60Co - Comments on evaluation of decay data
by R. G. Helmer

1 Decay scheme

This evaluation was originally completed in September 1996 with minor editing in February 1997 and post-review editing in January 1998. The literature available by January 1998 was included. In addition to the levels reported in this decay, there are levels in 60Ni below the decay energy at 2284 keV (0+) and 2626 (3+). However, based on the limits on the β- branches to these levels (see sect. 2.1), this scheme is considered complete. The scheme is internally consistent since the total decay energy computed by RADLST is 2823.8 (5) keV compared to the Q value of 2823.9 (5) keV.

2 Nuclear Data

Q value is from Audi and Wapstra 1995 (95Au04).

The half-life values available are, in days, are listed. If the value was published in years, it is shown here in years and also converted to days (365.242 days/year).

<table>
<thead>
<tr>
<th>Years</th>
<th>days</th>
<th>Reference</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>1936 (256)</td>
<td>60Li01</td>
<td>as quoted in 63Go03</td>
</tr>
<tr>
<td>5.08</td>
<td>1855 (29)</td>
<td>49Se20</td>
<td>as quoted in 63Go03</td>
</tr>
<tr>
<td>5.26</td>
<td>1921 (62)</td>
<td>50Br76</td>
<td></td>
</tr>
<tr>
<td>5.25</td>
<td>1917.5 (73)</td>
<td>51Si25</td>
<td>as quoted in 63Go03</td>
</tr>
<tr>
<td>5.27</td>
<td>1925 (26)</td>
<td>51To25</td>
<td>as quoted in 63Go03</td>
</tr>
<tr>
<td>5.21</td>
<td>1903 (15)</td>
<td>53Ka21</td>
<td></td>
</tr>
<tr>
<td>4.95</td>
<td>1808 (15)</td>
<td>53Lo09</td>
<td>omitted from analysis</td>
</tr>
<tr>
<td>5.24</td>
<td>1914 (11)</td>
<td>57Ge07</td>
<td></td>
</tr>
<tr>
<td>5.33</td>
<td>1947 (15)</td>
<td>58Ke26</td>
<td>as quoted in 65An07</td>
</tr>
<tr>
<td>5.263</td>
<td>1922.3 (11)</td>
<td>63Go03</td>
<td></td>
</tr>
<tr>
<td>5.242</td>
<td>1914.6 (29)</td>
<td>65An07</td>
<td></td>
</tr>
<tr>
<td>5.270</td>
<td>1924.8 (26)</td>
<td>68La10</td>
<td></td>
</tr>
<tr>
<td>5.2719(11)</td>
<td>1925.5 (4)</td>
<td>70Wa19</td>
<td>replaced by 83Wa26</td>
</tr>
<tr>
<td>5.24</td>
<td>1914 (77)</td>
<td>73Ha60</td>
<td></td>
</tr>
<tr>
<td>5.283</td>
<td>1929.6 (11)</td>
<td>77Va30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1925.2 (4)</td>
<td>80Ho17</td>
<td></td>
</tr>
<tr>
<td>5.282</td>
<td>1929.2 (26)</td>
<td>82HoZJ</td>
<td>replaced by 92Un01</td>
</tr>
<tr>
<td></td>
<td>1924.8 (10)</td>
<td>82RyZX</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1925.5 (3)</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1925.02 (47)</td>
<td>83Ru04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1925.5 (4)</td>
<td>83Wa26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1925.12 (46)</td>
<td>92Un01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1925.3 (3)</td>
<td>Adopted value and weighted average of all 19 values, internal uncertainty=0.17, reduced-$\chi^2$=2.98</td>
<td></td>
</tr>
</tbody>
</table>

The LRSW method would not alter this result because no input value contributes over 50% of the relative weight and the most precise value is within the range of the final uncertainty.

Several other averages were calculated in order to ascertain how much the result would vary with the analysis method. If only the ten values with $\sigma < 4$ days are included the weighted average is 1925.3 (4) with internal uncertainty = 0.17, reduced-$\chi^2$ = 4.57, and external uncertainty = 0.36. The Normalized Residual method (92Ja06) with all twenty values increases the uncertainties of three values, including that of 53Lo09, and then the weighted average is 1925.2 (3). The RAJEVAL method (92Ra08) with all twenty values rejects the value of 53Lo09 and increases the uncertainties of four others, and then the weighted average is 1925.3 (2).

These results are very consistent so the result does not depend significantly on the analysis method.
2.1 β\textsuperscript{-} Transitions

In addition to the main decay to the J\textsuperscript{π} = 4\textsuperscript{+} level at 2505 keV, there is the possibility of β\textsuperscript{-} decay from the 5\textsuperscript{+} parent to the 0\textsuperscript{+} levels at 0 and 2284 keV, the 2\textsuperscript{+} levels at 1332 and 2158 keV, and the 3\textsuperscript{+} level at 2626 keV.

The β\textsuperscript{-} decay to the 0\textsuperscript{+} levels at 0 and 2284 keV are unique 4\textsuperscript{th} forbidden with expected log\textit{f} values (73Ra10)>23 and corresponding Pβ < 1 x 10\textsuperscript{-9}% and < 1 x 10\textsuperscript{-13}%, respectively. The decay to the 3\textsuperscript{+} level at 2626 is 2\textsuperscript{nd} forbidden with an expected log\textit{f} ≥ 11 and a corresponding Pβ < 0.01%. This level decays mainly by γ's of 467 and 1293 keV; the Pγ(467) has been reported as <0.00023% (76Ca18) and <0.0004% (69Va20), which indicates Pβ(2626) < 0.001%.

The β\textsuperscript{-} decay to the 1332 level is unique 2\textsuperscript{nd} forbidden with an expected log\textit{f} ≥ 12.8 and a corresponding Pβ ≤ 12%. The measured values are (in %): 0.15 (1) (54Ke04), 0.010 (2) (56Wo09), 0.12 (61Ca05), and 0.08 (2) (68Ha03). The average of 0.12% (3) is adopted.

The decay to the 2158-keV level is unique 2\textsuperscript{nd} forbidden with an expected log\textit{f} ≥ 12.8 and a corresponding Pβ ≤ 0.02%. This branch is given as 0.000% (2) from 69Ra23. (Value is given as 0.18% (3) in 68Ha03, but this is apparently from a misinterpretation of the γ-ray spectrum.)

The decay to the 2505-keV level is then 100.0 - Pβ (1332) - Pβ (2158) = 0.12(3) - 0.000(2) = 99.88(3)%.

The β\textsuperscript{-} energies and log\textit{f} values are from the program LOGFT.

2.2 Gamma Transitions

The multipolarities are from the Adopted γ data in the Nuclear Data Sheets (93Ki10).

The total and K-shell internal-conversion coefficients, α and αK, for the 1173- and 1332-keV γ rays are from the evaluation of the experimental measurements (85HaZA) and the remaining values were interpolated from the Band tables (76Ba63).

The internal-pair-formation coefficients were interpolated from the theoretical values of 79Sc31 and are απ(1173) = 0.000 006 2 (7) and απ(1332) = 0.000 034 (4). The former is negligible since it is only about 5% of the corresponding α, but the latter is about 25% of the α, so it needs to be taken into account.

3 Atomic Data (Ni, Z=28)

The data are from Schönfeld and Janßen (96Sc06).

3.1 and 3.2 X Radiation and Auger Electrons

The data were computed by RADLST with the Schönfeld atomic data.

4 Radiation Emission

4.1 Electron Emission

Data were computed by the program RADLST.
4.2 Photon Emissions

The $\gamma$-ray energies are from $^{97}\text{He}$ for the 1173 and 1332 lines and the others are deduced from the level energies resulting from a fit to the $\gamma$-ray energies. Besides the 1173 and 1332 values, the input to this fit included:

- 346.93 (7) from $^{76}\text{Ca}$, where the authors average their result and that of $^{69}\text{Va}$;
- other: 346.95 (10) ($^{69}\text{Va}$); $^{76}\text{Ca}$ average.

Besides the 1173 and 1332 values, the input to this fit included:

- 826.06 (3) from $^{59}\text{Co}(p,\gamma)^{60}\text{Ni}$ ($^{75}\text{Er}$); others: 826.18 (20) ($^{69}\text{Va}$) and 826.28 (9) ($^{76}\text{Ca}$), but includes value of $^{69}\text{Va}$;
- 2158.57 (10) from $^{59}\text{Co}(p,\gamma)^{60}\text{Co}$ ($^{75}\text{Er}$); others: 2158.8 (4) ($^{70}\text{Di}$) from $^{60}\text{Co}$ decay and 2158.9 (2) ($^{69}\text{Ra}$) and 2159.6 (8) ($^{60}\text{Cu}$) from $^{60}\text{Cu}$ decay.

For the relative $\gamma$-ray emission probabilities, the following data were used.

<table>
<thead>
<tr>
<th>$\gamma$ energy (keV)</th>
<th>Relative $\gamma$-ray emission probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>347</td>
<td>100</td>
</tr>
<tr>
<td>467</td>
<td>$&lt;0.005$</td>
</tr>
<tr>
<td>826</td>
<td>100</td>
</tr>
<tr>
<td>1173/1332</td>
<td>0.0012 (2)</td>
</tr>
<tr>
<td>2158</td>
<td>$&lt;0.002$</td>
</tr>
<tr>
<td>2505</td>
<td>100</td>
</tr>
</tbody>
</table>

These relative emission probabilities were normalized by requiring that the total $\beta^-$ emission probability is 100%.

For the 1132 $\gamma$ ray, this means

$$P_\gamma(1132) = \frac{(100.00 - P_\beta(2505) \times [1+\alpha(2505)]) - P_\gamma(347) \times [1+\alpha(347)] - P_\gamma(2158) \times [1+\alpha(2158)]}{1.00 + \alpha(1132) + \alpha(347)}.$$  

For the 1173 $\gamma$ ray, this means

$$P_\gamma(1173) = \frac{(100.00 - P_\beta(2505) \times [1+\alpha(2505)]) - P_\gamma(347) \times [1+\alpha(347)] - P_\gamma(2158) \times [1+\alpha(2158)]}{1.00 + \alpha(1173) + \alpha(347)}.$$  

6 References

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