

## <sup>68</sup>Ge - <sup>68</sup>Ga -- Comments on evaluation by E. Schönfeld

### Remarks and Comments

These remarks and comments are only for evaluators; they should not be printed in the LPRI-PTB "Table of Radionuclides". Complete references are given only in those cases where the reference is not already included in the list of references (Section 6).

### 1 Decay Scheme

The decay scheme of Ga-68 is taken from Vo *et al.* (1994) who discovered 5 very weak transitions between already known levels in the decay scheme established by Lange *et al.* (1973). The first excited state in Ga-68 is at 175 keV. As can be seen from the  $Q$  value an energy of this amount is not available. Thus, the decay scheme of Ge-68 is complete.

From other excitation modes it is known that Zn-68 has the following additional levels below the  $Q$  value of the transformation Ga-68  $\rightarrow$  Zn-68: 2370,3(15); 2417,44(6) (4)+; 2510,2(15); 2750,38(8) keV 3- (M. R. Bhat, *Nucl. Data Sheets* 55(1988)1 and 76(1995)343). Radiations originating from these levels were not seen in the EC decay of Ga-68 (Vo *et al.*, 1994). Transitions to the 2417 and 2510 keV levels would be third and second forbidden and therefore the feeding of these levels - if any - should be much weaker. The values of the half-lives of the excited states of <sup>68</sup>Zn are taken from Bhat (1995). The values for total positron emission and total electron capture branching are taken from Schönfeld *et al.* (1994).

### 2 Nuclear Data

The following values of the half-life of <sup>68</sup>Ge have been taken into account:

1	250 d	H. H. Hopkins, Jr., <i>Phys. Rev.</i> 77(1950)717
2	288(6) d	G. Rudstam, Thesis, Univ. of Uppsala (1956)
3	275(20) d	B. Crasemann, D. E. Rehfuss, H. T. Easterday, <i>Phys. Rev.</i> 102(1956)1344
4	270,82(27) d	Waters <i>et al.</i> 1981
5	270,99(19) d	Schönfeld <i>et al.</i> 1994

Taking values 2 to 5 the limitation of relative statistical weight procedure would give 276(5) d because the weighted and unweighted mean do not overlap. Other procedures give 270,95(16) d (weighted mean), 270,9(3) d (modified Bayesian), 270,94(16) d (normalised residual) 270,95(16) (Rajeval). In the present case the latter value which coincides with the weighted mean was chosen as the adopted value.

The following values of the half-life of <sup>68</sup>Ga have been taken into consideration:

1	68,0 min	M. L. Perlman, G. Friedlander, <i>Phys. Rev.</i> 74(1948)442
2	67,7(3) min	G. L. Gleason, <i>Int. J. Appl. Rad. Isotopes</i> 8(1960)90
3	69,2(14) min	L. A. Rayburn, <i>Phys. Rev.</i> 122(1961)168
4	68,33(9) min	T. G. Ebrey, P. R. Gray, <i>Nucl. Phys.</i> 61(1965)479
5	68,2(1) min	M. Borman, E. Fretwurst, P. Schehka, G. Wrege, H. Büttner, A. Lindner, H. Meldner, <i>Nucl. Phys.</i> 63(1965)438
6	68,5(5) min	J. M. Ootukalam, M. K. Ramaswamy, <i>Amer. J. Phys.</i> 39(1971)221
7	67,80(8) min	Smith and Williams (1971)
8	67,629(24) min	Iwata <i>et al.</i> (1986)

Most of these values have been discussed by Iwata *et al.* (1986). Using values 2 to 8, the limitation of relative statistical weights procedure leads to 68,6(2) min because the weighted and unweighted means do not overlap. Other procedures give: 67,711(22) min (weighted mean) 67,71(9) min (modified Bayesian), 67,89(9) (normalised residual), 67,754(27) (Rajeval). The first two values of this set are heavily influenced

by value 8. Only the normalized residual and Rajeval procedures reduce the relative influence of value 8. Because a study of the paper of Iwata et al. shows that this is an extraordinary careful work including chemical purification and measurements over a period of 20 half-lives, the result of the modified Bayesian method is adopted as the most probable value. The value itself is practically identical with the weighted mean while the uncertainty covers the value 8 of Iwata *et al.*

The  $Q$  values are taken from Audi and Wapstra (1995). The  $Q$  value for the transformation of Ga-68 into Zn-68 is based on the maximum beta energy for the transition 0,0 measured by Slot *et al.* (1972).

## 2.1 Electron Capture Transitions

The energies are derived from the  $Q$  value and the level energies. The fractional probabilities for EC are calculated using the "Tables for Calculation of Electron Capture" (E. Schönfeld, PTB-Laboratory report 6.33-95-2 (1995)). These values are based on wave functions of Mann and Waber (1973) with exchange and overlap corrections of Bahcall and Vatai; see W. Bambynek et al., *Rev. Mod. Phys.* 49(1977)77. Note that the sum  $P_K+P_L+P_M$  is not equal to 1 because of a very small fraction of capture from the N shell.

The absolute transition probabilities for EC were recalculated from the paper of Schönfeld et al. (1994) (which are related originally to a simplified decay scheme) by inclusion of the weak gamma transitions. The sum of the  $P_{EC}$  for all EC transitions remains unchanged and is equal to 0,1086(11). The nature of the transitions are deduced from angular momenta and parities of the levels as given in the compilation of Bath (1995), which are the same as in the paper of Vo et al. (1994)). The log ft values are rounded to one digit after the comma.

## 2.2 Positron Transitions

The maximum energy for the transition 0,0 is taken from Slot et al. (1972). The other values are deduced from this value and level energies. The uncertainties of the level energies do not contribute significantly to the uncertainties of these values as their uncertainty is smaller than that of the  $Q$  value. The nature of the different transitions are deduced from spins and parities of the levels as given in the paper of Bath (1995) and in the paper of Vo *et al.* (1994).

The transition probabilities for positrons were recalculated from the values given in the paper of Schönfeld *et al.* (1994) taking into account the weak gamma rays observed by Vo et al. (1994). The sum of all positron emission probabilities remains unchanged in this procedure (0,8914(11)).

The ratio of EC and  $\beta^+$  for the transition 0,1 was interpolated from the table of N. B. Gove and M. J. Martin, *Nucl. Data Tables A* 10(1971)203, to be 1,50(6) (4%) and was used as an input value in the work of Schönfeld et al. (1994). The corresponding value for the  $\beta^+$  transition 0,0 comes out to be 0,099(3) in agreement with the theoretical value 0,102(4) interpolated from the table of Gove and Martin. The EC to  $\beta^+$  ratio for the transition 0,2 is also interpolated from the tables of Gove and Martin. For this ratio a relative uncertainty of 7 % is assumed.

## 2.3 Gamma Transitions

The level differences (as well as the gamma-ray energies in Section 4.2) were taken from a compilation of Helmer (1995, priv. comm.) which takes into account also data from sources other than the Ga-68 decay.

The transition probabilities are derived from the emission probabilities and the conversion coefficients. The absolute gamma-ray emission probabilities are calculated from the relative gamma-ray emission probabilities which are evaluated values (Section 4.2) and the absolute gamma ray emission probability of the main gamma transition (1077 keV) which was taken from Schönfeld et al. (1994) to be  $P_\gamma = 0,0322(3)$ . The 1656 keV transition was observed only indirectly via conversion electrons by Slot *et al.* (1973) ( $P_{ce(1656)}/P_{ce(1077)} = 0,010(2)$ ). The conversion coefficients are interpolated from the tables of Rösel *et al.* (1978). The mixing ratios are derived from the measurements of Vo *et al.* (1994). Others: see Krane (1977). Eight of the transitions have no admixtures but are pure (multipolarity E2) because the initial or the final level has  $J = 0$ .

### 3 Atomic Data

All these data are taken from E. Schönfeld and H. Janssen, *Nucl. Instr. and Methods in Phys. Res. A* 369(1996)527.

#### 3.1 X Radiation

The energies are based on the wavelengths compiled by J. A. Bearden, *Rev. Mod. Phys.* 39(1967)78. The relative probabilities for  $K_{\alpha}$  radiation are based on  $P(K_{\beta})/P(K_{\alpha})$  and  $P(K_{\alpha 2})/P(K_{\alpha 1})$  values as given in the above cited paper of Schönfeld and Janßen (1994). The relative probabilities for L quanta are derived from the corresponding absolute values (Section 4.2) setting  $P(K_{\alpha 1}) = 1$ .

#### 3.2 Auger Electrons

The energies of KLL and KLX Auger electrons are taken from the paper of F. P. Larkins, *Atomic Data and Nuclear Data Tables* 20 (1977) 313. The relative emission probabilities of K Auger electrons are taken from the above cited paper of Schönfeld and Janßen (1994). The relative emission probabilities of L Auger electrons are derived from the corresponding absolute probabilities (Section 4.1) setting  $P(KLL) = 1$ .

### 4. Radiation Emission

#### 4.1 Electron Emission

The energies of the Auger electrons are the same as above. The energies of the conversion electrons are calculated from the energies of the gamma rays and the corresponding electron binding energies. The emission probabilities of the Auger electrons are calculated from the transition probabilities of the EC transitions (2.1) and gamma transitions (2.3) using the atomic data given in Sections 3 and 3.2, the fractional electron capture probabilities and the conversion coefficients. The emission probabilities of conversion electrons are calculated from the transition probabilities and conversion coefficients given in Section 2.3.

#### 4.2 Photon Emission

The X ray energies are the same as in 3.1. The energies of the gamma rays were taken from Helmer (see 2.3). The emission probabilities of X rays were calculated from the transition probabilities of EC transitions (2.1), gamma transitions (2.3) and conversion coefficients (2.3) using the atomic data given in Sections 3 and 3.1. For the relative gamma-ray emission probabilities the following values have been considered :

$\gamma$ -ray energy keV	Vaughan et al. 1969	Carter et al. 1968	Lange et al. 1973	Vo et al. 1994	Schönfeld et al. 1994	Schötzig 1996	Adopted
227	-	-	-	0,0037(15)			0,0037(15)
483	-	-	-	0,0082(9)			0,0082(9)
579	0,7(1)	1,1(2)	1,00(12)	1,05(15)	1,14(15)	-	1,04(5)
683	-	-	-	0,0097(6)	-	-	0,0097(6)
806	2,2(2)	2,8(2)	2,95(12)	2,81(14)	2,90(31)	2,97(7)	2,92(7)
939	-	-	-	0,055(5)	-	-	0,0055(5)
1077	100	100	100	100	100	100	100
1166	-	-	-	0,0005(3)	-		0,0005(3)
1261	3,1(2)	2,9(2)	3,00(7)	2,75(14)	3,06(31)	2,91(6)	2,93(6)
1744	0,5(1)	0,28(4)	0,30(4)	0,295(15)	-	-	0,295(15)
1883	4,8(3)	4,1(4)	4,33(12)	4,6(2)	3,86(59)	4,14(8)	4,24(8)
2338	<0,1	0,04(2)	0,050(6)	0,031(3)	-	-	0,035(5)
2821	-	-	0,015(2)	0,0139(11)			0,0144(11)

Where there are only values from Vo et al., these have been adopted unchanged. In all other cases weighted means have been calculated. The obviously less precise values of Vaughan et al were included but in the calculation of a mean their uncertainties were taken to be twice the original uncertainties. The latest values of Schötzig (PTB, 1996, priv. comm.) are results of measurements based on a well established efficiency curve. For this reason they have been included in the averaging procedure although they are not published. In no case the uncertainty of any adopted value is taken to be smaller than the uncertainty of the most accurate single value for the corresponding transition.

The absolute emission probability of the annihilation quanta (most of them having 511 keV energy) is taken from Schönfeld et al. (1994) and is based on the assumption that each  $\beta^+$  particle produces 2 annihilation quanta.

## 5 Main Production Modes

Taken from Bath (1995).