Atomic Masses of $^{147m, 148m, 149m}$Tb, $^{148}$Dy, $^{150m, 152m}$Ho
Derived from Decay Properties

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Received November 9, 1984

Using nuclear fusion reactions of $^{40}$Ar ions with $^{112}$Cd, $^{114}$Sn and $^{116}$Sn and subsequent $\gamma$-ray spectroscopy, the probability ratios of positron emission and electron capture, $\beta^+ / EC_\gamma$ and $\beta^+ / (EC + \beta^+)$, are determined for individual $\beta$-transitions in the decay of $^{147m, 148m, 149m}$Tb, $^{148}$Dy and $^{150m, 152m}$Ho. From comparison with theoretical ratios the following $Q_{EC}$ values, given in keV, are derived: $^{147m}$Tb, 4.620(60); $^{148m}$Tb, 5.730(30); $^{149m}$Tb, 3.610(50); $^{148}$Dy, 2.680(30); $^{150m}$Ho, 6.625(120) and $^{152m}$Ho, 6.470(80). The present decay-energy data are compared with earlier measurements and the new information obtained for the mass surface around $^{146}$Gd is discussed.

1. Introduction

From spectroscopic investigations [1–4] it was concluded that at $Z=64$ a large energy gap in the single-particle spectrum exists, which intensifies effects of the $N=82$ neutron-shell closure. It is therefore of interest to establish accurately the atomic masses in this region of the nuclear chart in order to investigate the influence of the expected double-magic behaviour on the mass surface.

In the present communication we report on $Q_{EC}$ measurements of $^{147m, 148m, 149m}$Tb, $^{148}$Dy and $^{150m, 152m}$Ho, continuing our earlier work of mass measurements by $\gamma$-spectroscopic techniques [5–7]. Preliminary results of our investigations were reported recently [8].

The decay energies were derived from measurements of the electron-capture to positron-decay ratios $EC/\beta^+$ for specific $\beta$-transitions and comparison of the experimental ($EC/\beta^+$) values with theoretical ratios, which are strongly energy dependent. Presently, only allowed transitions were investigated, so that nuclear-structure effects were absent in the theoretical $EC/\beta^+$ ratios.

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The measured $Q_{EC}$ values are connecting the atomic masses of the $\beta$-decaying nuclei to daughter nuclei, which are again $\beta$ or $\alpha$ radioactive. In particular, the nuclei $^{147m, 148m, 149m}$Tb and $^{150m, 152m}$Ho are connected by $Q_{EC}$- and $Q_\alpha$-values to $^{144}$Sm, $^{145}$Sm, $^{145}$Eu, $^{146}$Gd and $^{147}$Gd. The masses of these nuclei are well known: $^{144}$Sm [9,35] is stable, the masses of $^{145}$Sm [10], $^{145}$Eu [5] and $^{147}$Gd [6] were redetermined in our earlier investigations, and accurate mass values for $^{146}$Gd were recently derived independently by reaction studies [11–13].

The $Q_{EC}$ values of $^{149m}$Tb, $^{152m}$Ho and $^{148m}$Tb can be tested for consistency with other decay-energy data, since the nuclei $^{149m}$Tb, $^{149}$Gd, $^{145}$Eu and $^{145}$Sm, as well as $^{152m}$Ho, $^{152}$Dy, $^{148m}$Tb and $^{148}$Gd, form closed cycles connecting their masses by $Q_{EC}$ and $Q_\alpha$ energies. The decay energies within such a closed cycle are consistent, if the total sum of the experimental decay-energies along the cycle is vanishing.

We have already earlier reported a decay energy of $^{148}$Dy [14]. Since that value deviates by 0.15 MeV from the one given by Spanier et al. [15], which was also derived from a measurement of a $EC/\beta^+$ ratio, the $^{148}$Dy decay was reinvestigated. A decay-energy...
Table 1. Information on the production and the investigations of $^{147m}$Tb, $^{148m}$Tb, $^{149m}$Tb, $^{148}$Dy and $^{150m}$Ho and $^{152m}$Ho

<table>
<thead>
<tr>
<th>Decaying nucleus</th>
<th>$^{147m}$Tb</th>
<th>$^{148m}$Tb</th>
<th>$^{149m}$Tb</th>
<th>$^{148}$Dy</th>
<th>$^{150m}$Ho</th>
<th>$^{152m}$Ho</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured quantity*</td>
<td>$\beta^+$/EC$_{K}$</td>
<td>$\beta^+$/EC$_{K}$</td>
<td>$\beta^+$/EC$_{K}$</td>
<td>$\beta^+$/EC$_{K}$</td>
<td>$\beta^+$/EC$_{K}$</td>
<td>$\beta^+$/EC$_{K}$</td>
</tr>
<tr>
<td>Target material (degree of enrichment (%)</td>
<td>$^{112}$Cd(99)</td>
<td>$^{112}$Cd(99)</td>
<td>$^{112}$Cd(99)</td>
<td>$^{114}$Sn(70)</td>
<td>$^{116}$Sn(98)</td>
<td></td>
</tr>
<tr>
<td>Nuclear reaction</td>
<td>$^{40}$Ar,$p$4$n$</td>
<td>$^{40}$Ar,$p$3$n$</td>
<td>$^{40}$Ar,$p$2$n$</td>
<td>$^{40}$Ar,$p$4$n$</td>
<td>$^{40}$Ar,$p$3$n$</td>
<td></td>
</tr>
<tr>
<td>Beam energy (MeV)</td>
<td>185</td>
<td>185</td>
<td>185</td>
<td>182</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>Tape cycle-time (s)</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

* The $\beta^+$/EC$_{K}$ ratio was obtained by measuring the intensity of annihilation quanta relative to the X-ray intensity. The $\beta^+$/EC$+\beta^+$ ratio was obtained by measuring the intensity of annihilation quanta relative to the cascading $\gamma$-ray intensity.

The determination of $^{148m}$Tb was also published earlier [14]. Presently, $^{148m}$Tb was strongly produced along with the other investigated terbium isotopes. We repeated therefore the measurement of $^{148m}$Tb as an additional consistency test.

2. Experimental Procedure

The experiments were carried out at the VICKSI accelerator at the Hahn-Meitner-Institut in Berlin. Collection and transportation of the produced activities were performed by using the He-jet technique combined with a fast cartridge-tape system [16, 17]. Detailed information on the production and the experiments is summarized in Table 1 and also described below.

Self-supporting targets of enriched $^{112}$Cd, $^{114}$Sn and $^{116}$Sn, having a thickness of 2 mg/cm$^2$, were bombarded by 200 to 240 MeV $^{40}$Ar beams at typical beam intensities of 5·10$^{11}$ atoms s$^{-1}$. Recoiling reaction products from the target were thermalized in helium gas (pressure: 70 kPa), which had been saturated with NaCl aerosol by passing the gas through an oven containing NaCl crystals heated to about 700°C. An improvement of the transport efficiency was obtained by letting the gas pass a liquid N$_2$ cooling trap with molecular sieve before entering the oven. The helium gas was swept out from the target chamber through a 10 m long Teflon capillary (inner diameter 1.2 mm) to the tape system. Reaction products transported along with the gas were collected on the tape and periodically moved to a counting position with several Ge detectors for measuring coincidences of $\gamma$-rays and X-rays.

The $\beta^+$ intensity was derived from the 511 keV peak intensity. In order to localize the source of annihilation radiation the tape passed through a narrow slot in an aluminium cylinder at the counting position. The cylinder wall was thick enough to stop all positrons with an energy of less than 4 MeV.

Two different detector arrangements were used. In a first experiment we employed four Ge detectors: two Ge(Li) detectors, equipped with lead, cadmium and copper absorbers, and two intrinsic Ge detectors. The four detectors were arranged in 90° geometry, which made a correction for angular correlation necessary.

This correction was smaller with another set-up, which consisted of only three Ge detectors, one large Ge(Li) and two intrinsic $\gamma$/X Ge detectors, each having an angle of 120° relative to the others.

Standard fast-slow coincidence set-ups were used to connect each detector with its two neighbours. Energy signals of the detectors were recorded together with time-to-amplitude converter (TAC) signals on magnetic tape and played back later for analysis with a computer.* The energy and efficiency calibration of the detectors was obtained with calibrated sources of $^{22}$Na, $^{133}$Ba, $^{152}$Eu, $^{226}$Ra and $^{241}$Am.

An additional calibration was performed to check the coincidence efficiencies: after having finished the on-line experiment, a source of $^{52}$Mn was placed in the counting position and data were recorded in the same way as during the preceding measurement. The decay characteristic of $^{52}$Mn is especially favourable for such a calibration, since the decay scheme is simple and well known, and the strong $\beta$-branch from the initial 6$^+$ state to the 6$^+$ state at 3.11 MeV in $^{52}$Cr has nearly the same $EC/\beta^+$ ratio as expected for the rare-earth isotopes under study. Furthermore, the data analysis was performed with the UNIVAC 1100 computer of the Gesellschaft für Wissenschaftliche Datenverarbeitung in Göttingen GmbH.