THE BETA DECAY OF $^{48}$Mn:
Gamow-Teller quenching in fp-shell nuclei

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Abstract: A new nuclide, $^{48}$Mn, has been identified and its decay has been studied, using on-line mass separation of $^{12}$C($^{40}$Ca, p3n) reaction products. The half-life of this nuclide was determined to be $150 (10) \text{ ms}$, and spectra of $\beta$-delayed protons and $\gamma$-rays have been obtained. A branching ratio of $2.7 (12) \times 10^{-3}$ was deduced for the emission of $\beta$-delayed protons, while an upper limit of $6 \times 10^{-6}$ was determined for $\beta$-delayed $\alpha$ particle emission. A partial level scheme is proposed for $^{49}$Cr on the basis of $\gamma$-singles and $\gamma\gamma$-coincidence data. The deduced Gamow-Teller strength function is compared with predictions from shell model calculations suggesting a quenching factor of $0.53 (17)$ for the lowest lying states. This result is discussed in comparison with other quenching factors from $\beta$-decay studies, in particular those obtained for mirror $\beta$-decays in the fp-shell.

1. Introduction

Much progress has been made in exploring the properties of proton-rich ($Z > N$) nuclei up to the titanium ($Z = 22$) isotopes, so that the experimental frontier in this mass region lies among nuclides with isospin projection $T_z = \frac{1}{2}(N - Z) = -2$ and $T_z = -\frac{3}{2}$. By contrast, in the region above titanium relatively little is known about the properties of nuclei which are more proton-rich than $T_z = -\frac{1}{2}$. The only reported...
$T_z = -1$ nuclei with $Z \geq 22$, whose decay has been (in part) characterized, are $^{44}$V [ref. 1] and $^{40}$Cr [ref. 2]. Beyond these, only the $T_z = -\frac{3}{2}$ series of $\beta$-delayed proton precursors with $A = 4n + 1$ have been identified between $^{45}$Cr and $^{61}$Ge [ref. 3] due to their large $\beta$-delayed proton branches.

One of the motivations for studying these nuclei is to reach and possibly pass the proton drip line, which is mapped rather completely \(^4\) up to the sd-shell ($^{16}$O to $^{40}$Ca) nuclei with a few singular cases of proton radioactivity for heavier nuclei between $^{53}$Co and $^{151}$Lu. In this mapping one would be able to make significant gains in the understanding of the structure of these nuclei by studying cases of ground-state proton radioactivity and of $\beta$-delayed emission of protons, two protons or $\alpha$ particles.

There is, however, an additional motivation for performing detailed measurements of the ($\beta$-delayed proton and $\gamma$-ray) decay of such nuclides. The large $Q_{\beta}$ values of nuclei with $Z > N$ lead to strong population of the isobaric analogue state (IAS) in the daughter nucleus by superallowed Fermi $\beta$-decay ($\Delta S = \Delta L = 0$), and furthermore allowed Gamow-Teller (GT) $\beta$-decay ($\Delta S = 1$, $\Delta L = 0$) can be studied under less energy-window restrictions. To reduce the latter constraint is of obvious importance, together with a "complete" measurement of the $\beta$-strength, in probing the action of the $\sigma T$ (or GT) operator in nuclear $\beta$-decay. As an example of this, already more than a decade ago, Wilkinson \(^5\) noted the reduction (quenching) of the low-energy part of GT$^+$ strength observed in $\beta^+$ decay as compared to shell-model calculations, which can be interpreted as renormalization of the weak axial-vector coupling constant in the nuclear many-body medium ($g'_A$) relative to the value for the free-neutron decay ($g_A$). According to a recent review \(^6\), the global GT quenching for the middle of the sd-shell amounts to 0.58 (5), based on a comparison of measured $\beta$-strength data with results from large-basis shell-model calculations. In recent years, missing GT$^+$ strength was also found in studies of charge-exchange reactions such as ($p$, n), the observed fraction of the GT sum rule strength being 50-65% for $A \approx 90$, while there is considerable scattering of these fractional values for lighter nuclei [see ref. 7] for a review.

It is outside the scope of the present paper to survey the extensive experimental and theoretical literature on GT quenching, or to quantitatively evaluate the possible nuclear (e.g., nucleon-hole excitations) and subnuclear (e.g., $\Delta$-isobar excitations) contributions to the strength reduction \(^6\sim\). As far as the relevant $\beta$-decay data are concerned, improved measurements and calculations are clearly needed, e.g., for fp-shell ($^{40}$Ca to $^{56}$Ni) nuclei or, more generally speaking, both inside a given shell-model region and for larger ranges of $A$.

We present in this paper the first study of $\beta$-delayed proton and $\gamma$-ray emission from the decay of the new nuclide $^{48}$Mn ($T_{1/2} = 150$ ms), which was produced through the $^{12}$C($^{40}$Ca, p3n) reaction at the GSI on-line mass separator. 16 $\gamma$-rays were assigned to the decay of $^{48}$Mn and incorporated into a partial level scheme of $^{48}$Cr up to its isobaric analog state at 5792.4 (6) keV. The GT strength distribution is deduced for
this energy interval from γ-ray data, and for excitation energies of 9 to 11.5 MeV from measuring β-delayed proton emission. The experimental results are compared with predictions from shell-model calculations both for \(^{48}\text{Mn}\) and for other nuclei.

2. Experimental techniques

The isotope \(^{48}\text{Mn}\) was first identified \(^5\) during ion source tests at the GSI on-line mass separator \(^1\). These measurements had originally been planned for testing some production aspects of deep-inelastic reactions. A 11.4 MeV/u \(^{40}\text{Ca}\) beam from the UNILAC at GSI Darmstadt was directed onto a 25 mg/cm\(^2\) natural tungsten foil acting as target and ion source window. In this experiment as well as in the one with a thinner tungsten window described below, reaction products are caught in a graphite catcher inside the source and are, after release from the catcher and extraction from the source, mass separated in a magnetic sector field as 55 keV beams of singly-charged ions. Finally, decay spectroscopy is performed on mass-separated samples, using various collector and detector arrangements.

During this test \(^5\), a series of isotopes close to the β-stability line was identified for elements between sulfur (\(Z = 16\)) and cobalt (\(Z = 27\)), which are presumably due to deep-inelastic \(^{40}\text{Ca} + \text{W}\) reactions. In addition some neutron-deficient isotopes were detected including \(^{48}\text{Mn}\). This isotope is evidently produced by fusion-evaporation reactions between the graphite catcher and the \(^{40}\text{Ca}\) beam, decelerated to approximately 7.3 MeV/u after passage through the tungsten foil.

In order to improve the β-singles, γ-singles and βγ-coincidence data obtained during this test, measurements were extended to yield γ-singles and γγ-coincidence information up to high γ-ray energies; in addition, a search for β-delayed emission of protons and α-particles was performed. For these measurements we used a 11.7 MeV/u \(^{40}\text{Ca}\) beam and a FEBIAD-F ion source \(^12\) with a 12.4 mg/cm\(^2\) thick tungsten window and a 27 mg/cm\(^2\) thick graphite target-catcher. The beam energy on target amounted to 9.8 MeV/u for the \(^{48}\text{Mn}\) measurements, while the production rates of neighboring proton-rich isotopes were partly determined for a higher beam energy.

In order to investigate β- and γ-rays, the mass 48 beam was directed onto an aluminized mylar tape. After collecting for a preselected time period, the activity was transported within 230 ms over a distance of 30 cm into the counting position, equipped with a thin 4π plastic scintillator for β-detection and a Ge(Li) detector for γ-detection. In order to also detect γ-rays of very short-lived isotopes, where decay losses during the transport of the tape may become appreciable, another Ge(Li) detector was mounted at the collection position.

In addition to this βγ detection system, another tape collector was used for βγγ measurements. In this case, the collector position was equipped with a thin 2π plastic scintillator detector and two large-volume hyperpure germanium detectors.
with photopeak efficiencies of 29% and 30.5% for 1.3 MeV γ-rays relative to a 7.5 cm × 7.5 cm NaI(Tl) detector. The 29% detector was closely facing the tape and the plastic detector, while the second one was mounted in 90° geometry at a somewhat larger distance; the absolute photopeak efficiencies were approximately 2.4% and 0.8% of 4π at 1.3 MeV γ-ray energy. The tape was moved regularly out of the collection position for reducing long-lived (mass 48) activity.

For charged-particle measurements, the mass-48 beam was implanted into a 43 μg/cm² carbon foil in front of a telescope. The latter consisted of two surface barrier detectors of 17 μm thickness, 50 mm² area and 718 μm thickness, 450 mm² area. In order to determine the branching ratio of β-delayed particle emission relative to the intensities of β-delayed γ-rays, the latter were measured simultaneously in a Ge(Li) detector mounted close to the telescope.

In order to determine half-lives from grow-in and decay of short-lived activities, the mass-48 beam was switched off periodically by means of an electrostatic device both for the telescope-Ge(Li) array and for the collection positions of the tape stations.

Using the GSI data acquisition system GOLDA 2 [ref. 13)], coincidence data were recorded, together with a time mark, event by event by a PDP11/45 computer; singles spectra were accumulated simultaneously in multispectrum mode.

3. Experimental results

In this chapter we present the measurements of positrons, β-delayed γ-rays and β-delayed protons, leading to a partial level scheme for 48Cr and to the determination of several log ft values for 48Mn → 48Cr β-transitions.

Observed source strengths and estimated overall efficiencies for 48Mn and some neighboring nuclei are compiled in table 1. The efficiency values represent rough approximations, since the production cross sections calculated on the basis of the HIVAP code 14) have not been verified experimentally.

Fig. 1 shows as examples of mass-48 measurements a β-coincident γ-ray spectrum up to 4.1 MeV. The singles γ-ray spectra have of course better statistics, but are more complex due to detection of room background. After accounting for single and double escape peaks as well as for peaks due to summing with 511 keV annihilation radiation, and leaving the γ-lines at 1660 and 2167 keV unassigned, 16 γ-transitions were ascribed to the decay of 48Mn. Energies and intensities of these transitions are listed in table 2; the intensities were corrected for γγ-coincidence summing in an approximate way, using the level scheme as discussed below. Examples for γ-ray decay measurements and for γγ-coincidence data are shown in figs. 2 and 3; the corresponding results are compiled in table 2.

Energy and intensity calibration of the γ-ray detectors were obtained up to 3.3 MeV by using 56Co and 152Eu sources. In particular, an "internal" calibration was performed by recording a mass-48 γ-ray spectrum in the presence of a 56Co
Yields of mass-separated fusion-evaporation residues produced in reactions between a $^{12}$C target and $^{40}$Ca beams of 7.3, 9.8 and 13.0 MeV/u energy on target (Results are given for 7.3 MeV/u unless noted otherwise)

### Table 1

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$T_z$</th>
<th>Half-life</th>
<th>Observed radiation</th>
<th>Reaction channel</th>
<th>Observed yield (atoms/s at 100 particle nA)</th>
<th>Overall efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{49}$Fe</td>
<td>$-\frac{1}{2}$</td>
<td>75 ms</td>
<td>$\beta^-$</td>
<td>3n</td>
<td>$3 \times 10^{-1}$ b)</td>
<td>0.13 b)</td>
</tr>
<tr>
<td>$^{50}$Mn</td>
<td>0</td>
<td>1.75 min</td>
<td>$\gamma$</td>
<td>1p1n</td>
<td>$2.2 \times 10^{5}$</td>
<td>4.5</td>
</tr>
<tr>
<td>$^{49}$Mn</td>
<td>$-\frac{1}{2}$</td>
<td>384 ms</td>
<td>$\beta$</td>
<td>1p2n</td>
<td>$1.7 \times 10^{4}$</td>
<td>11</td>
</tr>
<tr>
<td>$^{48}$Mn</td>
<td>$-1$</td>
<td>150 ms</td>
<td>$\beta$</td>
<td>1p3n</td>
<td>$1.8 \times 10^{5}$</td>
<td>4.4</td>
</tr>
<tr>
<td>$^{44}$Cr</td>
<td>$+\frac{3}{2}$</td>
<td>42.1 min</td>
<td>$\gamma$</td>
<td>2p1n</td>
<td>$1.5 \times 10^{6}$</td>
<td>4.4</td>
</tr>
<tr>
<td>$^{42}$Cr</td>
<td>$-\frac{3}{2}$</td>
<td>568 ms</td>
<td>$\beta$</td>
<td>$\alpha n + 2p3n$</td>
<td>$2.1 \times 10^{5}$</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{41}$Cr</td>
<td>$-\frac{1}{2}$</td>
<td>50 ms</td>
<td>$\beta^-$</td>
<td>$\alpha 3n + 2p5n$</td>
<td>2 c)</td>
<td>0.6 c)</td>
</tr>
<tr>
<td>$^{40}$V</td>
<td>$+\frac{3}{2}$</td>
<td>32.6 min</td>
<td>$\beta$</td>
<td>$\alpha + 3p2n$</td>
<td>$7 \times 10^{5}$</td>
<td>2.9</td>
</tr>
</tbody>
</table>

a) Overall efficiencies are estimated by comparing the measured intensities with thick target yields calculated on the basis of the HIVAP code.

b) $^{40}$Ca beam energy 13.0 MeV/u: A substantial fraction of the $^{49}$Fe nuclei has recoil ranges larger than the thickness of the graphite target catcher; the corresponding losses were avoided at lower $^{40}$Ca beam energies.

c) $^{40}$Ca beam energy 9.8 MeV/u.

Source. By including the well-known $\gamma$-ray energies from the decays of $^{48}$Sc, $^{48}$V and $^{48}$Cr [ref. 15] into this procedure, a reliable calibration was obtained up to $\gamma$-ray energies of 3.3 MeV. For higher energies, the calibration is extrapolated on the basis of observed single and double escape peaks.

Simultaneously to the $\gamma$-ray decay measurements, displayed in fig. 2, multiscaling data from the 4π$\beta$ detector were recorded, yielding a short-lived component of 156 (6) ms. This result is hampered by the fact, that in this fit a constant background for long-lived contaminants and a 41.6 s component due to $^{21}$F decay had to be subtracted. We adopt the result of 150 (10) ms (see fig. 2) as the best value for the $^{48}$Mn half-life, being in agreement also with the measurements of $\beta$-delayed protons shown in fig. 4. By comparing the measured proton intensity to the one for the 752.1 keV $\gamma$-ray recorded simultaneously, a branching ratio of 0.27 (12)% was found for $\beta$-delayed $\alpha$-emission was observed, corresponding to an upper limit of $6 \times 10^{-6}$ for this decay mode.

### 4. The $^{48}$Mn($\beta^+$) $^{48}$Cr decay scheme

From the measurements described so far, a partial $^{48}$Mn($\beta^+$) $^{48}$Cr decay scheme can be deduced (see fig. 5) which will be discussed in detail in this section.

Considering half-lives and energy sum relations of $\gamma$-rays measured in singles, and taking the measured $\gamma\gamma$-coincidence data into account (see table 2), 9 excited levels in $^{48}$Cr were identified. For 6 of these states an unambiguous correspondence
Fig. 1. Spectrum of β-delayed γ-rays up to 4.1 MeV transition energy, accumulated for the mass-48 beam over a counting time of 20 h; the 40Ca beam varied between 45 and 90 particle-nA. A 30.5% germanium detector was used in coincidence with a thin plastic detector at the collector position of one of the tape stations. The collected activity was removed every 16 s. All peaks marked by their energy (in keV) are assigned to the decay of 46Mn, except for lines at 1660 and 2167 keV marked by an asterisk, which could not be assigned firmly. Single-escape and double-escape lines are denoted by SE and DE, giving the corresponding total transition energy within brackets. Effects of summing are indicated as well as contaminating β-delayed γ-rays of 48Sc, 48V, 48Cr and of 20,21F; the observation of characteristic γ-rays from the latter two isotopes is tentatively assigned to formation of molecular mass-47 and mass-48 beams of 27Al20F and 27Al21F.
Fig. 2. Decay of the 752 keV γ-ray, obtained with a Ge(Li) detector at the counting station of a tape station. 5135 cycles were accumulated with 0.85 collection time and 0.2 s transport time each, the $^{40}$Ca beam current being 70 particle-nA. The straight line gives the result from a least-squares fit.

can be stated with adopted $^{15}$ $^{48}$Cr levels (see figs. 5 and 6). The latter come from in-beam γ-ray spectroscopy, using ($^3$He, nγ), ($^{12}$B, pγ), and ($^{16}$O, 2nγ) fusion-evaporation reactions, as well as from (p, t) and ($^3$He, n) transfer reaction studies. Out of the 16 γ-rays assigned to $^{48}$Mn β-decay, the transitions at 531.0, 752.1, 1106.1 and 1675.0 keV agree very well - both in energy and in level assignment - with results from in beam work. Very good agreement is also obtained for the 6 corresponding levels mentioned above, whose adopted $^{15}$ energies (in keV) and spins are 752.16 (10), 2$^+$; 1858.57 (16), 4$^+$; 3533.9 (3), (6$^-$); 4064.6 (3), (7$^-$); 4432 (5), (4$^+$); 5790 (10), 4$^+$. Furthermore, the 4640 (10) keV, 2$^+$ state observed in (p, t) reactions may have at least some overlap with the 4652.6 (6) level obtained in this work; complete identity seems to be ruled out in view of the allowed β-decay observed to the latter state and in view of its dominant deexcitation to the 2$^+$ level.

The 5790 (10) keV level has been identified in previous (p, t) work $^{15}$ to be the $I = 4$, $T = 1$ IAS built on the $^{48}$V ground state. This assignment is confirmed by our observation of superallowed β-decay of the $I^n$, $T$, $T_z = 4^+$, 1, −1 $^{48}$Mn ground state to its IAS at 5792.4 (6) keV in $^{48}$Cr, assuming $I^n = 4^+$ for this $^{48}$Mn state in analogy to its mirror nucleus $^{48}$V [ref. $^{15}$]. We shall discuss the $f_t$ value for this transition below.

The high precision of 0.6 keV or $10^{-4}$, obtained for the energy difference between this IAS and the $^{48}$Cr ground-state, may be incorporated into improved Coulomb energy systematics or applications of the isobaric multiplet mass equations. One can, for example, use an empirical method for fitting differences of Coulomb displacement energies $\Delta E_C$ between neighboring analog pairs for $T_z = 0$, 1 nuclei,
Fig. 3. γ-ray spectrum obtained with a coincidence gate on the 752 keV line, using the same data set as for fig. 1.

Z being the average charge between the pair:

$$\Delta E_C = k_1 (Z/A^{1/3}) + k_2$$  \hspace{1cm} (1)

From fitting this formula for nuclei with $A < 60$, Antony et al.\textsuperscript{16) } obtained $k_1 = 1490 \ (2) \text{ keV}$, $k_2 = -1437 \ (10) \text{ keV}$, and $-29 \ 202 \ (20) \text{ keV}$ for the $^{48}\text{Mn}$ ground-state mass. This yields an atomic mass difference of 13 616 (20) keV between the $^{48}\text{Mn}$ and $^{48}\text{Cr}$ ground-states. There does not seem to be much reason to refine these
The text is about the beta decay of $^{48}\text{Mn}$ and gamma rays from $^{48}\text{Mn}$. The table lists gamma rays with their energies, relative gamma intensities, half-lives, coincident gamma rays, and assignments. The assignment is made based on specific criteria, and the line observed at 5040.5 keV is due to gamma summing effects. The calculations are based on the newly obtained IAS/ground-state energy difference, with the IAS mass changes being slight. The mass difference for the $^{48}\text{Mn}$ and $^{48}\text{Cr}$ ground states is noted. The beta branching ratios were calculated, and there is a significant mismatch in the intensity balance. The results are discussed in the context of the gamma-ray deexcitation and the assignments made.

### Table 2

**Gamma rays from $^{48}\text{Mn}$**

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Relative $\gamma$-intensity</th>
<th>Half-life (ms)</th>
<th>Coincident $\gamma$-rays</th>
<th>Assignment $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>531.0 (5)</td>
<td>0.8 (4)</td>
<td></td>
<td>511, 1106</td>
<td>a, b</td>
</tr>
<tr>
<td>752.1 (2)</td>
<td>100 (4)</td>
<td>150 (10)</td>
<td>511, 760, 1106, 1140, 1364</td>
<td>a, b, c</td>
</tr>
<tr>
<td>760.2 (2)</td>
<td>3.0 (3)</td>
<td></td>
<td>511, 752, 4280</td>
<td>a</td>
</tr>
<tr>
<td>1106.1 (2)</td>
<td>39.5 (16)</td>
<td>157 (23)</td>
<td>511, 752, 3934</td>
<td>a, b, c</td>
</tr>
<tr>
<td>1139.7 (2)</td>
<td>6.9 (5)</td>
<td>190 (50)</td>
<td>511, 752, 3901</td>
<td>a, b, c</td>
</tr>
<tr>
<td>1364.0 (2)</td>
<td>22.6 (11)</td>
<td>134 (30)</td>
<td>511, 752, 3676</td>
<td>a, b, c</td>
</tr>
<tr>
<td>1675.0 (4)</td>
<td>2.1 (2)</td>
<td></td>
<td>511, 752</td>
<td>a, b</td>
</tr>
<tr>
<td>1728.8 (5) $^b$</td>
<td>$-0.9$ (3) $^b$</td>
<td></td>
<td>511, 531, 752</td>
<td>a, b</td>
</tr>
<tr>
<td>2259.2 (5)</td>
<td>1.9 (5)</td>
<td></td>
<td>511</td>
<td>b</td>
</tr>
<tr>
<td>2570.2 (5)</td>
<td>1.7 (5)</td>
<td></td>
<td>752</td>
<td>b</td>
</tr>
<tr>
<td>3174.1 (5)</td>
<td>2.4 (6)</td>
<td></td>
<td>511</td>
<td>b</td>
</tr>
<tr>
<td>3435.5 (6)</td>
<td>2.6 (8)</td>
<td></td>
<td>511, 752, 1106</td>
<td>a</td>
</tr>
<tr>
<td>3676.2 (4)</td>
<td>31.6 (31)</td>
<td>124 (20)</td>
<td>511, 752, 1364</td>
<td>a, b, c</td>
</tr>
<tr>
<td>3900.5 (5)</td>
<td>11.2 (13)</td>
<td>129 (60)</td>
<td>511, 752, 1140</td>
<td>a, b, c</td>
</tr>
<tr>
<td>3934.1 (5)</td>
<td>24.5 (27)</td>
<td>132 (20)</td>
<td>511, 752, 1106</td>
<td>a, b, c</td>
</tr>
<tr>
<td>4280.1 (5)</td>
<td>9.8 (1.8)</td>
<td></td>
<td>511, 752, 760</td>
<td>a</td>
</tr>
<tr>
<td>5040.5 (10) $^c$</td>
<td>$&lt;1.0$ (3) $^c$</td>
<td></td>
<td></td>
<td>b</td>
</tr>
</tbody>
</table>

$^a$ The assignment is made on the basis of (a) $\gamma\gamma$-coincidence relationships, (b) fit into level scheme (summing relation), (c) half-life measurement.

$^b$ Due to the close-lying 1730 keV $\gamma$-ray of $^{21}\text{O}$, the intensity of the 1728.8 keV line can only be estimated roughly.

$^c$ The line observed at 5040.5 keV is dominantly due to $\gamma\gamma$ summing effects.
For the $\beta$-transition to the IAS, we find $^{18}$) $T_1/2 = 3060 (330)$ s and $\log T_1 = 3.49 (5)$. A pure Fermi decay would have $B(F) = 2$, $T_1 = 3085 (2)$ s and $\log T_1 = 3.4893 (3)$ (see chapter 5). We conclude thus, that the observed decay of $^{48}$Mn to the 5792.4 keV state $^{48}$Cr is in fact superallowed, and that the present precision does not allow for a discussion of the possible dependence of the Fermi matrix element on strong magnetic fields $^{19,20}$). We shall briefly return to this question below.

For the 5 $^{48}$Cr levels between ground state and IAS, whose $\beta^+$ branching ratios have been determined from intensities of $\beta$-delayed $\gamma$-rays, $\log T_1$ [ref. $^{18}$)] values between 4.53 (10) and 5.42 (22) are found (see fig. 5). These transitions are thus allowed ones, and the resulting GT strength distribution will be discussed in the following chapter together with the one deduced from $\beta$-delayed proton measurements. In order to assign $^{48}$Cr excitation energies to the observed proton spectrum (in the absence of proton-$\gamma$ coincidence information), we assume that proton emission feeds the $^{47}$V ground state exclusively. This may not be entirely true considering the low-lying $^{47}$V excited states $^{21}$) with similar (low) spin values (see...
Fig. 5. Partial $^{48}\text{Mn}(p^+)^{48}\text{Cr}$ decay scheme. In addition to results from this work, some of known levels of $^{47}\text{V}$ [ref. 21) and $^{48}\text{Cr}$ [ref. 15) are included. The $^{48}\text{Cr}$ proton separation energy of 8103 (7) keV and the estimated Q-value of 13 600 (100) keV for the $^{48}\text{Mn}(p^+)^{48}\text{Cr}$ decay are taken from ref. 17).

fig. 5), and the GT strength distribution derived from the proton data under this assumption may be somewhat low both in intensity and in excitation energy. In view of this deficiency and of the large error in the branching ratio for $\beta$-delayed proton emission, proton data will not be used for deriving a GT quenching factor.

5. Discussion

The $f_I$ value of an allowed $\beta$ transition may be written as

$$f_I = K / \{ g^2 B(F) + g^2 B(GT) \} ,$$

with $K = 1.231 \times 10^{-94} \text{ erg}^2 \cdot \text{cm}^6 \cdot \text{s} [\text{ref. 23}])$. The effective weak vector coupling
constant $g'_V = 1.413 \times 10^{-49}$ erg cm$^3$ is deduced from measured $ft$ values of superallowed Fermi $\beta$-transitions between $I^+, T = 0^+$, 1 states, and $g_A$ is determined through the ratio $g_A/g'_V = 1.26$ from neutron decay $^{24,25}$.

The reduced transition probabilities $B(F)$ and $B(GT)$ for pure Fermi and GT decays, given in units of $g'_V^2/4\pi$ and $g_A^2/4\pi$ respectively, are thus related to the respective $ft$ value by the constants

$$K/g'_V^2 = 6170 \text{ s},$$  \hspace{1cm} (3)

$$K/g_A^2 = 3870 \text{ s}. \hspace{1cm} (4)$$

The reduced transition probability for a pure Fermi decay is $^{22}$

$$B(F) = T(T+1) - T_{zi}T_{zf}, \hspace{1cm} (5)$$

yielding $B(F) = 2$ for $\beta$-decay of $^{48}$Mn to the IAS in $^{48}$Cr.

The precision of the above mentioned constants $^{23-25}$, which is not discussed here, is a few parts in $10^3$ in the worst case, variations of $g'_V$ and $g_A/g'_V$ on this level being related to interesting nuclear-structure and/or weak-interaction phenomena [see e.g. ref. $^{24}$]. Considering the uncertainties of the results on $Q$-value, half-life and $\beta^+$ feeding obtained in this work, we are far from this level of precision and can therefore neglect the error of the constants as well as the slight difference in the phase-space factors for F and GT transitions $^{26,27}$. The latter approximation has been made in eq. (2) and when evaluating the experimental $ft$ values (see sects. 3 and 4).

In order to understand the observed $\beta$-strength, shell-model calculations of $^{48}$Mn and $^{48}$Cr have been performed using the large-basis shell-model code OXBASH $^{28}$. The model space used in the calculation was the fp-shell with active 1$f_{7/2}$, 2$p_{3/2}$, 1$f_{5/2}$, and 2$p_{1/2}$ orbits. The two-body matrix elements and the single particle energies for the calculation were taken from the work of van Hees and Glaudemans $^{29}$. This interaction was determined from a fit to energy levels for nuclei in the fp-shell with $A = 52-55$. Due to the size of the model space, the configurations were restricted to $(f_{7/2})^n(p_{3/2}f_{5/2}p_{1/2})^0 + (f_{7/2})^n-1(p_{3/2}f_{5/2}p_{1/2})^1$ where $n$ is the number of nucleons outside the $^{40}$Ca closed core. We retain the same model space assumption for the calculations described in this paper unless otherwise stated. Van Hees and Glaudemans found that this interaction reproduced excitation energies well (70 keV rms deviation), and $g$-factors, M1 matrix elements, and electric quadrupole moments reasonably well. Thus, for at least the low-lying states calculated for $^{48}$Cr and $^{48}$Mn, we might expect reasonable agreement. The only change in the interaction is that 1.9 MeV was added to the diagonal $T = 1$ matrix elements to approximately reproduce the correct excitation energy for the $4^+, T = 1$ IAS in $^{48}$Cr. This change will not affect the resulting shell-model wave functions, but is only a shift of the relative excitation of the $T = 0$ and $T = 1$ states.

As a test of the shell model we can compare the well known level structure of the $T_z = 1$ nucleus $^{48}$V to the shell-model prediction. In the shell-model $^{48}$V and
$^{48}$Mn have identical level schemes. The known$^{15}$ level scheme for $^{48}$V along with the calculated levels are shown in part (a) of fig. 6. In the figure only the known positive parity levels up to 1.0 MeV are shown for the comparison. The agreement between the measured and calculated levels is good, and is similar to that noted by van Hees and Glaudemans. Part (b) of fig. 6 is a further test where a comparison is made between the measured$^{15}$ and calculated $^{48}$Cr level schemes. The agreement is similar, but not quite as good as for $^{48}$V. In particular the excitation of the 4$^+$ state at 3.1 MeV seems to be at least 1.3 MeV in error. A reason for this discrepancy will be discussed later in relation to the measured $\beta$-strength function. In general,

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![Graph showing level schemes](image)

**Fig. 6.** Comparison of the measured and the calculated $^{48}$V and $^{48}$Cr level schemes. The calculated spectra are obtained from the shell model described in the text. The measured energies of excited levels are shown for positive parity states with $I > 0$ only.
however, the agreement is reasonable and we proceed to the comparison of the $\beta$-strength functions.

Before discussing the results for $^{48}\text{Mn}(\beta^+)$ decay it is interesting to consider the $\beta^+$-decays between mirror nuclei in the fp-shell. The mirror pairs from $A = 41$ to $A = 55$ were considered and the $B(\text{GT})$ values calculated for the dominant ground-state to ground-state transitions. In general there are weak GT $\beta$-decay branches expected to excited states, which have in a few cases been observed, but here we consider only the ground-state to ground-state GT strength. The experimental $B(\text{GT})$ values are extracted as previously described, but by in addition reducing the $B(\text{F})$ values by 0.3% to correct for isospin mixing. Table 3 lists the measured $\log f$ and $B(\text{GT})$ values for the mirror pairs together with the calculated $B(\text{GT})$ values and the ratio of $B^{\text{exp}}(\text{GT})/V^{\text{theory}}(\text{GT})$ (the GT quenching factor). Such a compilation has been made by other authors, but not using the van Hees–Glaudemans interaction, and not with a model space which includes the $2_{\text{f}5/2}, 1_{\text{p}3/2}$, and $2_{\text{p}1/2}$ orbits.

The general trend, emerging from these data on mirror pairs in the fp-shell, is to observe a quenching of approximately 0.6 in the measured $B(\text{GT})$ values. There is one case in table 3, $A = 55$, where a larger quenching is observed. This may be due to additional mixing of the ground state, in particular from the 2p orbits, which was not reproduced in the calculation due to inadequacies in the interaction or in the model space used. In one case, $^{45}\text{V}(\beta^+)$, it was found that the predicted $B(\text{GT})$ value was even smaller than the experimental one by approximately 33%. This decay was then recalculated allowing up to two particles in the $p_{3/2} f_{5/2} p_{1/2}$ orbits. The result, which is given in table 3, reproduces a quenching factor in agreement with the other mirror pairs. The calculation was repeated in the full model space of up to five particles in the higher orbits and the ratio was found to be 0.65 (10), in agreement with the 2p-2h calculation. It is apparent that there is a 2p-2h

<table>
<thead>
<tr>
<th>Parent</th>
<th>$I^+$</th>
<th>Daughter</th>
<th>$\log(ft)$</th>
<th>measured $B(\text{GT})$</th>
<th>calc. $B(\text{GT})$</th>
<th>meas. $B(\text{GT})$/calc. $B(\text{GT})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{41}\text{Sc}$</td>
<td>$^7_-$</td>
<td>$^{41}\text{Ca}$</td>
<td>3.453 (1)</td>
<td>0.74 (2)</td>
<td>1.29</td>
<td>0.58 (2)</td>
</tr>
<tr>
<td>$^{47}\text{Ti}$</td>
<td>$^7_-$</td>
<td>$^{47}\text{Sc}$</td>
<td>3.513 (7)</td>
<td>0.56 (3)</td>
<td>0.82</td>
<td>0.68 (4)</td>
</tr>
<tr>
<td>$^{49}\text{V}$</td>
<td>$^7_-$</td>
<td>$^{49}\text{Ti}$</td>
<td>3.636 (17)</td>
<td>0.26 (4)</td>
<td>0.40</td>
<td>0.65 (10)</td>
</tr>
<tr>
<td>$^{47}\text{Cr}$</td>
<td>$^7_-$</td>
<td>$^{47}\text{V}$</td>
<td>3.705 (11)</td>
<td>0.13 (2)</td>
<td>0.24</td>
<td>0.54 (8)</td>
</tr>
<tr>
<td>$^{49}\text{Mn}$</td>
<td>$^7_-$</td>
<td>$^{49}\text{Cr}$</td>
<td>3.671 (24)</td>
<td>0.19 (5)</td>
<td>0.24</td>
<td>0.79 (21)</td>
</tr>
<tr>
<td>$^{51}\text{Fe}$</td>
<td>$^7_-$</td>
<td>$^{51}\text{Mn}$</td>
<td>3.655 (10)</td>
<td>0.22 (2)</td>
<td>0.37</td>
<td>0.59 (5)</td>
</tr>
<tr>
<td>$^{53}\text{Co}$</td>
<td>$^7_-$</td>
<td>$^{53}\text{Fe}$</td>
<td>3.634 (42)</td>
<td>0.27 (10)</td>
<td>0.36</td>
<td>0.75 (28)</td>
</tr>
<tr>
<td>$^{55}\text{Ni}$</td>
<td>$^7_-$</td>
<td>$^{55}\text{Co}$</td>
<td>3.634 (11)</td>
<td>0.26 (3)</td>
<td>0.64</td>
<td>0.41 (5)</td>
</tr>
</tbody>
</table>

The measured $\log ft$ values are from a recent compilation. The calculated $B(\text{GT})$ values are from a shell model with 1p-1h configurations in all cases except $^{45}\text{V}$, where a model space up to 2p-2h was allowed (see text). The uncertainties for the GT quenching are strictly from the experimental uncertainties in life time, branching ratios and $Q_{\text{EC}}$ values.
contribution in the $^{45}$Ti ground state which, when excluded from the calculation, forces too much of the wavefunction to be in the $1f_{5/2}$ orbit. This retards the GT transition and gives too small a predicted $B(GT)$ value. One sees a hint of this in the $^{49}$Mn and $^{53}$Co cases also. The effect of model space was also tested in the case of $^{43}$Ti decay. In this case the 2p-2h and full (3p-3h) calculations gave quenching factors of 0.61 (4) and 0.60 (4) respectively, in agreement with the 1p-1h calculation. Despite the disagreement near $A = 55$ and inadequacies in the model space of 1p-1h, the shell-model does a reasonable job for nuclei in the middle of the $f_{7/2}$-shell where $^{48}$Mn lies.

The measured $^{48}$Mn $B(GT)$ strength is shown in fig. 7a, and is summed in 0.25 MeV bins. Up to 6.0 MeV excitation the strength is determined from the observed $\gamma$-transitions, and between 9.0 and 11.5 MeV from the $\beta$-delayed proton spectrum. Above 11.5 MeV the phase space factor for $\beta$-decay becomes small and hence we

![Measured B(GT) Strength (a)](image)

![Calculated B(GT) Strength (b)](image)

Fig. 7. Comparison of the measured and calculated $^{48}$Mn($\beta^+$) decay $B(GT)$ strength. The measured strength is shown in part (a). The dashed curves give the experimental sensitivity limits, below which $\beta$-decay was not observable in this experiment. Part (b) is the calculated strength. The dark areas represent $T_f = T_i - 1$ transitions and the clear areas $T_f = T_i$ transitions. The dash-dot line marked $Q_{EC}$ represents the limit of the strength which can be fed in $\beta^+$ decay and electron-capture.
would not expect to observe protons from this region on the basis of the calculated $B(\Gamma T)$ values, hence the experiment had low sensitivity in this region of excitation. The absence of measured strength between 6 MeV and 9 MeV is probably also due to a lack of sensitivity, in this case for detecting weak $\gamma$-lines. Hence, the regions below the corresponding dashed curve in fig. 7 should be considered to be unmeasured, except for the approximate upper limits set by the height of this curve. As previously mentioned, the determination of $B(\Gamma T)$ strength from singles measurements of $\beta$-delayed protons is complicated by the possibility of proton decays to excited states in $^{47}$V. Due to this uncertainty, for the further discussions of $B(\Gamma T)$ quenching in the $^{48}$Mn decay, we will consider only the $B(\Gamma T)$ strength determined from the $\gamma$-transitions.

The calculated $^{48}$Mn $B(\Gamma T)$ strength is shown in fig. 7b. The outline of the histogram represents the full strength and the dark areas represent the $T_f = T_i = 1$ strength, where $T_i$ is the initial total isospin and $T_f$ is the final total isospin. The clear areas represent the $T_f = T_i$ transition strength. The $T_f = T_i + 1$ strength occurs at much higher excitation and is a small contribution, and thus is not included in the figure. At higher excitation it is difficult to make a meaningful comparison due to the uncertainties in the $B(\Gamma T)$ values extracted from the protons. However, the general structure seems to agree, and the level densities seem consistent. At lower excitation the agreement between the measured and calculated structure is poor. In the regions where the experiment had low sensitivity, the predicted strength is approximately consistent with the observation of no strength.

The disagreement in the structure of the low-lying strength could come from two possible inadequacies in the shell model. The first possibility is that the interaction is not valid for these nuclei. Considering the general quality of the agreement between calculated and measured level schemes in this region, and the agreement of the calculation with the $B(\Gamma T)$ values measured for mirror nuclei, this explanation seems unreasonable, although, as we have seen, some improvements in the interaction are possible. The second possibility is that the limitation of only $1p$-$1h$ excitations of nuclei out of the $f_{7/2}$ orbit can explain the discrepancy, i.e., the wavefunctions may contain significant contributions of higher order excitations. To check this, a calculation should be performed with up to $2p$-$2h$ excitations allowed. However, the dimensions of the calculation, 3089 for the $4^+ T = 1$ states, are too large for the computers used in this study. Nevertheless, as a check of this effect one can consider the decay of a case where the dimensions are small enough to allow a large model space to be used. For this purpose $^{44}$V($\beta^+$) decay was calculated in four model spaces as shown in fig. 8a–d. Unfortunately, no detailed experimental data exist, but the effects of the model space on the calculations can be seen. Part (a) is calculated with the particles restricted to the $f_{7/2}$ orbit. It is expected that this model would not reproduce an experiment, since the $f_{5/2}$ orbit will play an important role for $\Gamma T$ transitions. What would be missing is the spin-flip contribution which one sees from 10 to 18 MeV excitation in part (b), which is calculated in the normal
Fig. 8. Effect of the model space on the calculated $B(GT)$ distribution for the case of $^{44}$V. Parts (a)-(d) are respectively the calculations with up to 0p-0h, 1p-1h, 2p-2h and 4p-4h excitations from the $f_{7/2}$ orbit. Assuming the 4p-4h calculation to represent a proper description of the real (experimentally unknown) $^{44}$V GT decay, ones sees that at least a 2p-2h description is needed for good agreement. The dash-dot line marked $Q_{EC}$ represents the limit of the strength which can be fed in $\beta^+$ decay and electron-capture. 1p-1h van Hees-Glaudemans model space. In part (c) one sees a significant change in the structure from part (b) when 2p-2h excitations are included. Due to the additional mixing the strength has spread out and moved to higher excitation. The shift to higher excitation may be due to the fact that the ground state is lowered in energy relative to the excited states because of deformations which can only be reproduced in the larger model space, and may be partially due to the fact that the interaction was fit in restricted 1p-1h model space. Part (d) shows the calculation in a full fp-model space with no restrictions. There is a little qualitative difference between the 2p-2h and the full model-space calculations. Thus, if it were possible to calculate for $^{48}$Mn, the 2p-2h description might be adequate. One interesting feature is that although the strength is spread out by including a larger model space,
the sum strength remains relatively constant. In particular for transitions to states below the IAS the strength is constant to within 10% for the 1p-1h, 2p-2h, and full calculations.

Returning to the $^{48}\text{Mn}(\beta^+)$ decay data shown in fig. 7, we see a similar trend in the $B(\text{GT})$ strength distribution as a function of model space, where now we compare experiment to the 1p-1h model space calculation. The strength is spread out and somewhat shifted to higher excitation energy. In the calculation the 4$^+$ state at 3.1 MeV has a large $B(\text{GT})$ value which identifies it as the so called antianalogue state. In the experiment this state appears to be shifted to higher excitation where the level density of 4$^+$ states is higher and mixing causes the strength to be spread. The shift of this state to higher excitation can be understood as coming from the underprediction of the ground-state binding energy, due to deformations which cannot be reproduced in the simple 1p-1h model space. This interpretation is consistent with the observation that it was necessary to shift the IAS by 1.9 MeV, which also was originally predicted at an excitation which was too low. Nevertheless, as we have seen in the case of $^{44}\text{V}$, it is reasonable to compare the measured and calculated strength below the IAS. Including the experimental errors and assuming no errors in the theory, one obtains a quenching factor of 0.53 (17) in the interval 0–5.8 MeV of excitation energy in $^{48}\text{Cr}$.

The new GT quenching factor, obtained for the $\beta$-decay of $T_z = -1$ $^{48}\text{Mn}$ and for the series of 10 $T_z = -\frac{1}{2}$ mirror $\beta$-decays from $^{41}\text{Se}$ through $^{55}\text{Ni}$, are compared to other quenching factors in table 4. For the $^{32}\text{Ar} \beta$-decay, Bj"ornstad et al. obtained a value of 0.49 (5). We redetermined the quenching factor for this decay by comparing the experimental results of ref. to a shell-model calculation using the sd-shell interaction of Wildenthal. The latter calculation yields a strong GT transition at 9.074 MeV, which is just at the edge of the $Q$-value window. Due to the uncertainty in the excitation of this state it is not certain whether it should be included in the sum of the theoretical GT strength. Including this state one gets a quenching factor of 0.64 (7), and without 0.78 (8). Hence, taking the limits of these error bars we get an estimate for the quenching, which now includes a theoretical uncertainty, of 0.69 (12). This value is consistent with the results of Brown and Wildenthal for the sd-shell and also consistent with our results for $^{48}\text{Mn}$ and mirror nuclei in the fp-shell. The heavier nuclei, on the other hand, seem to be characterized by stronger GT retardation. It should be pointed out however, that in these cases, full scale shell-model calculations have not been performed and the transitions are sensitive to configuration mixing. A similar retardation as in the light nuclei is observed for GT$^+$ in heavier nuclei measured by $(p, n)$ reactions. In heavier nuclei GT$^-$ is not as sensitive as GT$^+$ to configuration mixing effects.

We note also, that the calculated GT strength for the decay of $^{48}\text{Mn}$ to the IAS in $^{48}\text{Cr}$ is very small ($B(\text{GT}) = 10^{-5}$), and that this transition therefore represents a good candidate for investigating pure Fermi decay between high-spin ($I = 4$) states. The forbiddenness of this GT transition is consistent with results from earlier
### Table 4
Examples of GT$^+$ strength reduction from $\beta$-decay studies

<table>
<thead>
<tr>
<th></th>
<th>sd-shell nuclei</th>
<th>$^{32}$Ar $\rightarrow^{32}$Cl</th>
<th>fp-shell nuclei, mirror $\beta$-decays of $T_z= \frac{1}{2}$ nuclei $^{61}$Sc to $^{53}$Ni</th>
<th>$^{48}$Mn $\rightarrow^{48}$Cr</th>
<th>$^{96}$Pd $\rightarrow^{96}$Rh</th>
<th>$^{148}$Dy $\rightarrow^{146}$Tb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{EC}$ (MeV)</td>
<td>11.15 (5)</td>
<td>6.5-8.7</td>
<td>13.6</td>
<td>3.45 (15)</td>
<td>2.70 (3)</td>
<td></td>
</tr>
<tr>
<td>Observation window</td>
<td>8.75 (MeV)</td>
<td>0-5.8</td>
<td>1.8</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground-state to</td>
<td></td>
<td></td>
<td>6.5-8.7 ground-state to (9.7-11.5) transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model used</td>
<td>Large-basis shell model, Wildenthal sd-shell interaction</td>
<td>Large-basis shell model, Chung-Wildenthal interaction</td>
<td>Large-basis shell model, Wildenthal sd-shell interaction</td>
<td>Large-basis shell model, van Hees-Glaudemans interaction</td>
<td>Extreme single-particle shell model, including pairing effects and g.s.t. correlations</td>
<td>Quasi-particle random phase approximation including pairing effects and g.s.t. correlations</td>
</tr>
<tr>
<td>Ref.</td>
<td>this work</td>
<td>this work</td>
<td>this work</td>
<td>this work</td>
<td>this work</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>$^a)$</td>
<td>$^b)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a)$ 60% of the calculated strength lies inside the observation window.

$^b)$ Global GT reduction; values between 0.4 and 1.0 are found for individual transitions.
calculations \cite{36,37}, which showed that M1 transitions between certain \(^{48}\)Cr states, describable by \((\pi f_{7/2})^{-n}(\nu f_{7/2})^{n}\) configurations, are forbidden.

6. Summary and outlook

In this paper we have presented first experimental information on \(\beta\)-delayed \(\gamma\)-rays and protons from the decay of the proton-rich nucleus \(^{48}\)Mn. This isotope represents the heaviest member of the \(A = 4n, T_z = -1\) family of \(\beta\)-delayed proton precursors known to date. The decay is dominated, with a branching ratio of 0.598 (30), by the superallowed transition to the IAS at 5792.4 (6) keV in \(^{48}\)Cr. The experimental GT strength distribution, deduced for \(^{48}\)Cr excitation energies up to 5.8 MeV from \(\gamma\) and from 8.7 to 11.5 MeV from proton measurements, is compared to shell-model calculations, which yields a quenching factor of 0.53 (17) for the excitation-energy interval 0-5.8 MeV; this result agrees with the general trend observed in the eight cases of \(\beta^+\)-decay of mirror nuclei in the fp-shell.

The shell-model calculations were performed using the van Hees-Claudemans interaction and a model space up to 1p-1h in all cases except \(^{44}\)V (full basis) and \(^{45}\)V (up to 2p-2h). The \(^{44}\)V calculations show that the fraction of GT strength to states below the IAS is constant to within 10\% for 1p-1h, 2p-2h, and full basis. We thus consider the 1p-1h calculations to offer a basis for a comparison with the total GT strength measured up to the IAS.

It is interesting to note that Hardy and Towner \cite{38} arrived at a similar conclusion when investigating the role of 2p-2h admixtures in the ground-states of \(^{14}\)O and \(^{18}\)Ne. In these calculations in spite of considerable spreading of the strength distribution as configuration mixing changes, the fraction of calculated strength within the \(\beta\)-decay window remains remarkably constant and close to the 2h and 2p value, respectively.

To measure the GT strength also for the region 5.8-8.7 MeV of \(^{48}\)Cr excitation energies represents a challenge which might be met even at the presently available \(^{48}\)Mn intensity (\(\leq 180\) atoms/s) by using improved \(\gamma\)-detectors, e.g. a pair spectrometer. On the other hand, an improvement of the proton singles data and in particular a measurement of proton-\(\gamma\) coincidences is desirable, but calls for extended counting time.

For future experiments the analog transition in the \(\beta^+\) decay of \(4^+ \, ^{48}\)Mn may represent a suitable case, in particular in view of the very small calculated GT contributions, for testing the speculation, that Fermi matrix elements of high-\(I\) states are anomalously large \cite{19,20}.

This work as well as a previous study of the 384-ms \(^{49}\)Mn decay \cite{39} proves how valuable the combined tool of heavy-ion fusion-evaporation reaction and on-line mass separation is for detailed \(\beta\)-decay studies. For further probing the phenomenon of GT quenching in the fp-shell region, 90 ms \(^{44}\)V represents an interesting candidate: Predictions from full shell-model calculations are available as presented in this
paper, while $\beta$-delayed $\alpha$-emission\(^1\) is the only experimental information on the decay of this nucleus so far. Detailed spectroscopic measurements ought to be possible with available techniques in this case. For more proton-rich nuclei such as 50 ms $^{44}$Cr or 75 ms $^{49}$Fe, on the other hand, the presently available secondary beam currents of the order of atoms/s represent a serious limit for such studies.

The authors would like to thank C. Bruske, K. Burkard and W. Hüller for their assistance in operating the on-line separator and the collection systems, and J. Main, D. Marx and G.-E. Rathke for their help in the early stage of the experiment. The successful collaboration with the UNILAC crew is gratefully acknowledged, being an indispensable prerequisite for measurements at the GSI on-line mass separator over a decade by now. We would also like to thank Dr. H. Miyatake, I.N.S., University of Tokyo, for interesting discussions.

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