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β^--DECAY AND COSMIC-RAY HALF-LIFE OF ^{54}Mn

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Abstract

A superconducting solenoid electron spectrometer operated in the lens mode was adapted to search for the β^--decay of ^{54}Mn. The Compton-electron and other instrumental backgrounds have been significantly reduced by special shielding of the absorber system. An improved procedure has been developed to select the events by momenta. A limit of 2.7×10^{-5} has been established for the β^- branch.

1 Introduction

In the laboratory, ^{54}Mn decays with a 312 day half-life via an allowed electron capture transition to the 835 keV level in ^{54}Cr, although it is energetically possible for ^{54}Mn to decay via second forbidden unique transitions to the ground states of ^{54}Cr and ^{54}Fe by positron (β^+) and electron (β^-) emission. As a high energy cosmic ray, ^{54}Mn would be stripped of all its atomic electrons; electron capture would be prevented, and the long β^+ and β^- half-lives thus expected, could make ^{54}Mn serve as a cosmic-ray chronometer, if the partial half-lives could be measured. Although the β^- decay intensity is expected to be about two orders of magnitude larger than the β^+ decay, measurement of the β^- decay has been considered difficult partly because in absolute terms it is weak, and its endpoint energy of 697 keV falls below the spectrum produced by scattered conversion electrons. The weaker, but easier to detect, β^+ branch has been searched for and an experimental upper limit of 5.7×10^{-9} for the branching ratio was established by da Cruz et al.[1]. If the β^- and β^+ decays have the same *logft* values an upper limit of 2.9×10^{-6} could be inferred for the β^- branch.

In this paper we present the results of an attempt to observe the β^- decay directly using a magnetic electron spectrometer. This momentum selective instrument in combination with multiparameter data collection and analysis techniques resulted in an upper limit, independent of *log ft* assumptions.

2 β^- Measurements

The absence of any suitable coincidence radiation in ^{54}Fe following the ^{54}Mn β^- decay requires the *direct* measurement of the β^--energy spectrum. Since the β^--branch is expected to be very weak, any physical process producing a continuum even at low levels could interfere with the measurements. They include:

(a) Conversion electrons which deposit part of their energy in the detector.
(b) Electrons which scatter within the source or on the internal surfaces of the spectrometer before reaching the detector.
(c) "Shake-off" electrons, caused by the sudden change in the electrostatic field within an atom that occurs as a result of internal conversion or electron capture.
(d) Electrons produced by Compton-scattering of the 835 keV γ-rays which can produce electrons up to an energy of 639 keV.
(e) Continuum electrons from other beta emitters, which might be present as weak contaminants in terms of absolute activity, but whose β^- branches might be relatively strong.
(f) Direct interactions between the primary 835 keV γ-photons emitted in the ^{54}Mn electron capture or scattered photons, producing signals up to the primary γ-ray energy.
(g) Interactions with γ-rays from laboratory background.

The initial ^{54}Mn source was fabricated from radioactive material dissolved in HCl and purified chemically to reduce ^{65}Zn, ^{60}Co and ^{22}Na contamination. Several drops of the liquid were then deposited on a thin mylar foil mounted on an aluminium frame. The activity of this source was 4.8 μC*i*. Subsequent evaluation of the measurements revealed that Compton-scattering within the source material was significant, some of which was attributed to residues from the chemical purification. Compton-scattering from the source frame was also found to be a problem. A stronger source (12.7 μCi) was prepared directly from a batch of ^{54}Mn material without any additional chemical purification and was mounted on a mylar frame. (The only detectable radioactive contamination was ^{60}Co at a level of 3.9×10^{-5} of the ^{54}Mn activity.)

Electrons were transported in the magnetic field of the superconducting solenoid operated in lens mode[2]. That arrangement uses a baffle system, consisting of two axial absorbers, a diaphragm and a spirally cut paddle wheel baffle so that β-particles which reach the detector are forced to traverse two orbits (loops). In the ^{54}Mn measurement the field was swept to collect electrons with energies between ~25 keV and ~1 MeV, with detection efficiency of ≈0.1 - 0.5 % of 2π. Electrons were detected with a cooled Si(Li) diode, located on axis, 35 cm from the source. To improve the system, the internal surfaces were coated with low Z-material (Teflon).

3 Analysis and Results

An important advantage of the lens spectrometer is that, at a given magnetic field, only a part of the full β-spectrum is transported onto the Si(Li) detector[2]. This is governed by the momentum resolution, which is a geometrical property of this type of spectrometer. The relation between the transported β-ray energy (E) and the magnetic field (B) can be defined over the [E,B] plane:

$$B = C(r, \theta \ldots) \times k \sqrt{E^2 + m_o\, c^2 \times 2 \times E} \Big/ m_o c^2 , \qquad (1)$$

where C is a coefficient which contains in effect the response function of the spectrometer as defined predominantly by the baffle geometry but also by factors such as source position and emittance. Events caused by γ-rays in the Si(Li) detector are independent of field and therefore will be distributed equally along the magnetic field axis,

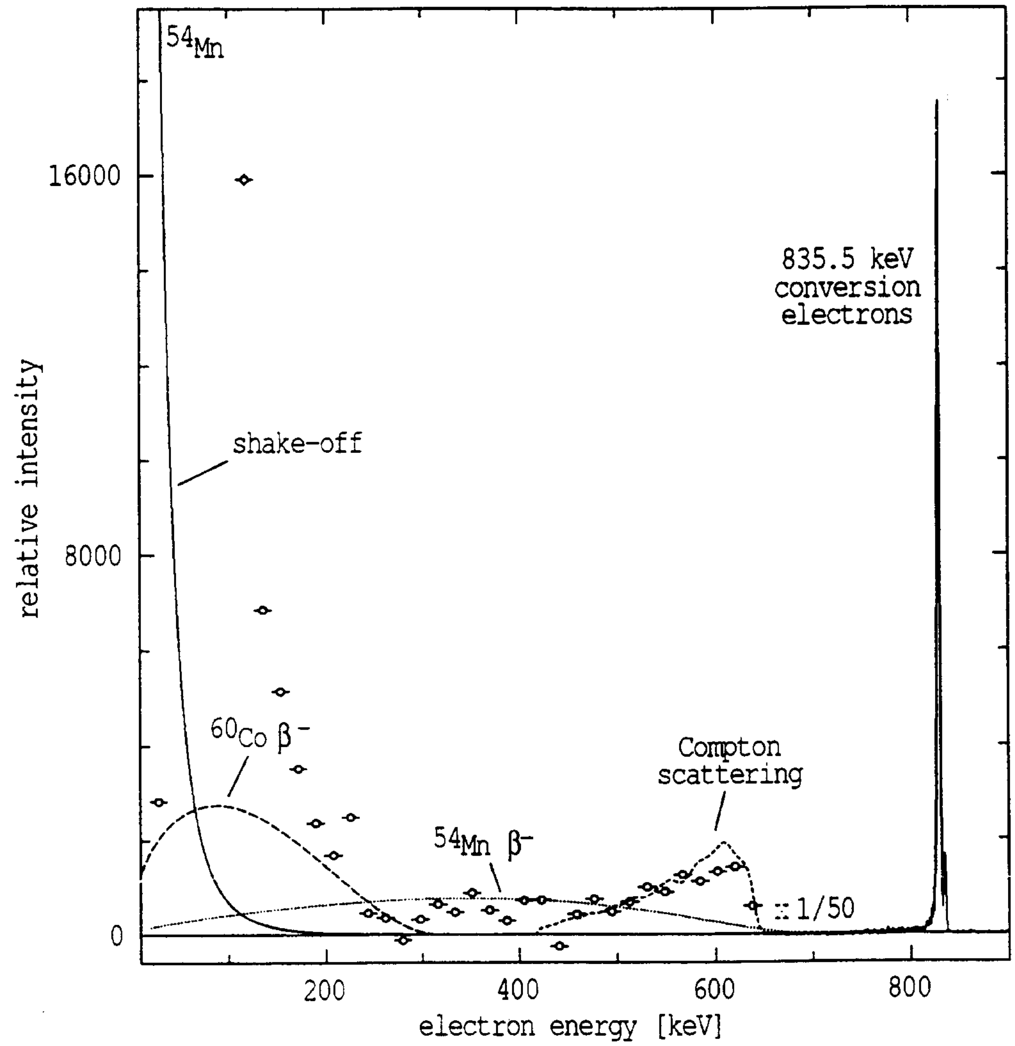

Figure 1 *The efficiency corrected spectrum of the ^{54}Mn β$^-$ measurement. Note that the spectrum below 640 keV has been scaled up by a factor of 50. The curve labelled as ^{54}Mn β$^-$ would correspond to an upper limit of 2.7×10^{-5}.*

while the events due to electrons which scatter from the detector will fall parallel with the energy axis in the [E,B] plane. Considering a simple approximation to the transport of β-rays along helical orbits of path radius (curvature), r, and angle of emission θ with respect to the solenoid axis, C is approximately:

$$C = \frac{1}{r} \times \sin\theta\ , \qquad (2)$$

Because of the geometric acceptance of the spectrometer, r and θ are correlated, the distribution of β-ray events in terms of C will be different for different geometrical origin. This relationship was used to identify the origin of the Compton electrons.

In the final analysis the event-by-event data were examined in the [E,C] plane and the contribution of γ-rays, scattered β-rays and Compton electrons produced mainly on the mylar target frame were removed. The resultant singles β-ray spectrum was corrected for detection efficiency and is shown in figure 1. It is important to note that the contribution of backscattered conversion electrons was eliminated in the region below 697 keV, the expected endpoint of the ^{54}Mn β^- decay. The spectrum contains very few counts at low energy and was plotted in 32 channel bins to reduce statistical fluctuations. The contributions from the shake-off process following electron capture and ^{60}Co radioactive contamination were deduced from known intensities and expected spectrum shapes. The Compton-electron spectrum obtained from computer simulation, assuming the source material as scattering medium, and was arbitrary normalised to experiment at feature near 600 keV. By comparing the measured spectrum and the contribution of different radiations, there is an excess of intensity at energies below 200 keV. The 300-450 keV energy region between these areas of residual contaminations has been used to set an upper limit on the ^{54}Mn β^- branch. This region contains 677(±8%) counts compared to a total of 3.54×10^4 835 keV conversion electrons of 8.7×10^{10} primary decays. Using the known detection efficiency and the expected shape of a second forbidden unique β spectrum an upper limit of 2.7×10^{-5} has been established for the β^- branch. This would correspond to a β^- half-life of $t_{1/2} > 3.0 \times 10^4$ years. This value is ≈32 times shorter than the estimated half-life of ^{54}Mn in cosmic rays, but this is the most stringent direct limit yet established for the β^- decay of ^{54}Mn.

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