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β^+–electron-capture decay of ^{69}Se

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The β^+–electron-capture decay of ^{69}Se, produced via the ^{40}Ca(^{32}S, 2pn)^{69}Se reaction, has been studied by β-delayed proton and γ-ray emissions using the recoil transport helium jet technique. The established decay scheme for ^{69}Se involves 13 up to now unreported γ emitting levels in ^{69}As. The total proton branching ratio has been measured to be $(4.5\pm1.0)\times10^{-4}$. The autocorrelation analysis of the delayed proton spectra indicates a level spacing in agreement with the back shifted Fermi gas model estimates. The Gamow-Teller beta strength distribution has been measured in 95% of the Q_β window, up to 6.5 MeV excitation energy in ^{69}As.

I. INTRODUCTION

In 1976, Hardy and his co-workers opened the field of the β delayed proton emission study for the $T_z=\frac{1}{2}$ nuclei ^{65}Ge, ^{69}Se, ^{73}Kr, ^{77}Sr and interpreted their results with detailed statistical calculations.[1–3] Since then a large number of new data have been obtained in the field of delayed charged particle emission, showing well resolved, sometimes unexpected structures in the registered particle spectra.[4–9] More particularly, a detailed study of the β-delayed proton emission of ^{65}Ge has been recently carried out by Vierinen[9] and the obtained spectra could be interpreted by a selective population of excited states in ^{65}Ga via Gamow-Teller β^+ decay. To go further into the details of the decay scheme of ^{69}Se and to look for the possible single level structure in the delayed particle spectrum, the study of the β^+–electron-capture decay of ^{69}Se and of the related delayed particle emission has been carried out with the help of the He-jet technique at the Strasbourg upgraded MP tandem.

II. EXPERIMENTAL PROCEDURE

A 100 MeV ^{32}S beam has been used to induce the reaction ^{40}Ca(^{32}S,2pn)^{69}Se on a 1 mg/cm^2 self-supported natural calcium target. This beam energy corresponds to the maximum production for the ^{69}Se isotope and to minimal contribution of the other exit channels in the fusion-evaporation process. The recoiling nuclei ejected from the target are thermalized in oil cluster loaded helium and transported by means of the gas flow to a low background area equipped with a fast tape transport device. The sources, collected continuously on a mylar tape, are moved each 50 s to a closed geometry gamma and particle counting station. High energy gamma rays up to 5.5 MeV are detected with two Ge (Li) counters of 20% efficiency. For low energy radiations a hyperpure germanium crystal with a beryllium entrance window is used. The emitted protons are detected in a water-cooled Si(Au) surface barrier counter of 280 mm^2 sensitive area and 100 μm thickness in a solid angle of 35% of 4π. Calibration is achieved with a composite α source of ^{239}Pu, ^{241}Am, and ^{244}Cm; the full width at half maximum (FWHM) is typically 18 keV. During the counting period, single spectra for protons and γ rays are registered and p-γ and γ-γ coincidence events are stored on magnetic tape for subsequent playback with gating conditions.

III. RESULTS

A. Gamma-emitting levels

The γ rays attributed to ^{69}As in the decay of ^{69}Se are listed in Table I with their relative intensity, the coincident transitions, and their assignment. Gamma lines are observed up to 3.8 MeV extending by 1.6 MeV the energy diagram established by MacDonald.[1] In our proposed decay scheme 13 up to now unreported levels are quoted (Fig. 1), four of them being located above the proton separation energy; there is no evidence for the existence of a state at 1911 keV, as the 1911 keV γ line is found in coincidence with the 66, 98, 399 keV γ rays. The 836 keV γ line, observed in coincidence with the 98 and 1476 keV γ rays is attributed to the decay of a level at 933.7 keV. The gamma branching ratios of the populated states in ^{69}As are reported in Table II. From our decay scheme it appears that only 85% of the β strength to the γ-emitting levels of ^{69}As have been observed by MacDonald, implying that the ground state feeding confines to 5 ± 18 %, i.e., to an upper limit of 23%. No direct measurement of the ground state transition has been performed in our work. The beta branches and their relative intensity deduced from the γ imbalances are reported in Table III with the corresponding logft values calculated from the Gove and Martin log$f$ tables[10] and with the quantities $T_{1/2}=27.4\pm0.2$ s (Ref. 1) and $Q_\beta=6790\pm40$ keV (Ref. 11). For all the observed β transitions a Gamow-Teller character is assumed, and the corresponding reduced transition probability[12] B'(GT) $=3880/ft$ is quoted. If we consider, in accordance with indications from Ref. 1 and our recent in-beam study,[13] that the spin parity of the ^{69}Se ground state is $J^{\pi}=\frac{3}{2}^{-}$, allowed β^{+} transitions restrict the spin and parity of the observed states in ^{69}As to $\frac{1}{2}^{-},\frac{3}{2}^{-},\frac{5}{2}^{-}$.

B. Particle-emitting levels

The total proton branching ratio has been determined by comparing after suitable efficiency corrections the total number of protons with the number of counts in the 322, 691, and 911 keV γ lines of ^{69}As registered simultaneously. The weighted mean of the calculated values is equal to $(4.5\pm1.0)\times10^{-4}$ and is located within the error bar of the corresponding quantity reported in Ref. 1.

The high resolution β^{+}-electron-capture delayed proton spectrum of ^{69}Se obtained in our work is reproduced in Fig. 2. The low energy part ($E_p<1.2$ MeV) of the spectrum is obscured by the positrons but well resolved lines appear up to 3.1 MeV, the strongest of them corresponding to the structure observed in the bell shaped distribution reported by MacDonald.[1] The peak shape analysis reveals a few single proton lines but most of the groups are fitted at least by two components. The assignment of these groups to the ^{69}Se decay is based on multispectrum analysis. As no significant estimate of the

TABLE I. Energy and relative intensity of γ rays following the β^{+}-electron-capture decay of ^{69}Se.

E_γ (keV)	I_γ	Coincident transitions	E_i	E_f (keV)
66.4±0.1	37.6±3.7	98,333,625,911,1700,1912 2245,2369,2866,3182,3230 3304,3487,3835	164	98
97.98±0.05	100	All transitions unless those labeled by*	98	0
291.9±0.3	2.7±0.3		790	497
332.6±0.4	1.5±0.2	66,98,1558	497	164
399.3±0.3	5.3±0.3[a]	98,1330,1912,1558,2376	497	98
497.4±0.5*	1.5±0.2		497	0
625.0±0.3	4.0±0.4	66,98,164,1330	790	164
691.8±0.5	25.2±2.5	98,1330	790	98
789.7±0.5*	7.1±0.8		790	0
835.7±0.4	2.4±0.4	98,1476	934	98
911.2±0.4	2.5±0.4	66,98	1076	164
977.8±0.4	1.8±0.3	98,1457	1076	98
1075.8±1.0	4.4±0.6	98,333,399	1865	789
1202.3±1.0	0.4±0.1	98		
1329.6±1.0	3.1±0.5	66,98	2119	789
1362.3±0.7	1.8±0.3	66,98	2152	789
1456.9±0.5	1.7±0.3	66,98	2533	1076
1475.9±0.5	1.6±0.3	98,836	2409	934
1557.6±0.5	1.1±0.2	66,98	2347	789
1563.0±1.0	0.4±0.1	98		
1593.0±1.0	1.0±0.2	98	1691	98
1620.0±1.5	2.4±0.4	98	2409	790
1646.4±1.0	2.1±0.3	98	1744	98
1654.5±1.0	1.8±0.3	66,98,399,497	2152	497
1691.2±1.0*	1.4±0.2		1691	0
1700.5±0.5	1.3±0.2	66,98,164	1865	164
1744.4±1.0*	1.0±0.2		1744	0
1766.8±0.5	6.2±0.9	98	1865	98
1848.6±1.0	0.9±0.2	98	2347	497
1866.0±1.0*	0.7±0.1		1865	0
1911.6±1.0	0.8±0.2	66,98,399	2409	497
1955.8±1.0	0.9±0.2	66,98	3031	1076
2052.8±1.0	0.9±0.2	98	2152	98
2069.1±1.0	0.4±0.1	66,98	3144	1076
2086 ±1.0	0.4±0.1	98	2184	98
2119.2±1.0*	0.5±0.1		2119	0
2244.6±0.5	0.8±0.2	66,98	2409	164
2310.2±0.5	1.3±0.2	98	2409	98
2368.6±1.0	0.7±0.1	66,98	2533	164
2375.6±1.0	1.4±0.2		2873	497
2435.0±0.5	0.20±0.05		2533	98
2866.5±0.5	0.16±0.04		3031	164

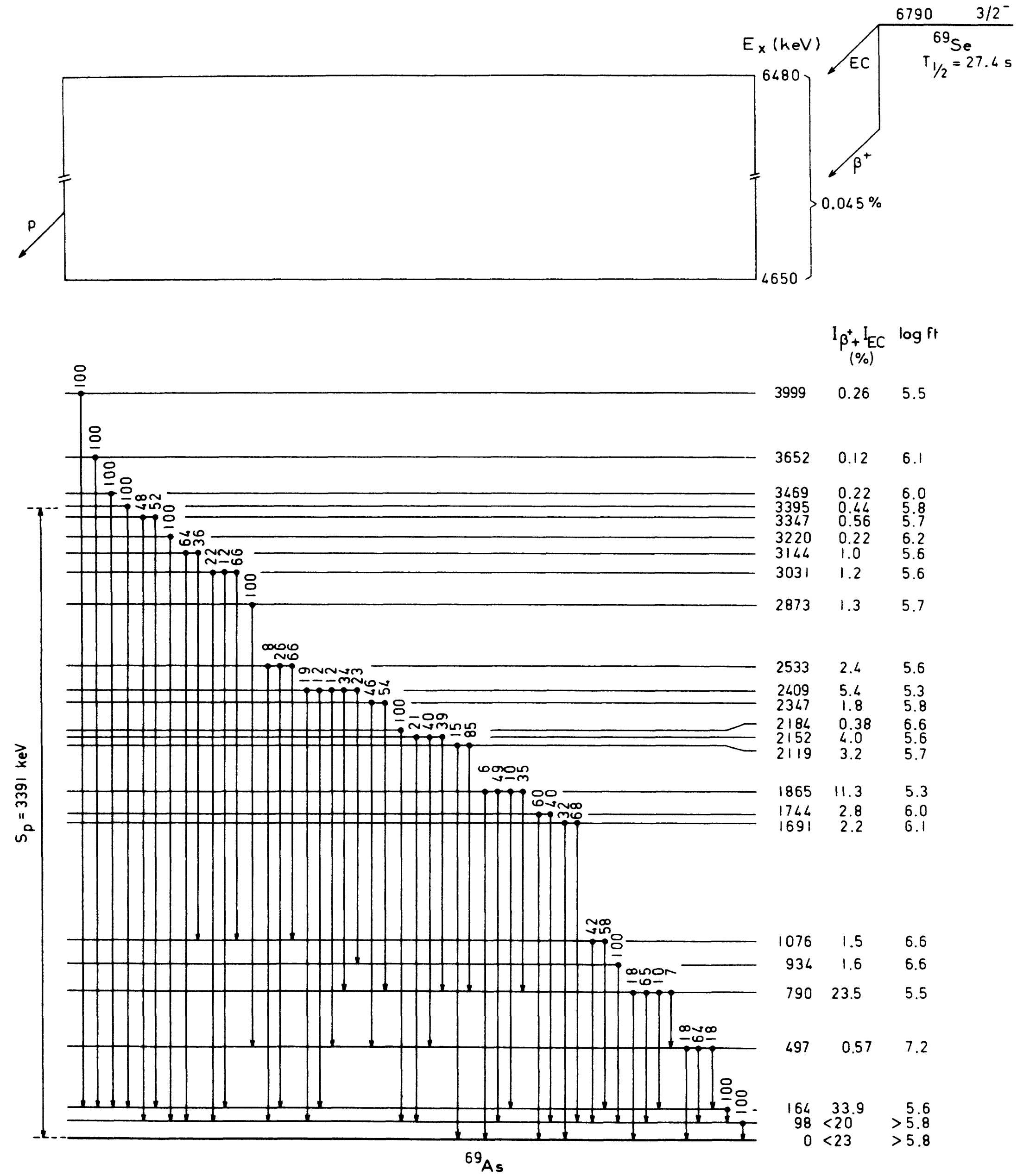

FIG. 1. Proposed decay scheme for ^{69}Se.

TABLE I. (*Continued*).

E_γ (keV)	I_γ	Coincident transitions	E_i	E_f (keV)
2932.4±1.0	0.30±0.06	98	3031	98
3045.9±1.0	0.72±0.10	98	3144	98
3122.0±0.7	0.35±0.07		3220	98
3181.9±0.5	0.32±0.05	66,98	3347	164
3230.0±0.5	0.50±0.08	66,98	3395	164
3248.7±0.7	0.30±0.05		3347	98
3304.3±0.7	0.25±0.04	66,98	3469	164
3487.0±1.0	0.13±0.03		3652	164
3835.0±0.7	0.30±0.05		3999	164

[a]Contaminated line. Intensity taken from Ref. 1.

proton feeding of the first excited state in ^{68}Ge could be obtained from our low efficiency proton-γ coincidence measurements, the particle emission is considered, according to the results of MacDonald,[1] to proceed essentially (98.6%) to the ground state of ^{68}Ge.

The single proton spectrum has been quantitatively analyzed by selecting 36 proton groups: the underlying structure of the broad lines has been neglected. The overall results are reported in Table IV. Uncertainties on

TABLE II. Gamma ray branching ratios in ^{69}As.

E_X (keV)	E_γ (keV)	I_γ (%)
98	98	100
164.4	66	100
497.2	333	18±2
	399	64±3
	497	18±2
789.5	292	7±1
	625	10±2
	691	64±3
	790	18±2
933.7	836	100
1075.7	911	58±7
	978	42±7
1691.1	1593	41±7
	1691	59±7
1744.4	1646	68±6
	1744	32±6
1865.0	1076	35±5
	1700	10±2
	1767	49±5
	1866	6±1
2119.1	1330	85±4
	2119	15±4
2151.5	1360	39±6
	1654	41±6
	2053	20±5
2184.0	2086	100
2346.8	1558	54±9
	1849	46±9
2408.8	1476	23±4
	1620	35±5
	1912	11±3
	2245	12±3
	2310	19±3
2532.7	1457	66±6
	2369	26±5
	2435	8±2
2872.8	2376	100
3030.9	1956	66±8
	2867	12±4
	2932	22±6
3144.3	2069	36±8
	3046	64±8
3220.1	3122	100
3346.5	3182	52±7
	3249	48±7
3394.5	3230	100
3468.7	3304	100
3651.7	3487	100
3999.4	3835	100

the listed proton energies are typically 10 keV. The corresponding levels in ^{69}As obtained with a proton separation energy $B_p = 3391 \pm 30$ keV (Ref. 11) and after correction for the recoil energy of the emitting nucleus are located within ±33 keV. The logft values in the Q_β-S_p window obtained for the unbound states are comprised between 5.8 and 7.0. As pointed out by Vierinen[9] in a similar study on the delayed proton precursor ^{65}Ge, these values are upper limits; indeed, due to the low absolute efficiency of the γ counters even a non-negligible γ decay of the involved levels can escape our observation. So it seems reasonable to infer that the proton unbound states in ^{69}As are populated by allowed β^+ transitions. If we consider, as mentioned above, the spin and parity of the ground state of ^{69}Se to be $J^\pi = \frac{3}{2}^-$, the β^+-electron-capture decay populates in ^{69}As unbound states with $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$. The proton emission to the $J^\pi = 0^+$ ground state of ^{68}Ge involves a parity change i.e., an odd angular momentum for the outcoming particle. In the 1–3 MeV proton energy range, the emission probability of a proton with $l = 3$ is smaller by a factor of 10^2 compared with the one corresponding to $l = 1$; so the contribution of proton emission from $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$ states is strongly favored and should prevail in the spectrum.

An experimental value of the level density above the proton separation energy in ^{69}As can be obtained from the autocorrelation analysis[14] of the delayed proton spectrum. In this procedure, the original distribution is smoothed by a Gaussian function with FWHM much larger than the detector resolution. A new distribution is obtained by dividing the registered spectrum by the smoothed one. The autocorrelation function of this new distribution can be fitted with an analytical expression of the theoretical autocorrelation function. From this an experimental value of the level spacing can be deduced. The treatment of the experimental data has been performed in several ways, subtracting or not an exponential background for the positron contribution, taking different values for the FWHM of the smoothing function, and applying the autocorrelation analysis either to the whole spectrum or to 500 keV energy bins. An example of processing is shown in Fig. 3. These different procedures yield for the level spacing values of the same order of magnitude, set between 2.7 and 5.4 keV. We have performed level density calculations for ^{69}As with both the Truran *et al.* model[15] and the back shifted Fermi gas model.[16] Above the proton separation energy the level spacing $D(\frac{1}{2}^-, \frac{3}{2}^-)$ for the states with $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$ is found to be three times larger in the Truran *et al.* approach than in the back shifted Fermi gas model for which the values are much closer to the experimental ones (Table V). As recommended by Dilg[16] for this mass region, we have taken the level density parameter a equal to 9 MeV^{-1}, value rather different from the one derived by MacDonald[1] from his experimental results ($a = 11$ MeV^{-1}).

IV. CONCLUDING REMARKS

In regard to the earlier work[1] performed on the $T_z = \frac{1}{2}$ delayed proton precursor ^{69}Se the set of the experimental

TABLE III. β branching, $\log ft$, and B'(GT) values in the ^{69}Se decay to γ emitting levels.

E_X (keV)	I_β (%)	$\log f_0 t$	$B'(\mathrm{GT}) \times 10^{-5}$
0	<23	>5.77	<659
98	<20	>5.79	<629
164	33.9 ± 3.0	$5.55^{+0.05}_{-0.06}$	1093 ± 174
497	$0.57+0.50$	$7.20^{+0.37}_{-0.97}$	24 ± 21
790	23.5 ± 2.0	$5.47^{+0.05}_{-0.04}$	1315 ± 123
934	1.6 ± 0.3	$6.59^{+0.10}_{-0.11}$	100 ± 23
1076	1.5 ± 0.5	$6.55^{+0.13}_{-0.18}$	109 ± 41
1691	2.2 ± 0.3	$6.11^{+0.06}_{-0.07}$	301 ± 51
1744	2.8 ± 0.3	$5.98^{+0.06}_{-0.08}$	406 ± 72
1865	11.3 ± 1.1	$5.31^{+0.06}_{-0.06}$	1900 ± 266
2119	3.2 ± 0.4	$5.71^{+0.07}_{-0.08}$	756 ± 123
2152	4.0 ± 0.4	$5.61^{+0.06}_{-0.06}$	952 ± 123
2184	0.38 ± 0.06	$6.61^{+0.09}_{-0.10}$	95 ± 20
2347	1.8 ± 0.2	$5.84^{+0.07}_{-0.07}$	561 ± 88
2409	5.4 ± 0.5	$5.30^{+0.06}_{-0.07}$	1945 ± 276
2533	2.4 ± 0.3	$5.62^{+0.08}_{-0.08}$	931 ± 148
2873	1.3 ± 0.2	$5.67^{+0.09}_{-0.10}$	830 ± 174
3031	1.2 ± 0.2	$5.58^{+0.08}_{-0.09}$	1020 ± 180
3144	1.0 ± 0.1	$5.57^{+0.09}_{-0.09}$	1044 ± 192
3220	0.22 ± 0.06	$6.19^{+0.21}_{-0.18}$	250 ± 83
3347	0.56 ± 0.07	$5.69^{+0.09}_{-0.09}$	792 ± 145
3395	0.44 ± 0.07	$5.76^{+0.10}_{-0.11}$	674 ± 153
3469	0.22 ± 0.04	$5.99^{+0.10}_{-0.11}$	397 ± 88
3652	0.12 ± 0.03	$6.11^{+0.11}_{-0.13}$	301 ± 77
3999	0.26 ± 0.04	$5.47^{+0.10}_{-0.12}$	1315 ± 309

data is completely modified. Well resolved structures appear in the transitions to unbound states and this could be an indication of the existence of favored transitions in the β^+-electron-capture decay. From the registered data the Gamow-Teller strength over a 6.5 MeV energy range could be inferred (Fig. 4). The total observed β

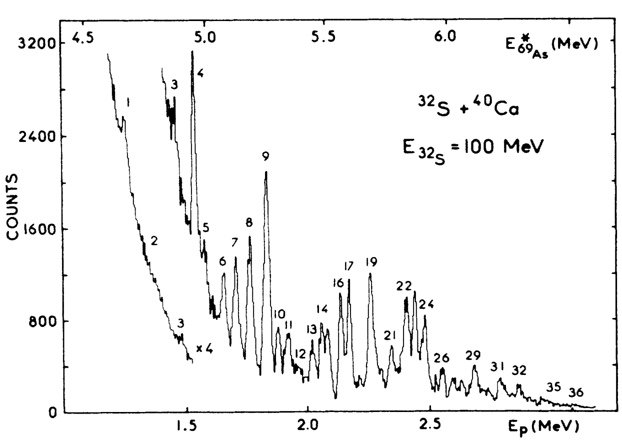

FIG. 2. The β-delayed proton spectrum of ^{69}Se obtained during a 113 h accumulation.

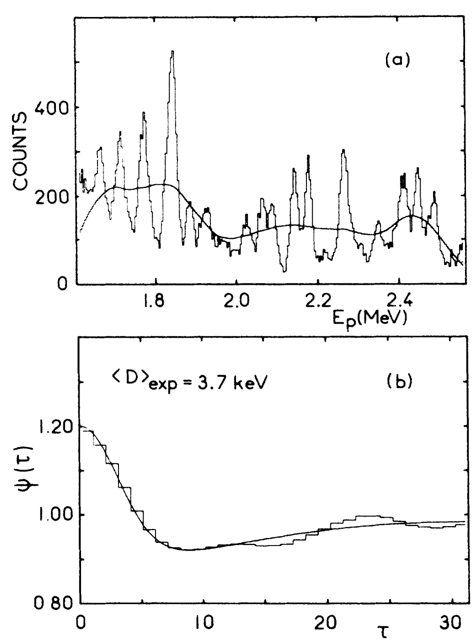

FIG. 3. Autocorrelation analysis of the part of the delayed proton spectrum between 1.6 and 2.5 MeV. (a) The experimental distribution and the smoothed spectrum obtained with a Gaussian folding function (30 channel FWHM). (b) The experimental autocorrelation function and the fitted theoretical curve.

TABLE IV. β branching, logft and B'(GT) values from the ^{69}Se delayed proton emission.

Proton group	E_p (keV)	Level in ^{69}As (keV)	$I_p \times 10^{-6}$	$\log f_0 t$	B'(GT) $\times 10^{-5}$
P1	1240	4649	23 ±5	$6.84^{+0.15}_{-0.17}$	56±18
P2	1337	4747	23 ±6	$6.73^{+0.16}_{-0.18}$	72±23
P3	1459	4871	9.7±2.4	$6.97^{+0.15}_{-0.17}$	42±13
P4	1522	4935	25 ±6	$6.49^{+0.13}_{-0.16}$	125±38
P5	1570	4984	10 ±2	$6.86^{+0.14}_{-0.17}$	53±17
P6	1634	5050	11 ±2	$6.75^{+0.14}_{-0.16}$	69±21
P7	1685	5102	17 ±4	$6.50^{+0.04}_{-0.16}$	123±37
P8	1744	5161	24 ±5	$6.29^{+0.13}_{-0.15}$	199±58
P9	1810	5228	38 ±8	$6.03^{+0.13}_{-0.15}$	362±104
P10	1855	5273	9.8±2.0	$6.59^{+0.03}_{-0.15}$	100±29
P11	1896	5314	14.5±3.2	$6.39^{+0.13}_{-0.15}$	158±46
P12	1948	5369	9.8±2.2	$6.51^{+0.12}_{-0.15}$	120±34
P13	1996	5416	11 ±2	$6.43^{+0.13}_{-0.14}$	144±40
P14	2032	5452	12 ±3	$6.38^{+0.12}_{-0.15}$	162±46
P15	2059	5480	11 ±2	$6.38^{+0.12}_{-0.15}$	162±46
P16	2111	5533	17 ±4	$6.14^{+0.12}_{-0.16}$	281±84
P17	2146	5570	16 ±4	$6.14^{+0.13}_{-0.15}$	281±81
P18	2183	5606	5 ±1	$6.60^{+0.13}_{-0.15}$	97±27
P19	2232	5657	26 ±6	$5.88^{+0.12}_{-0.15}$	511±148
P20	2272	5695	7 ±2	$6.42^{+0.12}_{-0.16}$	148±44
P21	2318	5741	14 ±3	$6.07^{+0.13}_{-0.16}$	330±99
P22	2374	5800	24 ±5	$5.79^{+0.13}_{-0.16}$	629±188
P23	2413	5841	17 ±4	$5.91^{+0.13}_{-0.16}$	477±146
P24	2453	5879	17 ±4	$5.86^{+0.14}_{-0.16}$	535±166
P25	2495	5923	4 ±1	$6.49^{+0.14}_{-0.16}$	126±39
P26	2523	5950	6 ±1	$6.24^{+0.14}_{-0.16}$	223±70
P27	2564	5994	6 ±1	$6.20^{+0.14}_{-0.17}$	245±81
P28	2600	6030	5 ±1	$6.22^{+0.15}_{-0.15}$	234±69
P29	2652	6081	10 ±2	$5.91^{+0.14}_{-0.17}$	477±160
P30	2706	6136	6 ±1	$6.03^{+0.15}_{-0.19}$	362±128
P31	2766	6197	7 ±2	$5.87^{+0.16}_{-0.18}$	523±180
P32	2807	6239	2.1±0.5	$6.34^{+0.16}_{-0.20}$	177±67
P33	2840	6273	5 ±1	$5.94^{+0.17}_{-0.20}$	445±165
P34	2889	6322	2.0±0.5	$6.14^{+0.18}_{-0.21}$	281±110
P35	2953	6387	3.0±0.7	$5.87^{+0.20}_{-0.23}$	523±216
P36	3049	6485	2.0±0.4	$5.92^{+0.22}_{-0.28}$	466±220

TABLE V. Comparison between experimental and calculated level spacing in ^{69}As.

E_p (MeV)	E_x(^{69}As) (MeV)	Calculated level spacing $D(\frac{1}{2}^-,\frac{3}{2}^-)$ (keV) a	b	Experimental level spacing (keV)
1.5	4.9	39	12	
2.0	5.4	22	7	3.7
2.5	5.9	13	5	

[a]With the Truran *et al.* formula Ref. 14.
[b]With the Dilg formula Ref. 15.

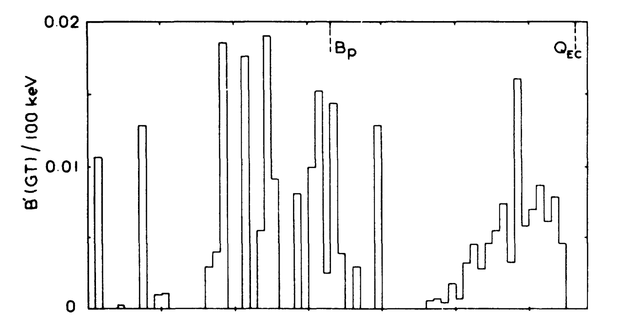

FIG. 4. B'(GT) strength distribution for the β^+–electron-capture decay of ^{69}Se. The experimental strength summed within 100 keV energy bites is plotted as a function of excitation energy in ^{69}As.

strength $\Sigma B'(\mathrm{GT})=0.27$ amounts only to 9% of the nuclear sum rule limit $S_{\beta^-}-S_{\beta^+}=3(N\text{-}Z)$, i.e., 3. A value of the same order of magnitude (6%) has been determined by Vierinen for ^{65}Ge, another $T_z=\frac{1}{2}$ proton precursor.[9]

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