Upgrade of equipment to measure precise β-decay branching ratios

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Our program [1] to test the Electroweak Standard Model via the unitarity of the Cabibbo-Kobayashi-Maskawa matrix requires precise measurements of the Q_{EC}-value, half life ($t_{1/2}$), and branching ratio (BR) for superallowed $0^+ \rightarrow 0^+$ β^+ decays. We make the $t_{1/2}$ and BR measurements by producing a pure sample of the activity of interest with the MARS spectrograph, collecting it on the tape of our fast tape transport and moving it rapidly to a shielded counting location. A high purity radioactive beam with energy of about 30 A MeV is extracted from the MARS focal plane into air and, after it passes through a 0.3-mm-thick BC-404 plastic scintillator and aluminum degraders, it is implanted into the 76-μm-thick Mylar tape of the tape-transport system for up to two half lives. Then the beam is turned off and the activity is moved in less than 0.2 s to the center of the counting station, where the decays are measured. For branching-ratio measurements the counting station consists of a 1-mm-thick BC-404 plastic scintillator very close to one side of the tape and a HPGE detector located 15 cm away on the other side of the tape. The beam-on/move/detect cycles are repeated until the desired statistics have been acquired. While the measurements themselves are superficially simple, the required accuracy (better than 0.1%) is very demanding. The desired accuracy demands a series of reliability tests that must be as complete as possible. Thus all parameters that could possibly affect the result are monitored continuously, on a cycle-by-cycle basis, and, wherever possible, redundancy is incorporated.

We reported in Ref. [2] a β-γ coincidence setup, based on FERA modules and KmaxNT [3] software, able to perform a precise BR measurement. We first used this equipment to measure the branching ratio of the superallowed decay of ^{22}Mg [4]. The setup records two types of events:

- Those observed during the implantation of the heavy ions. For each event of this type we record the energy deposited in the 0.3-mm-thick plastic scintillator, ΔE_{HI}, and the time of its implantation, t_{HI}, relative to the beginning of the cycle.
- Those observed during the "detect" portion of the cycle: *viz.* beta-gamma coincidences. For each such event we record: 1) the energy deposited in the HPGe detector, E_γ; 2) the energy deposited by the beta particle in the 1-mm-thick plastic scintillator, ΔE_β; 3) the time, t_{decay}, that the decay is recorded relative to the beginning of the detect period; and 4) the "coincidence time," $t_{\beta\text{-}\gamma}$, which is the time difference between the β and γ signals from the two detectors.

In an ideal case, all the events in the HPGe detector are gammas and all those in the 1-mm-thick plastic scintillator are betas originating in decays of the implanted source; then the BR can be extracted from the formula:

$$BR = N_{\beta\text{-}\gamma}/(N_\beta\, \varepsilon_\gamma), \qquad (1)$$

where $N_{\beta\text{-}\gamma}$ is the number of observed beta-gamma coincidences, N_β is the number of observed beta singles and ε_γ is the absolute efficiency of the HPGe detector. In the real case, corrections must be applied for dead-time losses, for real and random coincidence gains and losses, for gamma events appearing in the plastic scintillator and for small differences in the detection efficiencies for betas originating from different branches with different end-point energies. (The denominator in Eq. 1 incorporates all branches while the numerator involves only one.)

As is evident from Eq. 1, to obtain high precision in the measurement of BR, one requires comparable precision in the absolute efficiency, ε_γ, of the HPGe detector. The precise calibration of our HPGe detector [6-8] was accomplished using sources that were positioned at a well defined position relative to the HPGe detector, which had an uncertainty of ±0.1 mm or better. Our on-line measurements use the tape transport system, which cannot be positioned repeatedly with the same precision. To overcome this limitation, we have placed a laser sensor next to the HPGe detector and pointing to the Mylar tape; with this device we can read the distance between source and detector to 0.05-mm precision and record that distance on a cycle-by-cycle basis. Note that control over the transport length (i.e. the source positioning in the tape direction) can be accomplished by recording the ratio of beta-singles to implanted-heavy-ions, N_β/N_{HI}, for each cycle since an incorrect position results in a reduced value of the ratio. This, of course, requires us to scale the beta singles and implanted heavy ions for each cycle.

Using the experience gathered over years of operation, we have now made a major upgrade to the BR setup. Now, in addition to the information related to the two types of events (ΔE_{HI}, t_{HI}) and (ΔE_β, E_γ, $t_{\beta\text{-}\gamma}$, t_{decay}), we also record the following for each cycle:

- the number of implanted heavy ions, N_{HI},
- the number of beta singles N_β,
- the number of gamma singles N_γ,
- the number of beta-gamma coincidences,
- the tape-to-HPGe distance,
- integrated dead-time in the beta-singles channel,
- integrated dead-time in the gamma-singles channel, and
- integrated dead-time in the beta-gamma coincidence channel.

Moreover, the new configuration has added significant redundancy: all the “per-cycle” totals are scaled in parallel chains (FERA and CAMAC).

Finally, the coincidence electronics has been optimized to minimize the event losses due to “underflows” in the ΔE_β and E_γ channels. Such underflows can happen if the analog-to-digital convertor (ADC) abandons the conversion (having assessed a too low value in the given channel) or if the signal presented to the ADC sits on the tail of a preceding one, thus preventing the ADC from rearming. Both cases result in events with incomplete information, and eventually in a lost event. The new setup reduces these losses from about 7-10% to less than 0.1% in the ΔE_β channel, and from 3-5% to about 0.3% in the E_γ channel.

With added controls, improved efficiency of the coincidence electronics, and continuous monitoring of the source-detector position, the new setup is expected to let us reach the desired 0.1% precision in BR measurements.

[1] J.C. Hardy, I.S. Towner, V.E. Iacob, H.I. Park, L. Chen, V. Horvat, N. Nica, J. Goodwin, M. Bencomo, L. Trache and R.E. Tribble, *Progress in Research*, Cyclotron Institute, Texas A&M University (2011-2012), p I-3.
[2] V.E. Iacob and J.C. Hardy, *Progress in Research*, Cyclotron Institute, Texas A&M University (1999-2000), p. V-22.
[3] http://www.sparrowcorp.com
[4] J.C. Hardy *et al.*, Phys. Rev. Lett. **91**, 082501 (2003).
[6] J. C. Hardy *et al.*, J. Appl. Radiat. Isot. **56**, 65 (2002).
[7] R.G. Helmer *et al.*, Nucl. Instrum. Methods Phys. Res. **A511**, 360 (2003).
[8] R.G. Helmer *et al.*, J. Appl. Radiat. Isot. **60**, 173 (2004).