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E.B. Norman

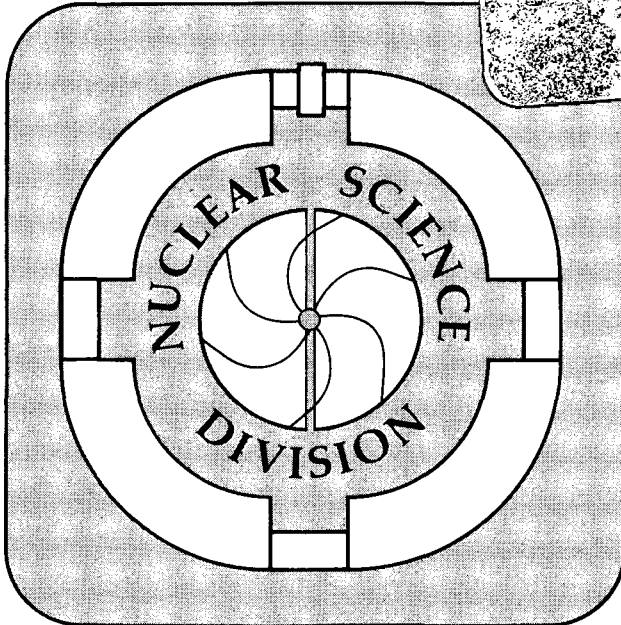
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INFLUENCES OF THE ASTROPHYSICAL ENVIRONMENT ON NUCLEAR DECAY RATES

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ABSTRACT

In many astronomical environments, physical conditions are so extreme that nuclear decay rates can be significantly altered from their laboratory values. Such effects are relevant to a number of current problems in nuclear astrophysics. Experiments related to these problems are now being pursued, and will be described in this talk.

1. INTRODUCTION

The decay rates of atomic nuclei are usually thought to be determined solely by the interplay of the strong, electromagnetic, and weak interactions between the neutrons and protons in the nucleus. As a result, it is generally taken for granted that these decay rates are unaffected by environmental factors. Under terrestrial conditions, this is an extremely good approximation. In many astronomical environments, however, physical conditions are so extreme that nuclear decay rates can be significantly altered from their laboratory values. In order to understand the nucleosynthesis and history of the chemical elements that we observe, it is necessary to know what the actual half-lives of nuclei are under the conditions of temperature and density that they have experienced.

At the high temperatures found in stellar interiors, nuclei are continuously irradiated by large fluxes of high-energy photons. These photons can be absorbed by a nucleus with the effect that the nucleus is excited to a higher energy level. In several cases of astrophysical interest, the beta decay of the ground state is a forbidden and hence very slow

transition, while those of the excited states are allowed transitions. Thus, if these excited states are populated, significant increases in the effective decay rate of the nucleus can result.

Another effect of the high temperatures found in stellar interiors is that during nucleosynthesis, matter is essentially fully ionized. For nuclei which beta-minus decay, this leads to the possibility of bound-state beta decay. In this process, the beta particle is emitted directly into a previously unoccupied bound atomic orbital. For decays with low endpoint energies, the increase in decay energy provided by the atomic electron binding energy can lead to large increases in the nuclear decay rate.

A final effect that also results from the absence of atomic electrons is of importance in cosmic-ray physics. Some of the species present in the cosmic rays are radioactive nuclei which, under terrestrial conditions, decay by electron capture. High-energy cosmic rays are fully stripped of their atomic electrons in passing through the interstellar medium. Thus, because there are no bound atomic electrons to be captured, dramatic decreases in the decay rates occur for such cosmic-ray nuclei. For some species, the result is that they become "stable", while for others, terrestrially unobserved beta-minus or beta-plus decays will determine their decay rates.

Effects such as these are relevant to a number of current problems in nuclear astrophysics. Nuclear physics experiments related to these problems are now being pursued and will be described in this talk.

2. THE S-PROCESS BRANCH AT ^{148}Pm

While it is generally true that in the s-process the neutron-capture rates are low compared to typical beta-decay rates, there are places along the s-process path where the half-lives are sufficiently long that neutron capture on these unstable nuclei competes with beta decay. If one knows the relevant isotopic abundances, neutron-capture cross sections, and beta-decay half-lives, such "branch points" allow one to infer the neutron density during the s-process.

Through recent measurements of the neutron-capture cross sections of $^{148,149,150}\text{Sm}$, Winters et al.¹ have shown that such a branch in the s-process path occurs at the odd-odd nucleus ^{148}Pm . The path of the s-

could absorb one of these photons and be excited to a higher-lying level which subsequently decays to the ground state. This process is illustrated in Figure 2.

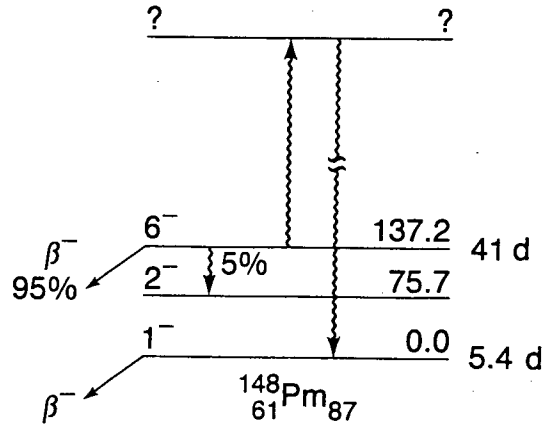


Figure 2. Schematic illustration of the process of photoexcitation of $^{148}\text{Pm}^m$ to a higher lying state that subsequently decays to $^{148}\text{Pm}^g$.

In order for the timescale for equilibration under s-process conditions to be shorter than the half-life of $^{148}\text{Pm}^g$, such mediating levels must lie below approximately 1 MeV excitation energy. Thus, to decide if this actually happens during the s-process, the positions and gamma-decay properties of levels in ^{148}Pm must be known.

As a first step toward answering the question of whether $^{148}\text{Pm}^{g,m}$ reach thermal equilibrium in the s-process, an experiment was carried out to locate low-lying levels in ^{148}Pm . The $^{149}\text{Sm}(d, ^3\text{He})^{148}\text{Pm}$ reaction was performed using a deuteron beam from the Princeton University cyclotron. The reaction ^3He particles were momentum analyzed with a QDDD spectrometer and were detected at the focal surface with a position-sensitive proportional counter followed by a plastic scintillator. From these measurements, the positions of twenty new states below 1-MeV excitation energy in ^{148}Pm were determined.

An example of the type of state that could mediate transitions between $^{148}\text{Pm}^g$ and $^{148}\text{Pm}^m$ is one of the $J^\pi = 4^-$ levels that are expected to be located at low excitation energy. Such a state should have sizable decay branches to both the $J^\pi = 2^-$ level at 76 keV (which decays to the

ground state) and to the isomer. To determine which, if any, of the levels observed in the present investigation serve as such a mediator during the s-process, the gamma-decay properties of these levels must be known. An experiment was performed at Lawrence Berkeley Laboratory to study electromagnetic transitions in ^{148}Pm . The $^{148}\text{Nd}(p,n)$ reaction was used to produce ^{148}Pm and gamma-ray singles and gamma-gamma coincidence data were acquired with the High Energy Resolution Array (HERA) of 20 Compton-suppressed germanium detectors. A number of the observed gamma rays have been placed in the level scheme of ^{148}Pm , but so far no level has been observed to decay to both the ground state and to the isomeric level. Further analysis of this data is currently in progress.

3. THE NUCLEOSYNTHESIS OF ^{180}Ta

One of the continuing puzzles in nuclear astrophysics is the origin of the naturally occurring $J^\pi = 9^-$ isomer $^{180}\text{Ta}^m$, which appears as 0.012% of natural tantalum.² Even this small abundance cannot be explained in terms of the conventional s- and r- processes. The presence of the stable 176- ^{180}Hf isotopes allows the standard s-process flow to bypass ^{180}Ta . The beta decays following r-process neutron captures would terminate at the first stable $A=180$ nuclide, ^{180}Hf . Recently, however, it has been suggested that $^{180}\text{Ta}^m$ may be synthesized via small beta-decay branches off the main s- and r-process paths.^{3,4} Beer and Ward³ have proposed a model in which $^{180}\text{Ta}^m$ is produced through the beta decay of $^{180}\text{Hf}^m$. These authors also pointed out that the r-process could contribute to the observed abundance of $^{180}\text{Ta}^m$ if a fraction of the beta decays of ^{180}Lu lead to the population of $^{180}\text{Hf}^m$, a fraction of which subsequently decays to $^{180}\text{Ta}^m$. Figure 3 summarizes the basic ideas of this model.

Searches for these small beta decay branches have been conducted. The beta decay of $^{180}\text{Hf}^m$ to $^{180}\text{Ta}^m$ has been observed,^{5,6} but the measured branching ratio is too small to allow the s-process to be the major source of $^{180}\text{Ta}^m$. Searches by two different groups for the beta decay of ^{180}Lu to $^{180}\text{Hf}^m$ have given conflicting results.^{7,8,9}

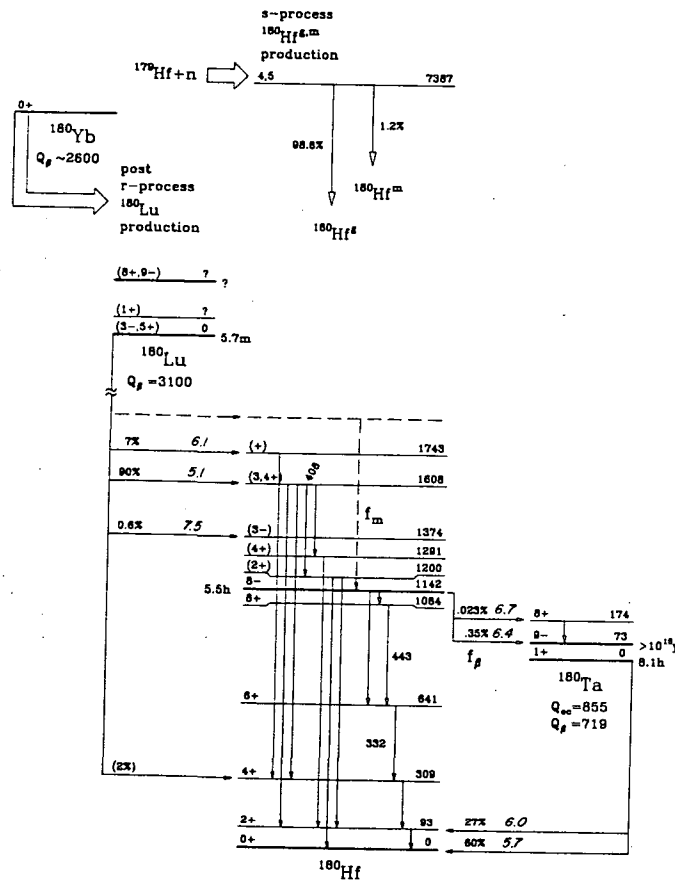


Figure 3. Partial level schemes of ^{180}Lu , ^{180}Hf , and ^{180}Ta and the neutron-capture production paths to ^{180}Tm .

Beer and Macklin¹⁰ have pointed out that two effects due to the high degree of ionization in an s-process environment enhance the laboratory beta-decay branches of $^{180}\text{Hf}^m$. First, the empty L shell inhibits the internal conversion of the 57.5-keV transition. This effect alone increases the half-life of $^{180}\text{Hf}^m$ against electromagnetic decay by a factor of 1.4. Second, the nearly empty K shell opens the door for bound-state beta decay which significantly supplements beta-decay strength into the continuum. Takahashi and Yokoi¹¹ have calculated the ratio of the rates for bound-state decay to that of decay into the continuum. For the $^{180}\text{Hf}^m$ decay to the $J^\pi = 8^+$ level at 174-keV excitation energy in ^{180}Ta , they find that this ratio ranges between 1.5 and 11 for plausible s-process conditions. A similar calculation for the direct decay to the $J^\pi = 9^-$ $^{180}\text{Ta}^m$ results in a

ratio between 0.5 and 3.

Regardless of what nuclear reactions are actually responsible for its production, one must consider the possibility of the destruction of $^{180}\text{Ta}^m$ in stellar environments via deexcitation to the short-lived $^{180}\text{Ta}^g$. Norman et al.¹² have shown that if it were possible for $^{180}\text{Ta}^g$ and $^{180}\text{Ta}^m$ to come into thermal equilibrium, then the effective half-life of the nucleus would be on the order of a day for a reasonable range of temperatures and densities.

To decide if such equilibration occurs during the s-process, the positions and decay modes of the low-lying excited states of ^{180}Ta must be known. From the experiments of Warde et al.¹³ and those of Dewberry and Naumann¹⁴ some fifty or so levels are now known to exist below about 1-MeV excitation energy in ^{180}Ta . Until recently however, nothing was known about the gamma-decay properties of any of these levels. In an attempt to provide this information another experiment was performed using the HERA at LBL. The $^{180}\text{Hf}(p,n)$ reaction was used to produce ^{180}Ta and gamma-ray singles and gamma-gamma coincidence data were acquired. In the analysis that has been performed to date, two families of gamma rays have been placed in the level scheme of ^{180}Ta . There is one group of transitions which ultimately feeds the ground state of the nucleus and another group which leads to the isomeric level. No "crossover" transition has yet been found, but the analysis is still continuing.

4. THE COSMIC-RAY LIFETIMES OF ^{54}Mn AND ^{56}Ni

Measurements of the elemental and isotopic composition and energy spectra of the cosmic-ray nuclei just below iron have indicated the presence of the radioactive nucleus ^{54}Mn in the cosmic rays.^{15,16} As can be seen from Figure 4, in the laboratory ^{54}Mn decays via electron capture with a half-life of 312 days. As a high-energy cosmic ray, ^{54}Mn would be stripped of its atomic electrons through interactions with the interstellar medium. Thus cosmic-ray ^{54}Mn would be stable were it not for the possibility of both beta-minus and beta-plus decay. Such decays are energetically allowed, although hindered because of the large spin changes required. The most likely decay of a bare ^{54}Mn nucleus is the beta-minus decay to the

ground state of ^{54}Fe , and the partial half-life for this branch has been estimated to be $(0.06 - 10) \times 10^6$ years.¹⁷ The measured fluxes of cosmic-ray ^{54}Mn could be used to determine the mean age of cosmic-ray secondary nuclei if this half-life were known.¹⁸

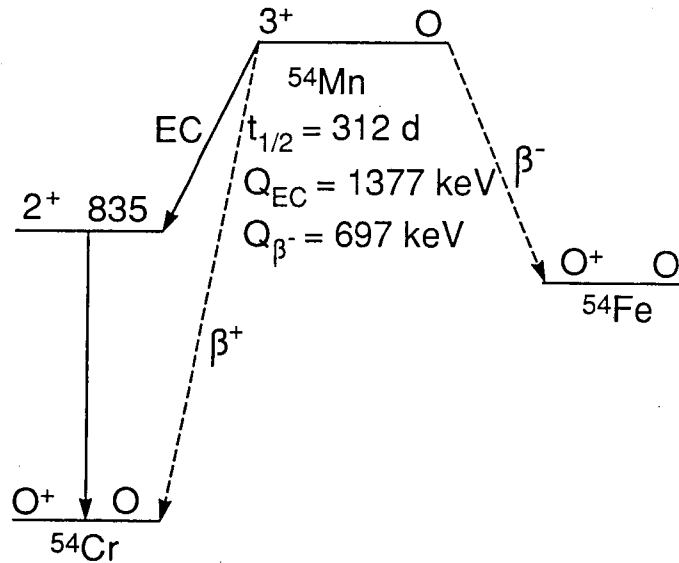


Figure 4. Decay scheme of ^{54}Mn .

We have recently begun a project to measure the beta-minus decay lifetime of ^{54}Mn . A source of ^{54}Mn is mounted in close geometry to a silicon surface-barrier detector telescope. This assembly is then placed at the center of a large annular sodium iodide detector. The well of the annulus is then filled with two sidecap sodium iodide detectors. Searches are then made for events in the silicon detector telescope that are in anticoincidence with signals in the sodium iodide array. Such events will include the sought-for beta-minus particles. In a series of preliminary experiments of this kind, we found that electrons produced by the 2.5×10^{-4} internal conversion decay branch of ^{54}Mn are a problem for our measurement. Such electrons can backscatter off the silicon detectors and thus deposit only a fraction of their total energy. This produces a large background that at present hides the sought-for beta particles. However, from analysis of the data taken thus far, we can set an upper limit on the beta-minus decay branching ratio of ^{54}Mn of 5×10^{-4} . Further

improvements of our system will soon be made in order for the beta-minus decay lifetime of ^{54}Mn to be measured.

A major product of charged-particle induced nucleosynthesis in stars is the doubly-magic nucleus ^{56}Ni . As can be seen in Figure 5, in the laboratory, this isotope decays via electron capture with a half-life of 6.1 days. In the absence of atomic electrons, however, ^{56}Ni would be stable were it not for the possibility of beta-plus decay. The most likely beta-plus decay branch is that to the $J^\pi = 3^+$ level at 158 keV in ^{56}Co , and the partial half-life for this branch has been estimated to be $(0.1 - 6) \times 10^6$ years.¹⁷

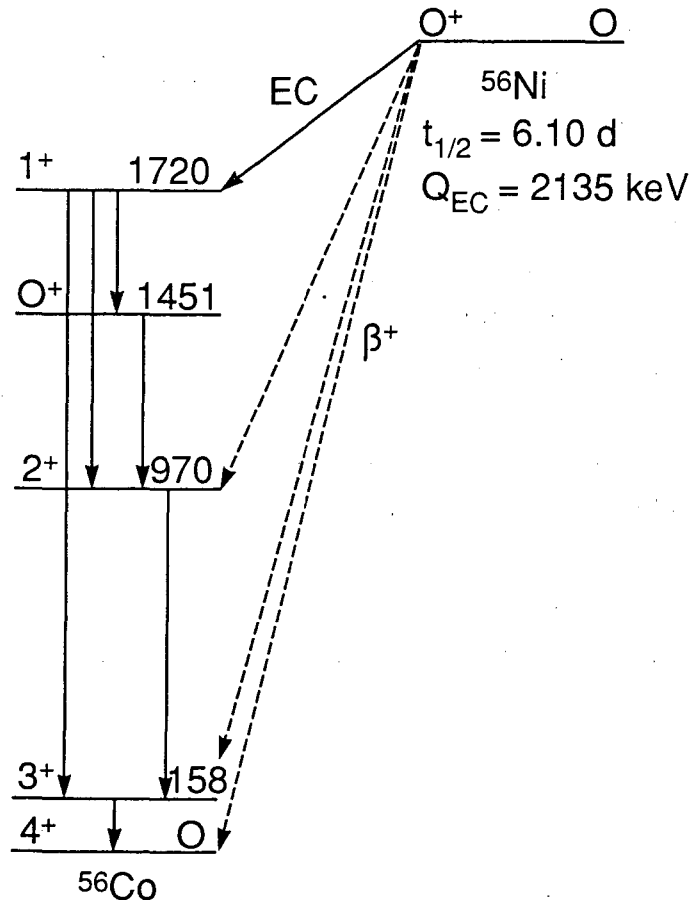


Figure 5. Decay scheme of ^{56}Ni .

Soon after the supernova explosion that produces the ^{56}Ni takes place,

temperatures are low enough that electrons are bound to nuclei and neutral atoms can exist. Thus, the half-life of ^{56}Ni would be its laboratory value. However, it is thought that supernovae may be sites of cosmic-ray production and acceleration. If ^{56}Ni produced in such explosions were accelerated to high energies then it too would be quickly stripped of its electrons. Thus, the cosmic-ray lifetime of ^{56}Ni would be determined by its beta-plus decay half-life. Future observations of ^{56}Ni in the cosmic rays could be used to determine the time interval between nucleosynthesis and cosmic-ray acceleration if this half-life were known.¹⁹

We plan to measure the beta-plus decay lifetime of ^{56}Ni using a four-fold coincidence technique. ^{56}Ni is produced by bombarding iron foils with a beam of ^3He ions provided by LBL's 88-Inch Cyclotron, and is then chemically separated from the target. To detect ^{56}Ni beta-plus decay, the activity is placed at the center of a large sodium iodide annular detector that is split into two optically isolated halves. Located inside the annulus on one side of the source is a germanium gamma-ray detector, and on the other side of the source is a silicon surface-barrier detector. This system is being used to search for events in which a positron is detected in the silicon detector, a 511-keV annihilation gamma ray is recorded in each half of the annulus, and a 158-keV gamma ray is recorded in the germanium detector. In a series of preliminary tests of this scheme, a large number of such four-fold coincident events have been observed. If these were naively assumed to be due to the sought-for decay, the inferred branching ratio would be on the order of 10^{-3} which is much greater than the expected value of 10^{-7} to 10^{-6} . The origin of these events is now being investigated.

5. CONCLUSIONS

It has been shown that under the physical conditions that occur in a variety of astronomical environments, several different processes can lead to the alteration of nuclear decay rates from their terrestrial values. Careful studies of specific nuclear properties can provide the quantitative information needed to properly incorporate these effects into nucleosynthesis calculations. These required measurements provide real challenges for

experimenters.

6. ACKNOWLEDGEMENTS

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