PRECISION Q-VALUE DETERMINATIONS FOR NEUTRON-RICH RUBIDIUM ISOTOPOES AT TRISTAN

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Abstract

Beta-ray end-point energies for Rb fission products were measured at the TRISTAN on-line mass separator using an intrinsic Ge \( \beta \) spectrometer. Coincidence measurements were used to establish feeding relationships and to verify level schemes in daughter nuclides. \( Q_\beta \) values are reported for 88,94,96,98\(^{\text{Rb}} \) and compared with results from other experiments and with predictions of mass formulae.

1. Introduction

The determination of accurate atomic masses in neutron-rich nuclei is necessary for further refinement of mass formulae which are used to predict properties of unknown nuclides far from stability. Improvement in the accuracy of these equations is important since they are used in calculations of both fundamental and practical significance. For example, improved accuracy in mass equations would aid in refining reactor decay-heat predictions, searches for delayed neutron emitters and in improving calculations of the competition between neutron capture and \( \beta \) decay on rapid time scales. The first two items are important for efficient and safe design of future fission reactors;\(^{11} \) the third relates to theories of astrophysical significance.\(^{2,3} \)

Masses of unstable neutron-rich nuclides traditionally have been determined by \( \beta \)-ray end-point measurements. If the excitation energy of the populated level or levels is known, then the mass difference between the two members of the isobaric chain is determined. Normally, plastic scintillators are used as \( \beta \) detectors and the \( \beta \)-ray singles spectrum and/or beta spectra in coincidence with \( \gamma \)-deexcitation of daughter nuclei are recorded. Recently, hyperpure intrinsic Ge detectors have been introduced. These offer the potential for determining end-point energies with higher precision than is possible with scintillation detectors, thus permitting more precise mass determinations for nuclides which undergo \( \beta \) decay.\(^{4,5} \)

For stable isotopes high resolution mass spectroscopy has been used to directly measure mass differences. Recently, Epherre et al.\(^{6} \) have used a clever adaptation of this technique to study radioactive nuclides far from stability. Using the on-line mass separator ISOLED at CERN they made precise direct mass measurements of \( 94-79\text{Rb}, 90-99\text{Rb} \) and numerous Cs isotopes. In some instances their results were found to be at variance with those determined by \( Q_\beta \) measurements.\(^{7-9} \) In the case of Cs isotopes the discrepancies between the two types of measurements were found to result from a significant error in the value of a reference mass used in calibrating the direct mass experiments.\(^{10} \) No such systematic error affected the Rb direct mass measurements.

The recent \( Q_\beta \) work on very neutron-rich Rb isotopes comes from three groups. Keyser et al.\(^{11} \) have determined \( Q \) values for \( 92-99\text{Rb} \) using a plastic scintillation counter-telescope/Ge(Li) spectrometer at the mass separators LOHENGRIN and OSTIS located at the high flux reactor of the Institute Laue-Langevin. Decker et al.\(^{9} \) have also reported \( Q_\beta \) values from OSTIS measured using an intrinsic Ge \( \beta \) detector. The results of Peuser et al.\(^{6} \) were obtained using a plastic counter-telescope at the Mainz reactor. There are major discrepancies among the various \( Q_\beta \) measurements (>1 MeV in some cases) as well as between some of the \( Q_\beta \) results and the direct mass measurements. The values reported by Keyser et al. are in agreement with the direct mass data within stated errors which, however, become quite large far from stability: \( 98\text{Rb}, +300 \text{ keV} \) \( Q_\beta \) method; \( +155 \text{ keV} \) direct mass method. In view of the somewhat unsettled situation for the neutron-rich Rb isotopes, we decided to begin our \( Q_\beta \) measurement program at TRISTAN in this mass region.

2. Experimental Methods

2.1 The TRISTAN Facility

The TRISTAN on-line mass separator at the High Flux Beam Reactor, Brookhaven National Laboratory became operational late in 1980. Detailed information about the capabilities of the separator and associated data acquisition/analysis systems can be found in references\(^{12,13} \) and citations therein. Initial operations have used a positive ion surface ionization source\(^{14} \) which contains \( \sim 5 \) of enriched \( 235\text{U} \) in a
graphite cloth matrix. The source is positioned in a neutron beam flux of $\approx 1.5 \times 10^{10}$ n/cm$^2$.sec external to the reactor containment shield. Pairs of alkali metals (Rb, Cs) and alkaline earths (Sr, Ba) are extracted, mass separated by a 90° magnetic sector and deposited on a movable tape. A tape transport mechanism permits timed movements of the source deposit relative to detectors positioned at the point of deposit (parent port) or at a secondary station (daughter port). Proper choice of time sequencing permits selective enhancement of an isobaric decay chain. Because of massive shielding of the ion source and primary separator components a low background is maintained at the counting stations.

2.2 Beta-Ray End-Point Measurements

We have developed a system for $Q_e$ value measurements similar in design to that reported by Wünsch et al.\textsuperscript{4,5} in which a hyperpure Ge detector is used to measure $\beta$ spectra. Our detector which has a surface area of 250 mm$^2$ and 10 mm active thickness is a cylindrical crystal equipped with a 12 mm titanium entrance window. The detector assembly is integrally mounted into the vacuum system of the TRISTAN moving tape collector so that the source-to-detector distance is 15 mm. Determination of energy loss for $\beta$ rays in the detector window and dead layer was made using conversion electron sources. The $\gamma$-ray sensitivity of the $\beta$ detector is employed as a means of energy calibration using the many well known high-energy lines of $^{90}$Rb measured on-line at the separator.\textsuperscript{15} To minimize systematic errors in $\beta$-ray end-point energies due to accidental summing pulse pile-up rejection circuitry was used and counting rates were kept below 3 kHz.

Additional information is provided by measuring $\gamma$-ray spectra in coincidence with $\beta$ rays using a 20% Ge(Li) detector located on the opposite side of the source. $\beta$-$\gamma$ coincidence measurements are necessary when there is more than a single $\beta$-branch of significant intensity; when $Q_e$ for decay of the daughter isotope is comparable or greater than $Q_e$ for the nuclide of interest; or when $\beta$ decay does not occur between ground states. We record event-mode ($\beta$-$\gamma$-$\gamma$) coincidence data which is sorted off-line into spectra for various $\beta$ branches. This complication has a compensating benefit, however, in that it provides data on alternative paths for checking derived $Q_e$ values. It also provides a means for testing the validity of the decay scheme.

Pile-up rejection circuitry and a constant-fraction timing coincidence system are interfaced with a digital readout data acquisition system based on a PDP-11/20 computer fed by a CAMAC driver. The CAMAC incorporates a microprogrammed branch driver which can multiplex up to eight separate data channel inputs. Coincidence data are event-mode recorded ($\beta$-$\gamma$-$\gamma$) on magnetic tape. An off-line PDP-11/34 computer is used for tape scanning, plotting and data analysis. Of particular interest for these studies is an interactive computer code, BDK, for analysis of $\beta$-ray spectra which has been described in detail by Rehfied.\textsuperscript{16} In most cases reported here this code was used to linearize data in the high-energy region of the $\beta$ spectrum, thus permitting accurate determination of the end point.

3. Results and Discussion

Experimental $Q_e$ values for some neutron-rich Rb isotopes are found in Table 1. In addition to the results of the present study we include for comparison values reported by others using intrinsic Ge detectors,\textsuperscript{9,16,17} plastic scintillation counter-telescopes,\textsuperscript{8,11} and a mass spectrometer.\textsuperscript{6} The mass spectrometer results have been adjusted by Keyser et al.\textsuperscript{11} to permit direct comparison with $Q_e$ measurements. Each of the Rb isotopes will be discussed in turn.

3.1 $^{88}$Rb

In Fig. 1 we show experimental data and a Fermi-Kurie fit to the end-point region of the $^{88}$Rb $\beta$ spectrum as measured at TRISTAN using an intrinsic Ge detector. We determine an end-point energy of 5313$\pm$5 keV in excellent agreement with the McGill and OSTIS results (Table 1). It should be

<table>
<thead>
<tr>
<th>$^{88}$Rb</th>
<th>$^{94}$Rb</th>
<th>$^{96}$Rb</th>
<th>$^{98}$Rb</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRISTAN (Ge)$^a$</td>
<td>5313$\pm$5</td>
<td>10,353$\pm$100</td>
<td>11,547$\pm$100</td>
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<tr>
<td>McGill (Ge)$^b$</td>
<td>5310$\pm$10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OSTIS (Ge)$^c$</td>
<td>5317$\pm$3$^{d}$</td>
<td>10,304$\pm$3$^{d}$</td>
<td>$&gt;11,334$250$^{d}$</td>
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<tr>
<td>LOHENGRII/OSTIS (plastic)$^e$</td>
<td>-</td>
<td>10,185$\pm$150</td>
<td>11,670$\pm$130</td>
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<tr>
<td>Mainz (plastic)$^f$</td>
<td>-</td>
<td>-</td>
<td>10,800$\pm$220</td>
</tr>
<tr>
<td>ISOLDE (direct)$^g$</td>
<td>-</td>
<td>10,125$\pm$50 (10,361$\pm$50)</td>
<td>11,735$\pm$85</td>
</tr>
</tbody>
</table>

\(a)\) this work. \(b)\) ref. 10). \(c)\) ref. 11). \(d)\) ref. 9). \(e)\) ref. 11). \(f)\) ref. 8). \(g)\) ref. 6 as adjusted in ref. 11).
noted that the very high precision of Ge $\gamma$-detector measurements for $^{88}$Rb is made possible by a number of favorable circumstances including a high fission yield, a convenient half life, a dominant ground state $\beta$-branch to stable $^{88}$Sr, and the availability of well-known calibration rays from $^{90}$Rb which bracket the end-point region.

3.2 $^{94}$Rb

There exist discrepancies among $Q_\beta$ values reported for decay of $^{94}$Rb which may be due to the existence of an as yet uncharacterized isomeric state in $^{94}$Rb. Ephrse et al.\(^6\) report a variation in the mass of $^{94}$Rb with temperature of the ionizing surface in their on-line mass spectrometer at ISOLDE. They surmised that the $^{94}$Rb isomer was approximately 200 keV less bound than the ground state and that its half-life was somewhat shorter than 2.7s, the ground state value. No direct observation of this isomer has been reported, however. Keyser et al.\(^11\) derived $Q_\beta$ values of $10,125\pm50$ and $10,361\pm50$ keV from the ISOLDE results for decay of the ground and isomeric states, respectively. They also made an independent measurement with a scintillation counter-telescope at LOHEN- GRIN/OSTIS and report $Q_\beta=10,185\pm150$ keV, overlapping within combined experimental precision both ground and isomeric results determined by direct mass measurements. Decker et al.\(^9\) have also reported a $Q_\beta$ value for $^{94}$Rb measured at OSTIS using an intrinsic Ge detector. Their result, $10,304\pm30$ keV agrees with the direct mass result for the isomeric state but is outside reported error for that of the ground state.

In our experiments at TRISTAN using an intrinsic Ge $\beta$-ray/Ge(Li) $\gamma$-ray spectrometer, $^{94}$Rb activity was collected for a period of 5.0s at the parent port during which data acquisition was operational, followed by a 0.5s interval in which the ion beam was deflected, counting was inhibited and the tape was moved so that the activity spot was in a shielded location. This duty cycle served to enhance $^{94}$Rb activity recording relative to longer-lived daughter products.

Analysis of the $\beta$-$\gamma$ coincidence spectra confirms the result of others that the most energetic $\beta$ branch feeds a level at 2414 keV in $^{94}$Sr. We derive an endpoint energy of $7939\pm100$ keV which implies $Q_\beta=10,353\pm100$ keV. Our result is in excellent agreement with Decker et al. and the ISOLDE isomeric value. It is barely within combined errors of the Keyser et al. result and outside limits for the direct mass ground state. It is perhaps possible that the Ge experiments are observing the decay of a different species than was seen in the plastic and lower temperature direct measurements. Better understanding of this discrepancy awaits elucidation of the isomer situation in $^{94}$Rb.

3.3 $^{96}$Rb

In a similar fashion we have determined $Q_\beta$ for $^{96}$Rb. Because of shorter half lives a 1.0s (collect, count)/0.3s (tape move) cycle was used to enhance $^{96}$Rb data collection relative to daughter activities. The end-point energy for the $\beta$-branch feeding the 1628 keV level in $^{96}$Sr was determined to be $9919\pm100$ keV yielding a $Q_\beta$ value of $11,547\pm100$ keV. This is in good agreement with Keyser et al. and falls slightly outside the stated error limit of the ISOLDE result. The Mainz group\(^9\) reports $Q_\beta=10,800\pm220$ keV substantially below all other results.

3.4 $^{98}$Rb

In the case of $^{98}$Rb decay there is an important disagreement between the decay scheme of Peuser et al.\(^8\) and that of Jung.\(^18\) The Mainz group reported $\beta$ feeding to a level at 2606 keV in $^{98}$Sr which deexcited by a $2172\pm91\pm45$ keV cascade to the ground state. Jung, however, placed the 2172 keV $\gamma$ ray as

![Fig. 2 Partial decay scheme for $^{98}$Rb.](image-url)
deexciting a level at 2316 keV via a 2316-
144 keV cascade (Fig. 2). Since the most
energetic 8 branch is seen in coincidence
with the 2172 keV \(\gamma\) ray it was necessary to
determine which of the above schemes was
correct. \(\gamma-\gamma\) coincidence spectra recorded
simultaneously with our \(8-\gamma\) measurements
clearly support the scheme reported by Jung.

![Graph showing the \(\gamma\) spectrum end-point region for \(98Rb\) decay.](image)

**Fig. 3** The \(\gamma\) spectrum end-point region
for \(98Rb\) decay.

Figure 3 shows the end-point region of
the \(98Rb\) \(\gamma\) spectrum. At very high \(\gamma\) ener-
gies in our detector response function prevented accurate Fermi-Kurie
analysis using the computer code BDK. For-
lunately, a simple semi-logarithmic plot
served to linearize the data in the end-
point region and permit the extraction of a
precise end point. We arrive at an end-
point energy of 10,026±150 keV yielding
Q_{\gamma}=12,343±150 keV. Our result is in ex-
cellent agreement with the direct mass measure-
ment and the somewhat less precise plastic
result of Keyser et al. Again the Mainz
value falls far lower than other.

3.5 Comparison with Mass Formulae

There appears to be substantial agree-
ment among experimenters for Q_{\gamma} values of
very neutron rich even-A Rb nuclides. The
situation is not quite as clear for the
odd-A isotopes largely due to decay scheme
uncertainties. In general, Q_{\gamma} measurements
strongly support the mass excess results of
Epherre et al. out through \(98Rb\), the most
neutron excess specie studied to date by \(\gamma\)
deay. Thus the Rb isotopes provide a well
founded basis for comparison with predic-
tions of mass formulae. In Fig. 4 the
differences between calculated and experi-
mental mass excess values for Rb isotopes
are plotted. The calculated results are
those tabulated by Maripuu\(^{19}\) and represent
a spectrum of different types of mass

![Graph showing a comparison of experimental and calculated mass excesses for Rb isotopes.](image)

**Fig. 4** Comparison of experimental and
calculated mass excesses for Rb
isotopes.

It is clear that for the neutron-
rich isotopes beyond \(94Rb\) there are system-
atic errors, often quite large, in the cal-
culated mass excesses.

It is of extreme importance to extend
our knowledge of other isotopic chains far
away from stability in order to see if sim-
ilar deviations occur, especially in the
fission product region. Without these data,
calculations which are based on the pre-
dictions of mass formulae for very neutron
rich nuclides, may be unreliable.

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