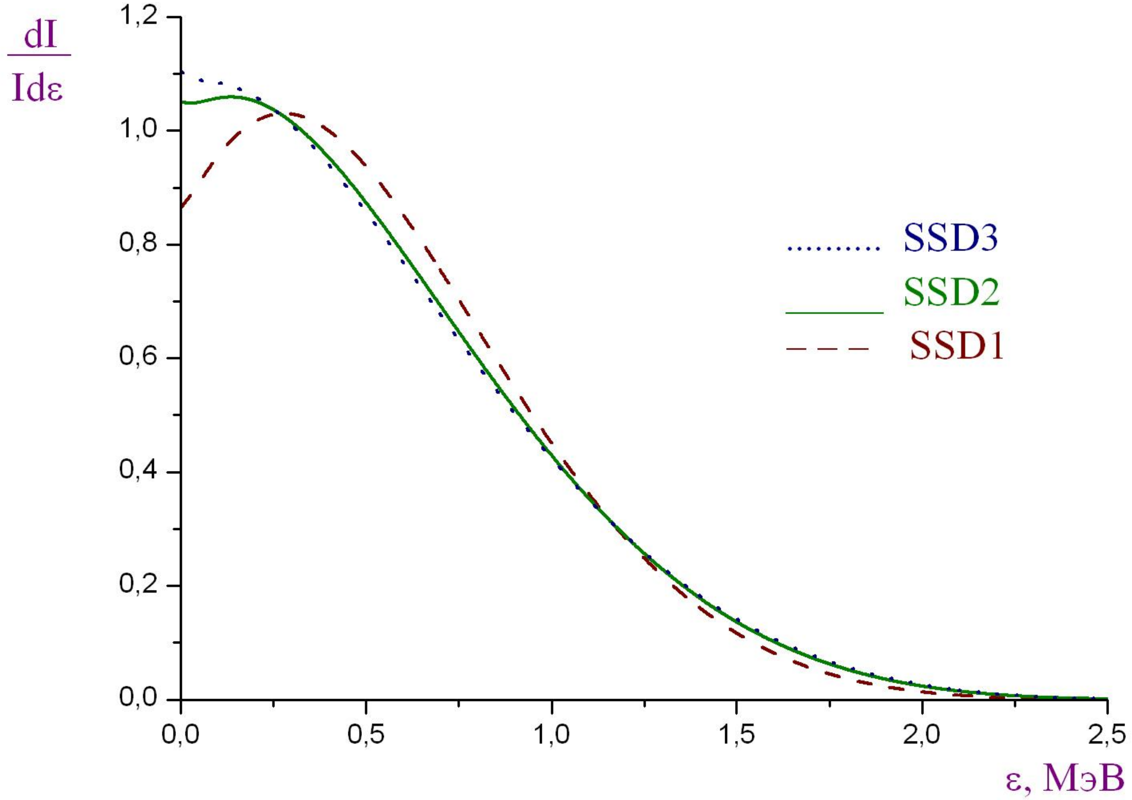
Nuclear matrix elements,corresponding to the g.s. of intermediate nucleus ^{100}Tc

$M_1^I = \left\langle 1^+_{g.s.} \middle\| \widehat{\beta}^- \middle\| 0^+_i \right\rangle$ and $M_1^F = \left\langle 0^+_f \middle\| \widehat{\beta}^- \middle\| 1^+_{g.s.} \right\rangle$

can be found from log *ft* values of electron capture and single beta decay

$$M_1^I = \frac{1}{g_A}\sqrt{\frac{3D}{ft_{EC}}}, \qquad M_1^F = \frac{1}{g_A}\sqrt{\frac{3D}{ft_{\beta^-}}},$$

$$T_{1/2}^{(2\nu)}(0^+ \rightarrow 0^+) = 2.997 \cdot 10^{14}\, yr \frac{10^{\log ft_{EC} + \log ft_{\beta^-}}}{H(T, 0_f^+)}$$

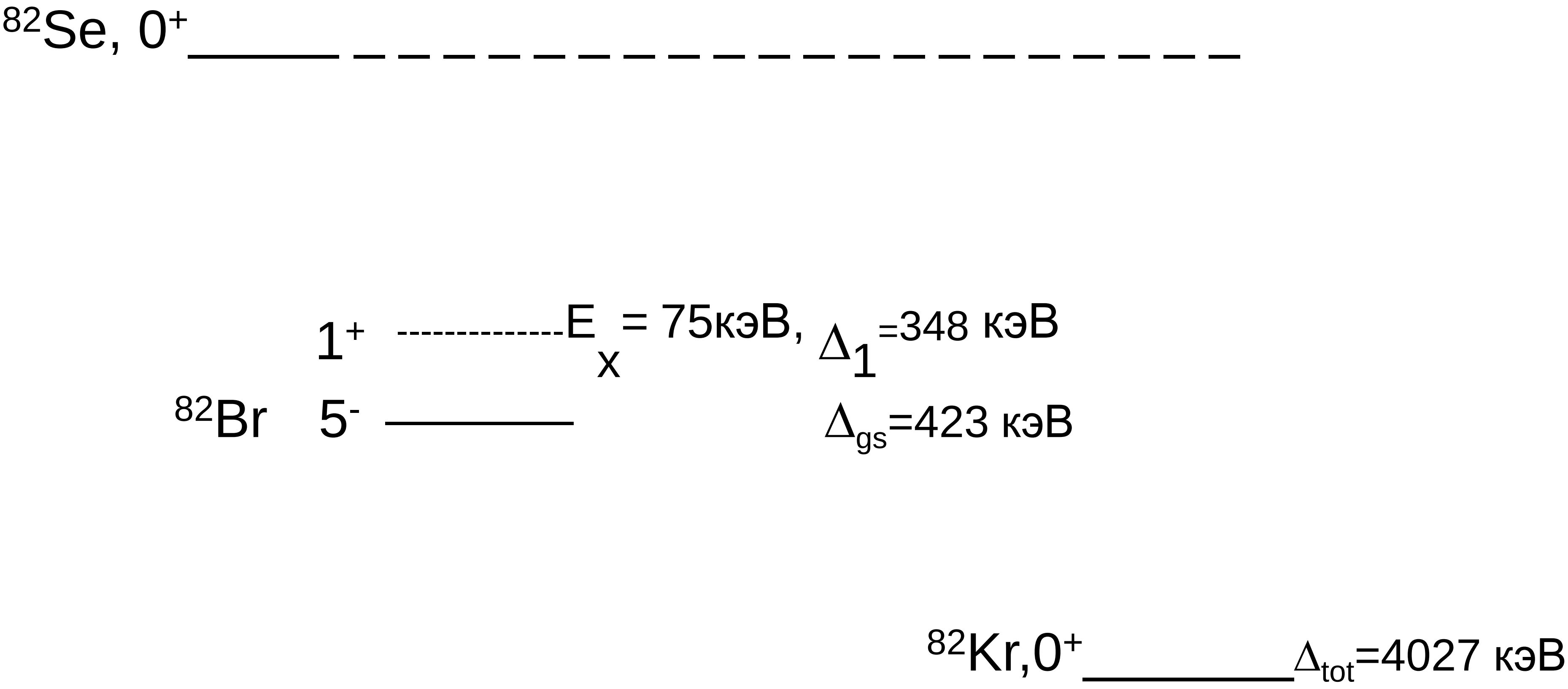


dI/Idε
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0,0
0,5
1,0
1,5
2,0
2,5
ε, МэВ
SSD3
SSD2
SSD1

$$^{100}Mo \rightarrow {}^{100}Ru + 2e^{-} + 2\bar{\nu}_e$$

$$T_{1/2}^{2\nu} = [7.1 \pm 0.37(stat) \pm 0.66(syst)] \cdot 10^{18} \text{ лет}$$

NEMO-3, J. Phys. G 41, 075204(2014)



^{82}Se, 0^+

1^+ --------------- E_x = 75кэВ, Δ_1=348 кэВ

^{82}Br 5^- Δ_{gs}=423 кэВ

^{82}Kr,0^+ Δ_{tot}=4027 кэВ

Charge exchange reactions for determination of nuclear matrix elements

^{82}Se(^{3}He,t)^{82}Br $$M_1^I = \left\langle 1_1^+ \left\| \hat{\beta}^- \right\| 0_i^+ \right\rangle$$

^{82}Kr(d,^{2}He)^{82}Br $$M_1^F = \left\langle 0_f^+ \left\| \hat{\beta}^- \right\| 1_1^+ \right\rangle$$

SSD $I = |M^I \cdot M^F|^2 \cdot$ Phase factor

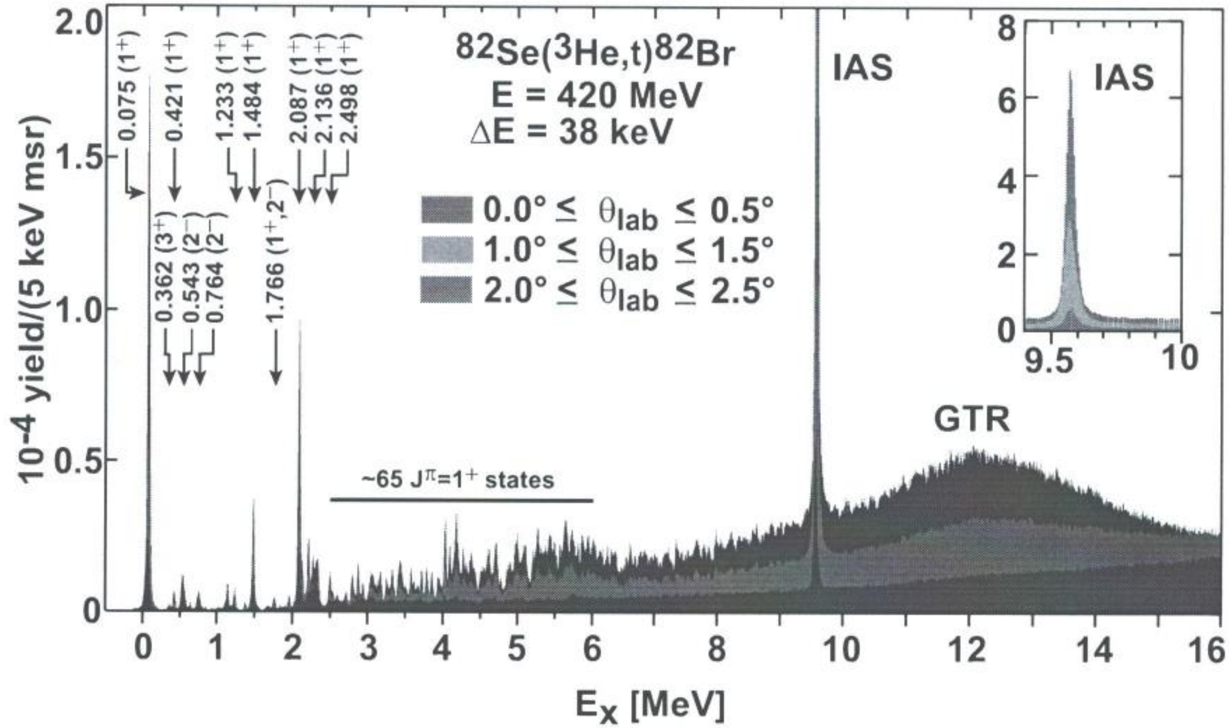


FIG. 2. Excitation-energy spectra of the ^{82}Se(^{3}He$,t$)^{82}Br reaction. The spectra were generated from three different angle cuts (indicated by colors) and overlaid to show the effect of the angular dependence. $\Delta L = 0$ transitions (GT and IAS) are forward-peaked and prominently appear in the spectrum at $0.0^\circ \leqslant \theta_{\mathrm{lab}} \leqslant 0.5^\circ$. Note, the energy scale is modified above 6 MeV. The inset magnifies the IAS region.

A. Distorted wave calculations

The angular distributions are shown in Fig. 3 for different isolated transitions. Distorted-wave (DW) calculations were performed to describe the cross-section angular distributions. They were performed in the same way as, for instance, described in Refs. [15,22] using the code FOLD [39] and the Love-Franey nucleon-nucleon interactions [18].

Optical-model parameters were interpolated from Ref. [40] for the case of a ^{82}Se target and a ^{3}He projectile. In the outgoing channel the triton potential depths were reduced by 15% according to the prescription in Ref. [41]. The relevant

note that for $J^\pi = 1^+$ transitions there seems to be a tendency of increasing $\Delta L = 2$ contributions with increased target mass. This has been observed for ^{96}Zr, ^{100}Mo, ^{128}Te, ^{130}Te, and ^{136}Xe [23–26] and attributed to an increasing number of matching open orbits near the Fermi surface [23], as $(N - Z)$ increases from $(N - Z) = 14$ (^{82}Se) to $(N - Z) = 28$ (^{136}Xe).

B. Determination of Gamow-Teller strength

The key relation for extracting the GT strength from the (^{3}He$,t$) charge-exchange reaction cross sections extrapolated to $q = 0$ is given by

TABLE II. Excitation energies, cross sections, B(GT) values for low-lying states populated through the ^{82}Se(^{3}He,t)^{82}Br reaction (two tables, left and right). In column one, excitation energies from Ref. [31] (spins quoted if known, errors if significant) are compared with those from the (^{3}He,t) reaction in column three (errors ±2 keV) (not in right table), followed by cross sections at $q = 0$, their GT fraction and the extracted B(GT) values. Cross-section errors are statistical ones only. Errors for B(GT) values include an extra 50% contribution from the non-GT part of the cross section at $q = 0$. Spin assignments in square brackets indicate the presence of closely spaced and unresolved states with different spins. Dividing lines are between full MeV values.

^{82}Br (Ref. [31])		^{82}Br		$\frac{d\sigma}{d\Omega}(q=0)$	GT	B(GT)	^{82}Br		$\frac{d\sigma}{d\Omega}(q=0)$	GT	B(GT)
E_x[keV]	J^π	E_x[keV]	J^π	[mb/sr]	%		E_x[keV]	J^π	[mb/sr]	%	
75.06	1^+	75	1^+	3.009(52)	82	0.338(31)	4033	1^+	0.35(7)	94	0.046(9)
362.80	(1^+)	362	3^+	–	–	–	4099	1^+	0.250(6)	91	0.032(2)
420.07	(2)	421	1^+	0.116(15)	86	0.014(2)	4170	1^+	0.373(8)	94	0.049(2)
540.99	$(2^+,3^+)$	543	2^-	–	–	–	4209	1^+	0.267(6)	98	0.037(1)
641.16	(3^+)	642	3^+	–	–	–	4272	1^+	0.230(5)	92	0.030(1)
763.71	$(1)^+$	764	2^-	–	–	–	4317	1^+	0.131(3)	99	0.018(1)
849.69	$(1^+,2,3^+)$	848	1^+	0.030(1)	14	0.0010(5)	4365	1^+	0.112(3)	94	0.015(1)
1139.93		1142	1^+	0.173(4)	28	0.007(3)	4391	1^+	0.120(3)	100	0.017(1)
1232.57(3)		1233	1^+	0.140(4)	68	0.013(2)	4433	1^+	0.110(3)	88	0.013(1)
1386(8)	$(^+)$	1378	1^+	0.055(1)	87	0.0070(4)	4511	1^+	0.086(3)	99	0.012(1)
(1489)		1484	1^+	0.567(9)	46	0.036(10)	4554	$[1^+,2^-]$	0.101(2)	96	0.014(1)
1678		1680	2^-	–	–	–	4601	1^+	0.141(4)	92	0.018(1)
(1774)		1766	$[1^+,2^-]$	0.106(2)	75	0.011(1)	4632	1^+	0.157(4)	88	0.019(1)
1955(4)		1958	1^+	0.100(2)	74	0.010(1)	4689	$[1^+,2^-]$	0.106(3)	93	0.014(1)
		2087	1^+	1.366(4)	77	0.149(17)	4772	1^+	0.243(6)	98	0.033(1)
		2136	1^+	0.258(6)	72	0.026(4)	4779	2^-	–	–	–
		2213	$[1^+,2^-]$	0.403(9)	90	0.051(3)	4869	1^+	0.088(2)	85	0.010(1)
		2272	1^+	0.315(9)	55	0.024(5)	4910	1^+	0.136(4)	93	0.018(1)
		2317	1^+	0.247(7)	21	0.007(3)	4971	1^+	0.206(5)	92	0.026(1)
		2351	1^+	0.227(4)	67	0.021(4)	5008	1^+	0.235(6)	97	0.032(1)
		2498	1^+	0.162(3)	73	0.017(2)	5066	1^+	0.176(4)	88	0.022(1)
		2543	3^+	–	–	–	5110	1^+	0.224(8)	98	0.031(1)
		2712	1^+	0.068(1)	58	0.006(1)	5211	1^+	0.129(3)	91	0.016(1)

Nuclear matrix element $M_1^I = \left\langle 1_1^+ \left\| \widehat{\beta}^- \right\| 0_i^+ \right\rangle$

is obtained from B(GT),

D. Frekers et al, Phys. Rev. C 94, 014614 (2016)

High energy-resolution measurement of the

Se82(He3,t)Br82 reaction for double-β decay and for solar neutrinos

$$\left| M(GT) \right|^2 = B(GT) \qquad M_1^I = 0.581.$$

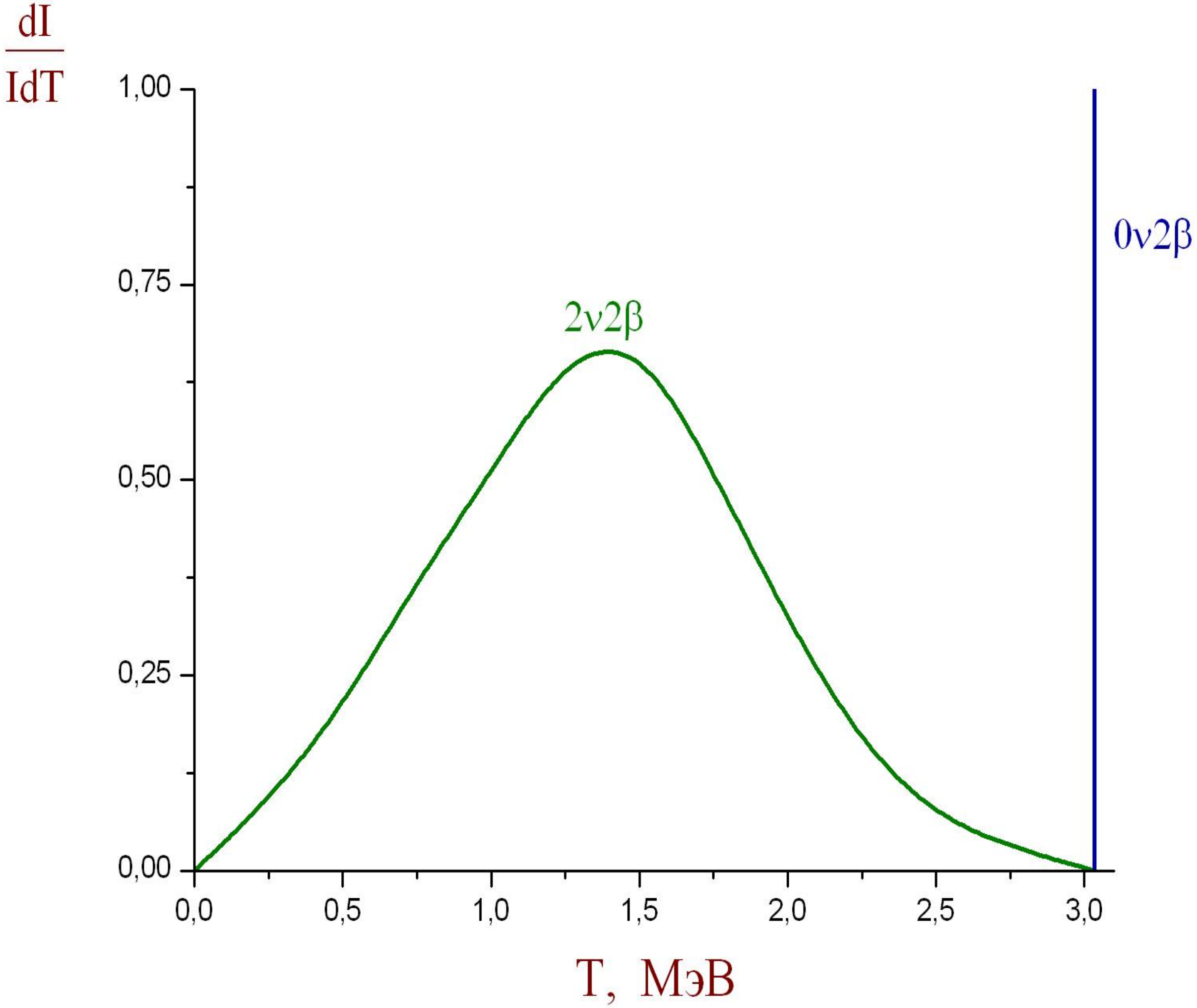
^{82}Kr(d,^{2}He)^{82}Br is to be investigated

$M_1^F = \left\langle 0_f^+ \middle\| \widehat{\beta}^- \middle\| 1_1^+ \right\rangle$ can be derived from $T_{1/2}^{2\nu 2\beta}$

SSD mechanism of 2ν2β-decay

NEMO-3 $T_{1/2}^{2\nu 2\beta}$ =9.39·10^{19} yrs

M_1^F =0.23, $B(GT^+) = 0.0529$



$\frac{dI}{IdT}$
1,00
0,75
0,50
0,25
0,00
0,0
0,5
1,0
1,5
2,0
2,5
3,0
T, МэВ
2ν2β
0ν2β

Conclusion

Charge exchange reaction investigations give information on nuclear matrix elements values for $2\nu2\beta$-decay

SSD hypothesis gives the possibility

to determine NME M_1^F from $T_{1/2}^{2\nu2\beta}$ value

Spectrum of total electron energy in two-netriuno double beta decay of 82Se is calculated

Thank you