Bound-state beta decay of highly ionized atoms

K. Takahashi
Department of Physics, The Ohio State University, Columbus, Ohio 43210

R. N. Boyd
Department of Physics and Department of Astronomy, The Ohio State University, Columbus, Ohio 43210

G. J. Mathews
University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

K. Yokoi
Science and Engineering Research Laboratory, Waseda University, Okubo, Shinjuku-ku, Tokyo 160, Japan
(Received 18 March 1987)

Nuclear β decays of highly ionized atoms under laboratory conditions are studied. Theoretical predictions of β-decay rates are given for a few cases in which bound-state β decay produces particularly interesting effects. A possible storage-ring experiment is proposed for measuring bound-state β-decay rates, which will be most easily applied to the decay of $^3H^+$.

I. INTRODUCTION

Bound-state β decay is a nuclear β decay process in which an electron is created in a previously unoccupied atomic orbital rather than in the continuum. The possibility that this process might occur was considered by Daudel *et al.* four decades ago,[1] but to date no experimental confirmation has been achieved. Nevertheless, many theoretical calculations have been performed for bound-state β decays such as for a neutron,[2,3] tritium,[2,4] neutral,[5] and highly (or fully) ionized[2,5–8] heavy atoms. In particular, recent theoretical studies[8,9] have affirmed the extreme importance of the bound-state β-decay process for the ^{187}Re-^{187}Os and ^{205}Tl-^{205}Pb nucleocosmochronometers. In addition, detailed studies of the bound-state β decay of neutral ^{187}Re have recently been made[10,11] in conjunction with the ^{187}Re-^{187}Os chronometry.

The difficulty of experimentally detecting bound-state β decay is related to the fact that atoms are usually neutral, or nearly so, under laboratory conditions. The phase space available for creating an electron in the unfilled outer atomic orbitals is small. Thus, the process is usually masked by continuum-state β^- (e^- emission) decay. Confirmation of the existence of the bound-state β decay, therefore, requires very precise measurements of both the total (continuum plus bound) decay rate (e.g., by counting atoms) *and* the partial, but normally overwhelming, continuum-state decay rate (e.g., by detecting e^-). Furthermore, if the initial atom is neutral, the bound-state β decay results mostly in a charge-neutral final state, which is difficult to detect in many experimental configurations.

One exceptional case which has been studied in this context is ^{187}Re, for which both the total decay and e^- emission rates have been measured separately. The total half-life $T_{1/2}$ is fairly well established by geological studies [43±5 Gyr (Ref. 12) and 45.3±2.4 Gyr (Ref. 13)] as well as by a direct atom-counting technique [43.5±1.3 Gyr (Ref. 14)]. However, the reported values for the continuum-state β^- decay half-life $\tau_{1/2}$ are diverse [66±13 Gyr (Ref. 15), 47±5 Gyr (Ref. 16), and 35±4 Gyr (Ref. 17)]. To deduce the bound-state decay contribution, which is expected to be 1% or less,[10,11] from these currently available data is clearly impossible. Indeed, the adoption of the recent values for $\tau_{1/2}$ (Ref. 17) and $T_{1/2}$ (Refs. 13 and 14) would lead to the unacceptable conclusion that the bound-state decay contribution is negative!

The other case which has been studied is that of ^{3}H decay. Several precise measurements have been performed to determine its half-life to sufficient accuracy to "detect" the bound-state decay contribution (predicted to be 0.69% for neutral ^{3}H).[2] Recently, Budick[18] has theoretically studied the possible atomic and molecular effects on the ^{3}H half-life by calculating the β-decay half-lives $t_{1/2}$ for $^3H^+$, ^{3}H, $^3H_2$, and $^3H^-$, and has shown in particular that $t_{1/2}(^3H^-) < t_{1/2}(^3H_2)$. The slight differences in the existing data on ^{3}H half-life, though difficult to interpret, seem to be consistent with this conclusion. Budick's calculation indicates that the various (nonperfect overlap, screening, and exchange) corrections to the continuum-state decay largely cancel, and that the difference between those two half-lives are mainly due to that in the bound-state decay contributions. Therefore, the above finding may provide indirect evidence for the existence of the bound-state β decay.

With the rapid progress of experimental techniques, including storage rings to be attached to heavy-ion accelerators, one can anticipate the possibility of detecting β decays of highly ionized atoms. (It should be noted that continuum-state β decay also depends on the degree

of ionization.) Therefore, we present some theoretical predictions, with special emphasis on the several nuclei which we consider to be the best, or most interesting, candidates for eventual experiments to detect bound-state β decay and test the theoretical predictions thereof. Furthermore, we propose a storage-ring experiment to measure bound-state β-decay rates.

In Sec. II the selection of nuclei of potential interest and the theoretical results are described. Experimental prospects are discussed in Sec. III. Conclusions are given in Sec. IV.

II. THEORETICAL PREDICTIONS

A. Nuclei of interest

A measurement of bound-state β decay might be possible if (1) a beam can be prepared with atoms sufficiently ionized to increase the phase space available to the process, (2) the half-life for β decay is not so long that the event rate is too low, and (3) the continuum-state β decay is not overwhelming.

Let us suppose that condition (1) can be met. Condition (2) cannot be met if second-forbidden and higher-forbidden β transitions dominate; we therefore disregard such cases. Condition (3) can be controlled to some extent by choosing nuclei with low neutral atomic mass differences (i.e., the β decay Q values for nuclei). The nuclei which satisfy these conditions can be classified into three categories:

(a) accelerator-produced β-unstable nuclei such as ^{3}H, ^{63}Ni, ^{106}Ru, ^{151}Sm, ^{171}Tm, ^{191}Os, etc.,

(b) naturally occurring β-unstable nuclei such as ^{187}Re, ^{228}Ra, and ^{227}Ac, and

(c) stable nuclei such as ^{163}Dy, ^{193}Ir, and ^{205}Ti.

B. Method

The main difficulty in formulating bound-state β decay (except that of fully ionized atoms) arises from the nonorthogonality between the eigenfunctions of the initial and final Hamiltonians,[2,19] which result from the sudden change of the nuclear charges by one unit during nuclear β decay. While it is relatively easy to calculate the nonorthogonality effects for few electron systems with low Z such as ^{3}H, for which nonrelativistic wave functions can be used, it becomes impractical for heavy atomic nuclei. (However, in this context Chen *et al.*[11] have recently performed a self-consistent calculation of bound-state β decay of neutral ^{187}Re.) While the effect of the nonorthogonality on β transition rates results in some 30% enhancement for the bound-state β-decay rate of neutral ^{3}H, however, it becomes rapidly smaller as Z increases. [The average excitation energy of the final atom, resulting from the nonorthogonality, increases with Z, but is still less than ≈ 0.2 keV (Ref. 20) for the highest Z considered here.] Thus, nonorthogonality effects are negligible in all cases considered here, except the case of neutral ^{3}H. In some β decays in heavy atoms, on the other hand, the change of electronic energies with ionization state is no longer negligible compared with the nuclear transition energy. Specifically, the canonical formalism of Bahcall[2] (as well as a simpler version by Batkin[5]) does not explicitly treat cases in which continuum-state β decay rates change significantly as a result of ionization. Indeed, this effect is crucial[8,9] in discussing the β decay of highly ionized atomic nuclei in categories (b) and (c) above.

We have calculated β-decay rates for highly ionized heavy atoms from a model which is deduced from recent work by Takahashi and Yokoi,[8] who formulated various β decay processes for heavy nuclei embedded in a plasma of electrons and ions at high temperature and high density. The method is not throughly self-consistent, but should be sufficiently accurate for application for highly ionized heavy atoms.

In this model the decay rate of an ion species I can be written as

$$\lambda_I^{(m)} = \begin{cases} \sum_F (\ln 2/f_0 t) f^*_{IF(m)} & \text{for } m = a, nu \ , \\ \sum_F (\ln 2/f_1 t) f^*_{IF(m)} & \text{for } m = u \ , \end{cases} \tag{1}$$

where the summation runs over the final ionic states F, and $m = a$, nu, and u distinguishes the allowed, nonunique first-forbidden and unique first-forbidden transitions, respectively. The quantities $f_0 t$ and $f_1 t$ are the usual ft values.[21] The f^* functions depend on the degree of ionization of either the initial or the final state. The explicit formulas for f^* in the cases of continuum-state and bound-state decays can be obtained from Eqs. (14a) and (14b) of Ref. 8, respectively, by ignoring those corrections which were introduced to deal with stellar environments. Several approximations used in numerical calculations are also essentially the same as those discussed in Ref. 8.

As for light atoms, the above method is only applicable to fully ionized atoms, since it ignores the nonorthogonality between the initial and final atomic wave functions. In the case of neutral ^{3}H, we therefore refer to previous works[2,18] which took this effect into account.

C. Complete ionization

The β decay rates calculated for fully ionized atoms are summarized in Table I and compared with experimental values for neutral atoms.

The bound to continuum state decay ratios calculated by Bahcall[2] and Batkin[5] for some cases with $Q_n > 0$ are considerably lower than the present values. This is expected since those authors used nonrelativistic wave functions for the bound electrons. At $Z = 80$, for instance, the relativistic K-electron $g_K^2(R)$ is about 5 times as large as its nonrelativistic counterpart $4(\alpha Z)^3$. (The ratios presented in their analyses may better be compared with λ_b/λ_n in our notation, since they did not consider the possible change of λ_c with respect to the degree of ionization.)

The energetics depend on the degree of ionization, resulting in changes of rates, not only of bound-state decays, but also of continuum-state decays. As can be seen

in Table I (^{187}Re, ^{210}Pb, ^{227}Ac, and ^{241}Pu), some continuum-state decays are energetically forbidden when the atom is fully ionized. This is simply because the atomic binding energies liberated by ionization, i.e., the total electron binding in the neutral atom, B_n, increases with Z. If $Q_n < B_n(Z+1) - B_n(Z)$, the continuum-state β decay is energetically forbidden for fully ionized atoms. This atomic binding energy difference amounts to as much as 15.3 keV for Re-Os and 22.4 keV for Pu-Am. (A tabulation of B_n values can be found in Ref. 25; they are essentially the same as ours.) In general, λ_c becomes considerably smaller than λ_n if Q_n is small (see, e.g., ^{155}Eu cases in Table I, remembering the strong energy dependence of phase space for e^- emission).

The screening effect on continuum-state decay rates, which also depends on the degree of ionization, is appreciable only at the extremely-low-energy tail of the spectrum and, in particular, in unique first-forbidden transitions.

The bound-state decay gains the binding energy of the

TABLE I. Beta decay rates calculated for fully ionized atoms compared with experimental values for neutral atoms. All the decay rates λ are in units of sec^{-1}, and the exponents are abbreviated in square brackets: for example, 1.8[−9] means 1.8×10^{-9}. The second column, Q_n, is the β^- decay Q value in keV for *neutral* atoms (Ref. 22). The logft values are calculated with experimental information (Refs. 22–24) and f values from Ref. 21; those in parentheses are uncertain and include those obtained (Refs. 8 and 9) from systematics. In column 4, $m = a, nu$ or u distinguishes allowed, nonunique first-forbidden or unique first-forbidden transitions, respectively, as in Eq. (1). λ_n is the experimentally known (Refs. 23 and 24) laboratory (neutral atom) β^- decay rate. λ_c and λ_b are the continuum-state and bound-state β decay rates in the bare nuclei, respectively. Columns 7 and 8 are, respectively, the ratios λ_b/λ_c and $(\lambda_b+\lambda_c)/\lambda_n$, given for each *isotope*.

Parent	Q_n (keV)	logft	m	λ_n (sec^{-1})	λ_c (sec^{-1})	λ_b (sec^{-1})	b/c	$b+c/n$
^{3}H	18.62	3.06	*a*	1.8[−9]	1.8[−9]	1.8[−11]	1.0[−2]	1.01
^{14}C	156.5	9.04	*a*	3.8[−12]	3.8[−12]	6.0[−14]	1.6[−2]	1.01
^{32}Si	225.0	8.02	*a*	2.2[−10]	2.1[−10]	1.4[−11]	6.5[−2]	1.05
^{33}P	248.5	5.02	*a*	3.2[−7]	3.1[−7]	2.1[−8]	1.6[−2]	1.05
^{35}S	166.8	5.00	*a*	9.2[−8]	9.0[−8]	1.2[−8]	1.3[−1]	1.1
^{45}Ca	256.5	5.98	*a*	4.9[−8]	4.8[−8]	5.9[−9]	1.2[−1]	1.1
^{63}Ni	65.9	6.64	*a*	2.2[−10]	1.9[−10]	3.0[−10]	1.6	2.2
^{66}Ni	227.0	4.12	*a*	3.5[−6]	3.4[−6]	1.0[−6]	3.0[−1]	1.3
^{93}Zr	60.1	(10.0)	*u*	1.4[−14]	1.1[−14]	1.3[−14]	1.2	1.8
^{95}Nb	159.8	5.09	*a*	2.3[−7]	2.1[−7]	2.4[−7]	1.2	2.0
^{106}Ru	39.4	4.30	*a*	2.2[−8]	1.2[−8]	2.1[−7]	1.7[+1]	1.0[+1]
^{107}Pd	33.2	9.93	*u*	3.4[−15]	1.8[−15]	8.2[−15]	4.6	3.0
^{110}Ag^m	83.7	5.37	*a*	2.2[−8]	1.7[−8]	7.8[−8]	2.9	3.3
^{151}Sm	76.3	7.53	*nu*	2.3[−10]	1.5[−10]	2.3[−9]	1.5[+1]	1.1[+1]
	54.8	9.13	*nu*	2.1[−12]	1.1[−12]	3.8[−11]		
^{155}Eu	252.7	8.78	*nu*	5.8[−10]	5.8[−10]	9.0[−10]	3.6	3.8
	192.7	8.57	*nu*	4.0[−10]	3.5[−10]	9.2[−10]		
	166.2	7.91	*a*	1.2[−9]	9.7[−10]	3.3[−9]		
	147.4	7.47	*a*	2.2[−9]	1.8[−9]	7.6[−9]		
	134.7	8.73	*a*	8.9[−11]	7.2[−11]	3.6[−9]		
	106.6	8.94	*nu*	2.7[−11]	2.0[−11]	1.6[−10]		
^{163}Dy	−2.8	(5.0)	*nu*	0	0	1.6[−7]	∞	∞
^{171}Tm	96.4	6.32	*nu*	1.1[−8]	7.6[−9]	1.0[−7]	1.6[+1]	1.2[+1]
	29.7	6.45	*nu*	2.3[−10]	4.0[−11]	2.3[−8]		
^{187}Re	2.64	(11.0)	*u*	5.1[−19]	0	1.4[−14]	∞	3.2[+9]
	−7.11	(7.5)	*nu*	0	0	1.6[−9]		
^{191}Os	141.3	5.32	*a*	5.2[−7]	4.0[−7]	3.4[−6]	8.5	7.4
^{193}Ir	−56.3	(7.5)	*nu*	0	0	1.6[−10]	∞	∞
	−57.9	(7.4)	*nu*	0	0	1.7[−10]		
	−76.5	(7.5)	*nu*	0	0	8.8[−12]		
^{205}Tl	−53.5	(12.0)	*u*	0	0	7.0[−17]	∞	∞
	−55.8	(5.4)	*nu*	0	0	6.6[−8]		
^{210}Pb	63.1	7.84	*nu*	1.9[−10]	7.7[−11]	7.5[−9]	1.1[+4]	8.5[+2]
	16.6	5.46	*nu*	8.0[−10]	0	8.3[−7]		
^{228}Ra	39.0	(6.5)	*a*	2.3[−9]	1.8[−10]	2.3[−7]	2.8[+4]	1.3[+3]
	14.7	(5.0)	*a*	1.5[−9]	0	4.9[−6]		
^{227}Ac	44.1	7.09	*nu*	5.4[−10]	9.8[−11]	7.2[−8]	2.0[+3]	2.6[+2]
	34.8	6.97	*nu*	3.5[−10]	2.9[−11]	8.3[−8]		
	19.6	6.75	*nu*	1.0[−10]	0	1.1[−7]		
^{241}Pu	20.8	5.79	*nu*	1.5[−9]	0	1.9[−6]	∞	1.2[+3]

electron created in the final atom. (Note that the electron rest mass is included in obtaining Q_n.) For example, the actual Q value for creating a K electron is

$$Q_n - [B_n(Z+1) - B_n(Z)] + B_K \ ,$$

where

$$B_K = m_e c^2 \{ 1 - [1 - \alpha^2 (Z+1)^2]^{1/2} \} \ .$$

In the case of ^{187}Re, the Q value becomes $2.64 - (15.34) + 85.79 = 73.09$ keV, which makes the bound-state decay to the 9.75 keV first excited state of ^{187}Os energetically possible.

D. Partial ionization

The results for highly ionized atoms are displayed in Figs. 1(a)–(1c) for some selected transitions.

Figure 1(a) shows the β transition rates for highly ionized ^{151}Sm and ^{191}Os versus the number of electrons bound to the initial nucleus. These represent the cases in which Q_n is relatively large, so that the bound-state decay contributions are appreciable only in very highly ionized cases.

Figure 1(b) presents the results for ^{187}Re, for which Q_n is as low as 2.64 keV. It explicitly shows that the continuum-state β^- decay (to the ground state of ^{187}Os) becomes energetically forbidden if ^{187}Re atoms are more than 47 $(=75-28)$ times ionized. An important observation[8] is that the transition to the 9.75 keV first excited state of ^{187}Os becomes energetically possible if $N_e(^{187}\text{Re}) < 10$. Since this is a nonunique first-forbidden transition, in contrast to the unique first-forbidden transition to the ground state, an enormous enhancement of the total β decay rate results. We have adopted a logft value of 7.5 for the unknown nonunique first-forbidden transition. This value was obtained[8] after a survey of the reduced matrix elements of transitions observed between the $\frac{5}{2}^+\frac{5}{2}$[402]p and $\frac{3}{2}^-\frac{3}{2}$[512]n Nilsson states. The absolute decay rate for this transition may be uncertain by a factor of 2 or so.

As one may expect, λ_b decreases monotonically with respect to N_e, except for the atomic shell closure effect. However, the peculiar behavior of λ_b for the unique first-forbidden transition in ^{187}Re needs some explanation. The reason for the increase of the decay rate from $N_e = 3$ to $N_e = 4$ is that the predominant contributions in both cases are coming from the creation of a $2p_{3/2}$ electron rather than a $2s_{1/2}$ or $2p_{1/2}$ electron. The Q values for such $2p_{3/2}$ transitions for $N_e = 3$ (the final atomic state is an excited state) and $N_e = 4$ (the final state is energetically close to the ground state) are 10.9 and 13.5 keV, respectively, explaining the slight increase of λ_b. Similar situations can be observed at the highest shell closures.

Figure 1(c) demonstrates that certain nuclei which are terrestrially stable might be used to observe the bound-state β decay process if they are highly ionized.

The astrophysical implications of bound-state β decays of some nuclei studied here are discussed elsewhere.[7–9]

III. EXPERIMENTAL PROSPECTS

A. Neutron

The simplest case, at least theoretically, would be that of neutron decay. However, the bound-state β decay of a neutron is expected to occur only four times per million decays.[2] Apparently, neither the direct measurement of the neutron half-life nor the indirect but more precise one (through the determination of the coupling constants)[26] can achieve that kind of accuracy, at least for some time to come.

B. Tritium

Probably the best candidate for detecting the bound-state β decay and testing the theoretical predictions is ^{3}H decay. The expected bound-state β decay contribution is 0.7% for neutral ^{3}H (Refs. 2 and 18) and 1.0% for $^3H^+$. Indeed, this level of effect could be readily detected in the storage ring experiment shown in Fig. 2. The experiment involves detection of the number of continuum-state decays of $^3H^+$ in one configuration, and of both bound-state (enhanced) and continuum-state decays in the other configuration. To estimate event rates, consider a ring about 100 m long with four 25 m straight sections, connected via 90° bending magnets of (assumed) negligible length, in which are stored tritium ions. A plausible (conservative) number of stored ions is 10^{10}. Assume that the tritium beam energy is 100 MeV. If an 18.6 keV antineutrino is emitted from a triton transverse to the beam direction, the ratio of transverse to longitudinal momentum for the triton after the decay will be 2.5×10^{-5}. This implies a spot size from the $^3He^+$ ions at the end of a 25 m flight path of less than 1 mm diameter.

Thus most of the $^3He^+$ ions produced by bound-state decay would continue around the storage ring, in the first configuration indicated in Fig. 2, until they hit the gas stripper at A; they would therefore not be detected at D. In the second configuration, they would be detected at D (with an enhancement factor of about 3) together with the $^3He^{2+}$ ions produced by continuum-state decay along the leg CD. The total event rate would be about 3.5×10^5 per day; one would be looking for a 2–3 % effect on top of that. This should be readily obtained within a day or two of running time.

Could a conventional accelerator beam line transmitting a $^3H^+$ beam be used for this experiment? While that may be possible, we feel the use of a storage ring has several major advantages. Because this experiment would probably be done by alternating short gas-stripper on and off runs, either the time stability of the beam is critical (a difficult task for an accelerator) or the beam current integration must be accurate to a fraction of a percent, also a difficult task. An alternative technique which could replace extremely precise beam integration would detect tritons scattered from a target to provide the beam intensity measurement. But beam spot motion on the target would render that means of beam integration to high accuracy difficult also, given that no slits

could be placed in the beam line to limit beam spot motion. Such slits would generate copious quantities of He ions which would, by themselves, make precision measurements impossible.

The beam intensity in a storage ring, by contrast, varies with a long decay constant; this could easily be combined with the data rates to correct for the variation in beam intensity with time of very high accuracy. Furthermore, such beams are inherently well defined and clean; thus no appreciable He ion backgrounds can be produced. Thus, we feel that the inherent advantages of the storage ring strongly suggest its use in achieving the precision necessary to provide a meaningful test of the theoretical predictions for bound-state β decay.

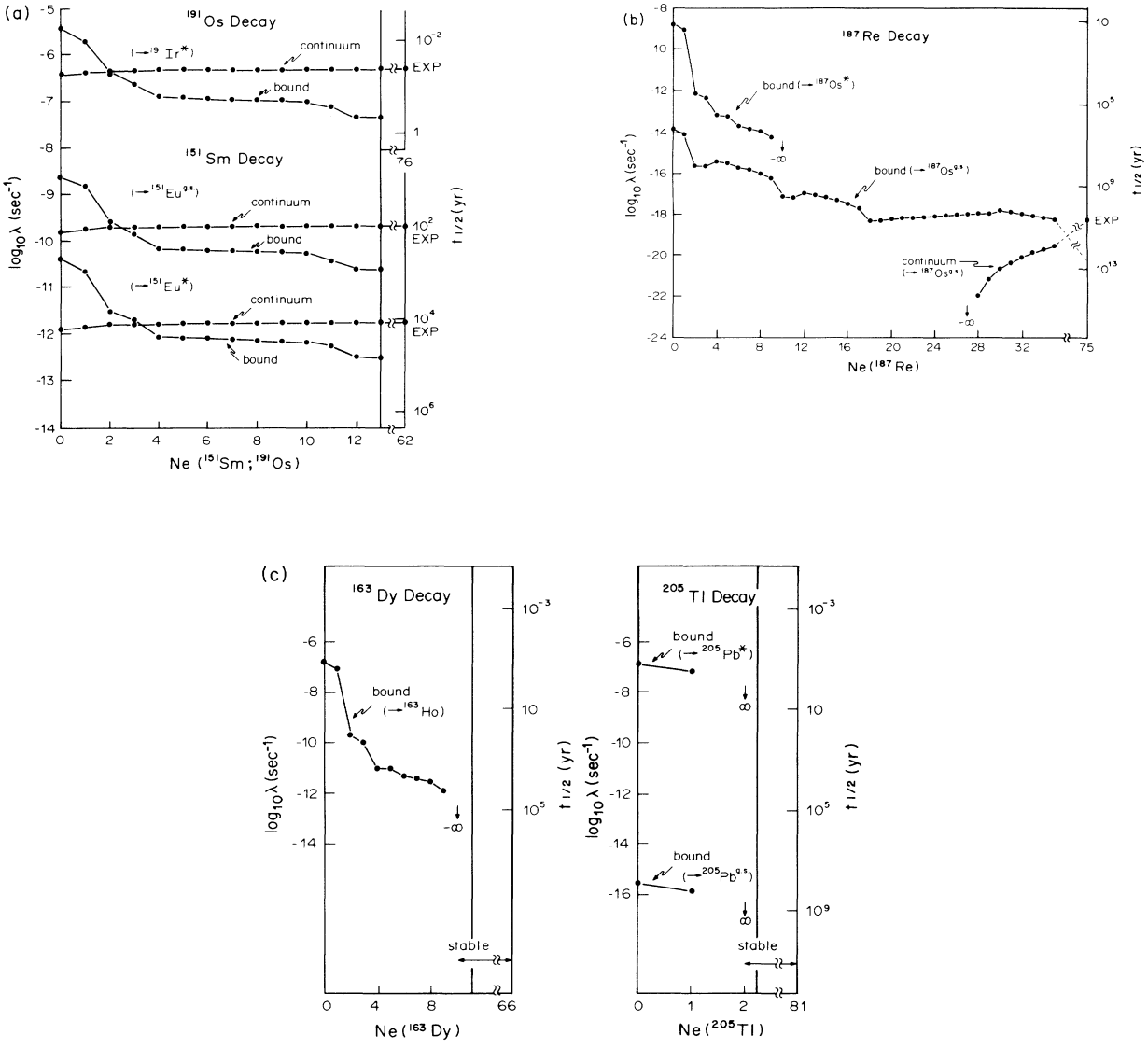

FIG. 1. (a) Logarithm of the bound-state and continuum-state β-decay rates (in $\sec^{-1}$), calculated for the nonunique first-forbidden transitions of ^{151}Sm and the allowed transition from ^{191}Os, vs the number of electrons bound to the *initial* nucleus, i.e., $N_e = Z -$(degree of ionization). The final nuclear states are ^{151}Eu(g.s.) and ^{151}Eu*(21.54 keV), and ^{191}Ir*(171.38 keV), respectively. The corresponding half-life $t_{1/2}$ (in yr) can be read on the right-hand-side scale. The laboratory values are indicated as EXP. (b) Same for ^{187}Re decay. The unique first-forbidden transition feeds the ground-state ^{187}Os, while the transition to ^{187}Os*(9.75 keV) is nonunique first forbidden. (c) Same for ^{163}Dy and ^{205}Tl decays. The allowed transition of ^{163}Dy is to the ground-state ^{163}Ho. The ^{205}Tl decays to the ground and first-excited (2.33 keV) states of ^{205}Pb are unique and nonunique first-forbidden transitions, respectively; for the latter (unknown) transition, $\log ft = 5.4$ is adopted (see Yokoi *et al.* in Ref. 9).

C. Heavy ion cases

As we have seen, several heavy ions would be expected to exhibit significant effects due to bound-state decay. For instance, fully ionized ^{163}Dy, ^{187}Re, and ^{205}Tl would decay only through the bound-state β decay process, with the expected half-lives of about 50 d, 14 yr, and 120 d, respectively. Heavy ion storage rings are expected to be able to store fully stripped heavy ions for extended periods of time; such facilities might be used in experiments similar to the one described above to measure the effects of bound-state β decay in heavier nuclei. It would probably be essential to use fully stripped ions for these studies, since the β decay events would otherwise be simulated by the background from electron charge exchange with residual gas in the storage ring. While the effect of the "analyzing magnet" would be considerably less dramatic for heavy ions separated in Z by one unit than for ^{3}H, a flight path consisting of the distance from the "analyzing magnet" to the next bending magnet in the ring would provide sufficient separation between beam ions and daughter ions. For example, in the hypothetical storage-ring discussed for ^{3}H, the 25 m separation between successive magnets (having pole faces normal to the stored beam) would provide a separation of 0.3 m between ^{187}Re and its (fully stripped) decay product ^{187}Os, a much longer separation than necessary to perform a clean separation. The only fundamental limitation on this technique occurs if the half-lives are so long that the corresponding event rates are too small. Even this would allow experimental tests on any nuclide with a half-life shorter than roughly 10^6 yr, assuming 10^{10} stored ions and a required event rate of 100 decays/d. This would allow measurement of many of the predicted half-lives listed in Table I.

A measurement of the β-decay rate of fully ionized ^{187}Re will be a precision test for theoretical predictions of the ^{187}Re decay rate in stellar interiors, which is one of the key (and uncertain) quantities in ^{187}Re-^{187}Os nucleon-cosmochronology. In addition, a measurement of the β-decay rate of fully ionized ^{205}Tl, and a determination of the ft value for its decay to the first excited state in ^{205}Pb thereof, will be very useful for the analyses of solar neutrinos with the planned ^{205}Tl detectors.

Finally, it should be noted that very recently Cohen *et al.*[27] have proposed a possible neutrino-mass measurement in the bound-state β decay of neutral ^{3}H by the use of laser spectroscopic techniques.

IV. CONCLUSION

Theoretical predictions for bound-state as well as continuum-state β decay rates of highly ionized atomic nuclei are presented. We have proposed a measurement of the bound-state β decay rates with the use of a storage ring, which will be most easily applied to, but is not restricted to, the decay of $^3H^+$.

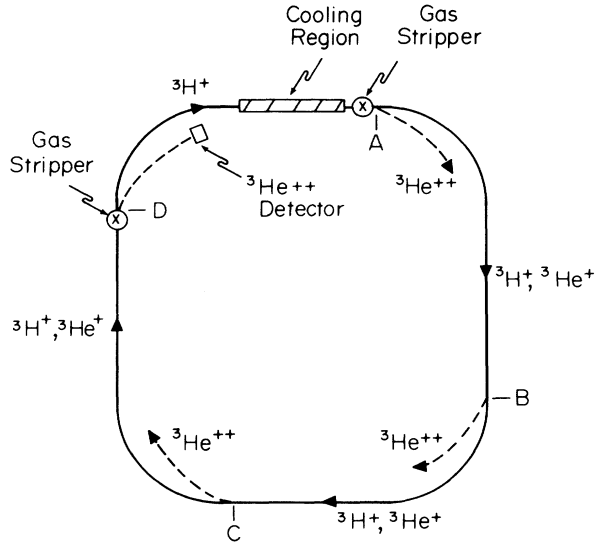

FIG. 2. Possible scheme for observing the bound-state β decay of $^3H^+$. Possible decays either to $^3He^{2+}$ (continuum-state decay) or $^3He^+$ (bound-state decay) begin at A, a gas stripper, which converts all ^{3}He ions to $^3He^{2+}$. Measurement (1): Stripper at D is off. Any $^3He^{2+}$ ions produced along AB will be removed at the magnet at B, any produced along BC will be removed at C, and any produced along CD will be removed and detected at D. Any $^3He^+$ ions produced along AB, BC, or CD will essentially track the $^3H^+$ beam, and so will not be detected. Measurement (2): Stripper at D is on. Any $^3He^{2+}$ produced along AB or BC will be deflected at B or C, respectively, so still will not be detected. Any $^3He^{2+}$ ions produced along CD will be detected at D. Any $^3He^+$ ions, the bound-state decay products, produced along AB, BC, or CD will essentially track the $^3H^+$ ions up to point D. At point D, however, they will be stripped to $^3He^{2+}$, so will be detected along with the $^3He^{2+}$ ions produced by continuum-state decay. Note that the products of bound-state β decay get enhanced by a factor of about 3 over the continuum-state β-decay products in this scheme, a helpful effect for the less abundant reaction product. Thus, the comparison of intensities with and without the stripper at D gives the fraction of the $^3H^+$ decays which go to $^3He^+$ bound states.

ACKNOWLEDGMENTS

The authors wish to acknowledge a helpful discussion with R. Pollock. This work was supported in part by the National Science Foundation under Grant PHY 8600749, the Ohio State University Office of the Vice President for Research and Graduate Studies, and by the U.S. Department of Energy under Contract No. W-7405-Eng-48.

[1]R. Daudel, P. Benoist, R. Jacques, and M. Jean, C.R. Acad. Sci. (Paris) **224**, 1427 (1947); R. Daudel, M. Jean, and M. Lecoin, J. Phys. Radium **8**, 238 (1947); C. R. Acad. Sci. (Paris) **225**, 290 (1947).

[2]J. N. Bahcall, Phys. Rev. **124**, 495 (1961).

[3]P. M. Sherk, Phys. Rev. **75**, 789 (1949).

[4]S. G. Cohen, Phys. Rev. **84**, 591 (1951); E. Galzentani, M. Marinaro, and S. Okubo, Nuovo Cimento **15**, 934 (1960).

[5]I. S. Batkin, Izv. Akad. Nauk SSSR, Ser. Fiz. **40**, 1279 (1976) [Bull. Acad. Sci. USSR, Phys. Ser. **40**, 149 (1976)].

[6]N. Gilbert, C. R. Acad. Sci. (Paris) **247**, 868 (1958).

[7]A. A. Joukoff, Astron. Astrophys. **3**, 186 (1965); Ph.D. thesis, Free University of Brussels, 1968 (unpublished); D. D. Clayton, Nature (London) **224**, 56 (1969); F. Perrone, Ph.D. thesis, Rice University, 1971 (unpublished); G. Hiergeist, Diploma thesis, University of Munich, 1976 (unpublished); J. Conrad, Ph.D. thesis, University of Heidelberg, 1976 (unpublished); J. Conrad and H. D. Zeh, Z. Naturforsch **33a**, 887 (1978).

[8]K. Takahashi and K. Yokoi, Nucl. Phys. **A404**, 578 (1983).

[9]K. Yokoi, K. Takahashi, and M. Arnould, Astron. Astrophys. J. **117**, 65 (1983); **145**, 339 (1985); M. Arnould, K. Takahashi, and K. Yokoi, *ibid.* **137**, 51 (1984); see also K. Takahashi and K. Yokoi, At. Data Nucl. Data Tables **36**, 375 (1987).

[10]R. D. Williams, W. A. Fowler, and S. E. Koonin, Astrophys. J. **281**, 363 (1984).

[11]Z. Chen, L. Rosenberg, and L. Spruch, Phys. Rev. A **35**, 1981 (1987).

[12]B. Hirt, G. P. Tilton, W. Herr, and W. Hoffmeister, in *Earth Science and Meteorites,* edited by J. Greiss and E. D. Goldberg (North-Holland, Amsterdam, 1963), p. 273.

[13]J. M. Luck and C. J. Allègre, Nature (London) **302**, 130 (1983); see also J. M. Luck, J.-L. Birk, and C. J. Allègre, *ibid.* **283**, 256 (1980).

[14]M. Lindner, D. A. Leich, R. J. Borg, G. P. Russ, J. M. Bazan, D. S. Simons, and A. R. Date, Nature (London) **320**, 246 (1986).

[15]R. L. Brozinski and D. C. Conway, Phys. Rev. **138**, B1368 (1965).

[16]J. A. Payne, Ph.D. thesis, University of Glasgow, 1965 (unpublished); see also F. J. Dyson, in *Aspects in Quantum Theory,* edited by A. Salam and E. P. Wigner (Cambridge University, London, 1972), p. 213.

[17]S. D. Naldrett, Can. J. Phys. **62**, 15 (1984).

[18]B. Budick, Phys. Rev. Lett. **51**, 1034 (1983).

[19]J. N. Bahcall, Phys. Rev. **129**, 2683 (1963); P. Benoist-Gueutal, C. R. Acad. Sci. (Paris) **230**, 624 (1950); Ph.D. thesis, University of Paris, 1953 (unpublished).

[20]R. Serber and H. S. Snyder, Phys. Rev. **87**, 152 (1951); T. A. Carlson, C. W. Nestor, Jr., T. C. Tucker, and F. B. Malik, *ibid.* **169**, 27 (1968).

[21]N. B. Gove and M. J. Martin, Nucl. Data Tables **10**, 205 (1971).

[22]A. H. Wpstra and G. Audi, Nucl. Phys. **A432**, 1 (1984).

[23]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).

[24]*Chart of Nuclides,* 5th ed., edited by W. Seelmann-Eggebert *et al.* (Kernforschungszentrum Karlsruhe, Karlsruhe, 1981).

[25]K.-N. Huang, M. Aoyagi, M. H. Chen, B. Crasemann, and H. Mark, At. Data Nucl. Data Tables **18**, 243 (1976).

[26]D. H. Wilkinson, Nucl. Phys. **A377**, 474 (1982).

[27]S. G. Cohen, D. E. Murnick, and R. S. Raghavan, Hyperfine Interact. **33**, 1 (1987).