A Search for Bound-state Beta Decay of ^{193}Ir in the Galactic Cosmic Rays

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Abstract

Bound-state beta decay (β_b decay) is an uncommon beta decay mode in which the electron is emitted into a bound atomic state rather than into the continuum. Because of the exclusion principle, the final atomic state must be initially empty, so isotopes which can only decay by β_b decay are stable as neutral atoms. However, when completely ionized as in the galactic cosmic rays, these isotopes can decay. The isotope ^{193}Ir has been predicted to undergo β_b decay. ^{193}Ir is the most abundant isotope of iridium in the Solar System. The results from the Trek detector suggest a depletion of iridium in the galactic cosmic rays. Such a signal would be consistent with the β_b decay of this isotope. This would be only the third example of β_b decay ever observed and the first observation in a natural system.

1 Introduction:

The possibility that ionized atoms could undergo β_b decay has been known for over fifty years (Daudel, 1947; Daudel, Jean & Lecoin, 1947). However, fully stripped nuclei which can be stored for a sufficiently long period to measure half-lives are available in the laboratory only at dedicated heavy-ion storage rings, such as the one at GSI. This type of beta decay has been observed for the first time only recently in ^{163}Dy (Jung, 1992) and ^{187}Re (Bosch, 1996). A naturally-occurring sample of fully ionized nuclei is the galactic cosmic rays (GCR). We expect the effects of β_b decay to be apparent in observations of elemental abundances in the GCR.

Perhaps the most fascinating aspect of β_b decay is that it forces a reconsideration of nuclear stability. That is, "stable" atoms can become unstable to β_b decay when fully ionized. For purposes of discussion, we define a *β_b-isotope* as an isotope which is stable, or very nearly so, as a neutral atom, but which decays by β_b decay when fully ionized. Altogether there are four such isotopes in nature: ^{163}Dy, ^{187}Re, ^{193}Ir, and ^{205}Tl. We have included ^{187}Re as a β_b-isotope because of its extremely long continuum beta decay half-life (42.3 Gyr (Lindner et al., 1989)).

2 Trek measurement:

The Trek experiment, flown on space station *Mir* from 1991 to 1995, was designed to measure the abundances of platinum group elements, lead, and actinides in the GCR. It was composed of an array of 150 BP-1 (Wang et al., 1988) barium-phosphate track-etch detectors (Fleischer, Price & Walker, 1975). A complete description of the experiment can be found in Weaver et al. (1998). The analysis of the Trek experiment is now complete (Westphal et al., 1998). Though originally designed to answer questions about the source of GCR, the range of elements analyzed encompasses three β_b-isotopes: ^{187}Re, ^{193}Ir, and ^{205}Tl. The natural abundances of ^{187}Re and ^{205}Tl are extremely low, so we would not expect any cosmic ray experiment to say anything definite about these isotopes. However, Ir, at least in the Solar System, is as abundant as its neighbor, Os, and ^{193}Ir is the most abundant of the two stable isotopes of Ir. Evidence for β_b decay of this isotope in the GCR would constitute the first observation of β_b decay in a natural setting.

The analysis of the Trek experiment produced a spectrum of charges. The data were fit to gaussians centered on each element using maximum likelihood methods. The abundances were then corrected for angular acceptance and scanning efficiency.

The predicted β_b half-life of ^{193}Ir is 140 yr (Takahashi et al., 1987), while the lifetime of nuclei in the GCR is of order 10 Myr (Lukasiak et al., 1994). While this long half-life may put detection beyond the reach of laboratory storage rings, we expect ^{193}Ir to be effectively absent from the GCR. In addition, the β_b daughter nucleus is ^{193}Pt, which is unstable to electron capture as a neutral atom, but which is stable in the GCR.

The GCR abundances of the platinum-group elements measured by Trek are summarized in Table 1. We compare the observed GCR abundances to the Solar abundances of Anders & Grevesse (1989). The Trek observed abundances are corrected for detector acceptance, but not for propagation through the interstellar medium. In particular, the osmium abundance may be modified by nuclear spallation reactions. The iridium upper limit is consistent with a remnant population of ^{191}Ir, while the platinum abundance is consistent with the solar abundance plus an additional amount of "fossil" ^{193}Ir. We have defined the "Pt-group" to include the total elemental abundance of atomic numbers $75 \leq Z \leq 79$.

Ratio	Solar	Measured at Detector
Os	0.252 ± 0.019	$0.38^{+0.06}_{-0.05}(\mathrm{stat.})^{+0.07}_{-0.03}(\mathrm{syst.})$
^{191}Ir	0.092 ± 0.013	
^{193}Ir	0.155 ± 0.013	
Ir	0.247 ± 0.018	< 0.21
Pt	0.500 ± 0.043	$0.48^{+0.04}_{-0.06}(\mathrm{stat.})^{+0.02}_{-0.01}(\mathrm{syst.})$

Table 1: Solar System abundance ratios (Anders & Grevesse, 1989) compared with abundance ratios observed in the Trek experiment (Westphal et al., 1998). All ratios are (species/Pt-group).

3 Source abundances:

In this region of interest, nuclei are formed by the s-process or the r-process. The s-process refers to the *slow* capture of neutrons onto seed nuclei with enough time on average for ordinary continuum beta decay to take place between neutron captures. In contrast, the r-process involves the *rapid* capture of neutrons onto seed nuclei. This probably takes place in supernovae. Extremely neutron-rich nuclei are formed until it becomes energetically unfavorable for the nucleus to absorb another neutron (this is the so-called "neutron drip line"). Neutron magic numbers—such as the $N = 126$ magic number—constitute bottlenecks in the r-process, *i.e.*, nuclei build up around $N = 126$ and proceed no further. These nuclei beta decay back to the line of stability. The platinum-group nuclei are synthesized principally by the r-process and are the result of the $N = 126$ bottleneck. Only a very small fraction of platinum-group nuclei are synthesized by the s-process. In addition ^{187}Os is a "fossil" of ^{187}Re.

It is important to consider the source abundances for the GCR. Our calculations show that the most favored models for the source of GCR are, first, a fresh (young) source of pure r-process material (Binns et al., 1989), and, second, a source consisting of galactic material (similar to solar material but with additional material from more recent episodes of nucleosynthesis) with preferential acceleration by volatility (Meyer, Drury & Ellison, 1997). We have considered a number of nucleosynthetic models (Käppeler, Beer & Wisshak, 1989; Binns et al., 1989; Beer, Corvi & Mutter, 1997) for the s-process. We obtained r-process abundances by subtracting the s-process from Solar abundances. All three sources agree on the abundances of Pt-group elements, with the exception of some uncertainty in the s-process abundance of Ir. However, because the ratio r/s for Pt-group elements is at least a factor of ten, uncertainty in the s-process abundance of Ir does not significantly alter the overall abundance of Ir. Furthermore, the Trek experiment has strongly ruled out a GCR source dominated by s-process abundances. We also considered local galactic abundances, which could, in principle, differ from Solar values of abundances. We considered the nucleosynthetic and galactic chemical evolution model of Thielemann, Metzinger & Klapdor (1983), but found that contemporary galactic abundances of Pt-group elements do not differ significantly from Solar values. Within the uncertainties, the abundances of Os and Ir are equal in every case. Finally, the atomic properties of the platinum-group, including volatility, are all very nearly the same, so preferential acceleration by volatility would not lead to observed abundances significantly different from Solar values.

4 Further research:

It is our intention to perform detailed propagation calculations from the GCR source to the detector, including the disappearance of ^{193}Ir. It may be possible to improve the charge resolution of the Trek detector in the region of platinum-iridium-osmium by analyzing more surfaces of the detector. Only a maximum of twelve out of a possible 32 surfaces contributed to the final results (Westphal et al., 1998), and it may be possible to directly determine the abundance of iridium in the cosmic rays if we can separate it from neighboring osmium and platinum. Using a Monte Carlo simulation of the Trek detector (Weaver et al., 1998), we can predict the charge resolution we would expect in this charge region with the analysis of all 32 possible surfaces. Based on these simulations, we could expect a charge resolution potentially as good as 0.30e, an improvement over the twelve sheet Trek analysis which yielded 0.38–0.45e resolution. We are currently planning to undertake such an analysis as a preparation for the ECCO detector (Westphal et al., 1999).

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