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Proposal to the ISOLDE and Neutron Time-of-Flight Committee

NUCLEAR BINDING AROUND THE RP-PROCESS WAITING POINTS ^{68}Se AND ^{72}Kr

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Abstract

Encouraged by the success of mass determinations of nuclei close to the Z = N line performed at ISOLTRAP during the year 2000 and of the recent decay spectroscopy studies on neutron-deficient Kr isotopes (IS351 collaboration), we aim to measure masses and proton separation energies of the bottleneck nuclei defining the flow of the astrophysical rp-process beyond A ~ 70. In detail, the program includes mass measurements of the rp-process waiting point nuclei ^{68}Se and ^{72}Kr and determination of proton separation energies of the proton-unbound ^{69}Br and ^{73}Rb via β decays of ^{69}Kr and ^{73}Sr, respectively. The aim of the project is to complete the experimental database for astrophysical network calculations and for the liquid-drop type of mass models typically used in the modelling of the astrophysical rp process in the region.

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1) Introduction

The astrophysical rapid proton capture process (rp process) [1] is a part of the explosive hydrogen burning occurring during astrophysical events such as accretion in a close binary system. During the accretion a rapid nucleosynthesis is triggered and the burning starts as a hot CNO cycle. At high temperatures around $T_9 > 0.3$ it continues as rp process until the fuel for the nuclear burning is exhausted. The burning lasts about 10-100 s and the event is known as an X-ray burst. The rp process has been considered as possible means to produce the so-called p-nuclei around A = 90 -100 that are shielded by stable isotopes from being produced during standard process scenarios like the r- or the s-process. The path and rapidity of the process are mainly defined by the rates of beta decays and proton captures along the N = Z line. Thus, experimental data on beta-decay half-lives and, in particular, nuclear masses are needed for reliable modelling of the process path and resulting isotopic abundances.

In high temperature and density conditions of $T_9 > 1$ and $\rho > 10^4$ g/cm^2 the astrophysical rp process can proceed beyond A = 64 and Z = 32 [2] and may continue possibly up to A = 100 [3]. The speed of the process beyond A = 64 is defined largely by two waiting points along the process path at ^{68}Se and ^{72}Kr. These nuclei have long beta-decay half-lives of 35.5 and 17.2 s, respectively. If only one-proton captures are considered, the process is delayed by the beta-decay half-lives in these waiting points since the one-proton capture daughters ^{69}Br and ^{73}Rb are proton unbound. However, if the one-proton daughters live long enough to capture another proton i.e. if two-proton capture becomes possible, the effective lifetime of the waiting point can be significantly reduced [3]. This is illustrated in Fig. 1., taken from [3], where the total stellar half-life of ^{68}Se is plotted as a function of the proton capture Q-value for the first proton-capture reaction ^{68}Se(p,γ)^{69}Br. About 1 MeV difference in the Q-value induces 4 orders of magnitude difference in the total stellar half-life of this waiting-point nucleus. It is thus well justified to claim that these Q-values i.e. *the mass differences* are the most important parameters defining the rate of the rp process above A = 64.

There are several approaches to attack the existing uncertainties in these proton capture rates of the waiting point nuclei. Our aim is to use two of them. First is to measure directly the decay energies of the inverse proton decays of ^{69}Br and ^{73}Rb via beta decays of ^{69}Kr and ^{73}Sr, respectively. Another one is to collect a complete experimental database of nuclear masses in the vicinity of the waiting points and, using this information, tune the mass models to provide reliable estimates for the neighbouring masses and proton separation energies. In particular, experimental mass values for the waiting point nuclei ^{68}Se and ^{72}Kr will serve as basis for reliable modelling for the two-proton capture rates on these nuclei. We propose to use both of these approaches to significantly reduce these nuclear physics uncertainties in the modelling of the astrophysical rp process.

The region of interest is shown in Fig. 2) as a part of the nuclide chart. Measurements on the proton separation energies of ^{69}Br and ^{73}Rb will be performed using a sensitive method of detecting β-delayed protons with a high-efficiency detector array [4]. Absolute masses of ^{68}Se and ^{72}Kr will be determined by using the Penning-trap mass spectrometer ISOLTRAP [5, 6].

2) Beam production

In the following we describe the status of the production methods of the isotopes of interest and highlight the need of improvements where necessary. Presently, the minimum yield needed for a successful measurement with the ISOLTRAP mass spectrometer [5, 6], is about 1000 atoms/s. Provided that the measurements are performed at low background conditions the very sensitive proton spectroscopy can be exploited already with yields of about 1 atom/hour.

a) Production of Se isotopes

Beta decay of ^{68}Se had been studied at ISOLDE SC by P. Baumann et al. [7]. The ZrO_2 fiber target (thickness 6 g/cm^2) equipped with a "hot plasma" ion source MK5 gave 120 ions/μC in the molecular sideband ^{68}SeCO$^+$. However, the population of this molecular sideband was not necessary optimal since the carrier gas was produced indirectly by leaking O_2 into the ion source which oxidizes the hot graphite grid of the MK5 ion source. A more direct, and probably more efficient way is a direct feeding into the target of a well-defined flux of CO or CO_2. Systematic off-line studies at ISOLDE were started [8] and will be continued within the thesis work of Angélique Joinet. Moreover, the increase of the proton beam energy (from 600 MeV at ISOLDE SC to 1400 MeV at ISOLDE PSB) provides in this region a gain in cross-section of about factor of five.

In parallel we will study the performance of a Nb foil target. It allows to increase the target thickness by a factor of about eight (50 g/cm^2 instead of 6 g/cm^2). Since ^{68}Se has a relatively long half-life (35.5 s) the significant gain in production rate should outweight the possibly increased decay losses.

Together we are confident that a ZrO_2 fiber (or Nb foil) target + $CO_{(2)}$ gas leak + MK5 ion source will provide the required intensity of at least 1000 ions/s (with 2.5 μA proton beam in average).

a) Production of Kr isotopes

In the autumn 2000 experiment (IS384) the ^{72}Kr ions were produced with a rate >1000 ions/μC from a ZrO_2 fiber target (thickness 6 g/cm^2) equipped with a water-cooled transfer line and a MK7 ion source. During December 2000 a test was performed using three different proton beam energies (600 MeV, 1000 MeV and 1400 MeV) to study the energy dependence of the production rate of Kr isotopes from a Nb foil target with the same ion source. Fig. 3a) shows the observed yields from this test together with the yields measured in the IS351 experiment [9-11]. The difference between both measurements shows the typical scattering between "identical" target and ion source units.

Note that the release of krypton (like any noble gas) is mainly diffusion controlled and not affected by desorption delays. Thus, a thin foil Nb (2 μm) target should give for the most short-lived isotopes $^{69-71}$Kr a similar yield improvement which was observed for short-lived Li and Be isotopes from a thin foil Ta target [12, 13].

In summary (i.e. using a thin Nb foil target with 1.4 GeV protons and a MK7 source of "average" ionization efficiency), it can be concluded that at least an order of magnitude higher yields compared to the IS351 experiment are reachable. These yields will be sufficient to perform both, the mass determination of ^{72}Kr and the decay spectroscopy of ^{69}Kr.

b) Production of Sr isotopes

Pure beams of neutron-deficient Sr isotopes can be obtained in the molecular sideband SrF^{+} by using a fluorinated target [14]. The addition of CF_4 gas into the target helps moreover to reduce the desorption times and improves therefore the release of Sr [15]. This is essential to reduce decay losses in the case of short-lived isotopes like ^{73}Sr.

Fig. 3b) shows the production rates of Sr isotopes in the molecular sideband SrF^{+} using a 1 GeV proton beam onto a standard Nb foil target with tungsten surface ionizer. The extrapolation down to ^{73}Sr was obtained by using calculated production rates (full squares), correcting them for decay losses and normalizing the curve to the observed yield of ^{76}SrF^{+} [16]. As discussed before, also here a significant improvement is expected from a thin foil Nb target.

On the other hand, the normally strongly produced Rb isobars are no problem on mass 73 – ^{73}Rb being proton unbound [17]. Thus the experiment could also be performed with atomic ^{73}Sr^{+} ions which are produced by dissociation of SrF molecules in the hot tungsten cavity. Using the RILIS, the ionization efficiency of Sr+ could be further enhanced. An efficient ionization scheme for Sr is already known [18]. The only expected isobar ionized in a tungsten ionizer is ^{73}Ga. Due to the large mass difference between ^{73}Sr and ^{73}Ga (38 MeV), the latter could be suppressed almost completely even with a moderate resolving power of the HRS of 6000.

Based on the discussion above, we are planning to produce ^{73}Sr with a (thin) Nb foil target, equipped with a CF_4 gas leak and a tungsten surface ionizer. Using the HRS we will choose the optimum way to separate on-line, after having measured the yield of atomic Sr^{+} and molecular SrF^{+} ions.

3) Measurements of the ground-state proton-decay energies of ^{69}Br and ^{73}Rb

Recent observations on ^{69}Kr [19, 20] and ^{73}Sr [21] have confirmed the beta-decaying nature of these isotopes. On the other hand, the proton-unbound nature of ^{69}Br and ^{73}Rb has been confirmed in various experiments [17, 19, 22]. Previous attempts to measure the ground-state proton decay of ^{69}Br at ISOLDE via beta decay of ^{69}Kr [9] led to an improved information on the mirror beta decay of ^{71}Kr [10] and a first experimental value for the half-life of ^{70}Kr [11], also significant for the rp process. ^{73}Rb has been studied previously also at ISOLDE [17] and found proton-unbound.

The estimated decay scheme for ^{69}Kr based on ref. [20] is to be shown in Fig. 4). The decay scheme of ^{73}Sr is very similar. About 20% of the β decays of ^{69}Kr and ^{73}Sr should lead to the ground states in the proton emitter nuclei ^{69}Br and ^{73}Rb, respectively. Subsequently, the ground states decay by proton emission to the ground state of the daughters ^{68}Se and ^{72}Kr. These transitions are observable as distinct proton peaks of energies below 1 MeV. The mass difference of the proton emitter and the daughter can be deduced by measuring the energies of the emitted protons. In addition, the lifetimes of the states could be measured provided that the states live longer than a few ns. Note that 180 keV mass difference in the decay scheme between ^{69}Br and ^{68}Se is most likely too small since the upper limit for the half-life of the ground state was deduced to be <100 ns [19] leading to a mass difference of at least 450 keV. About 80% of the β decays in both ^{69}Kr and ^{73}Sr proceed through the IAS at about 4 MeV excitation energies in the proton emitter nuclei leading to protons emitted with about the same energies. The detection of these protons is crucial to identify the produced isotopes. In summary, we are aiming for detecting 100 protons due to the ground-state decay for both ^{69}Kr and ^{73}Sr.

a) Experimental setup

Since these measurements are relying on beta-delayed proton emission a high-efficiency and high-resolution detector for protons is required. A detector array providing nearly 50% detection efficiency is under construction at ISOLDE [4]. In its first version, it provides a 2π solid angle for protons with a 4π trigger detector for beta-particles. The detector will later be extended to a full 4π version. The radioactive ion beam is brought into the detector through a small aperture and implanted on a thin carbon foil. Particle identification, needed for resolving the low-energy protons below 1 MeV from β particles will be based on time-of-flight (TOF) of particles at low energies. At higher energies the identification is based on pulse shape analysis [23]. The low-energy threshold of the detector would be determined by the noise level of the individual detectors and the electronics. The threshold should be below 100 keV.

4) Masses of the waiting point nuclei ^{68}Se and ^{72}Kr

Figure 2 shows the region of interest and illustrates also the success of mass measurements performed at the ISOLTRAP mass spectrometer [5, 6] during the year 2000. The nuclei to be studied either by direct mass measurements or by beta-decay studies are marked with shaded grey squares. The masses of the isotopes marked with dark full squares were measured within an uncertainty of 5 to 30 keV in the measurements during the year 2000. The highlight of the measurements was the mass measurement of ^{74}Rb. The triple-trap mass spectrometer was tuned to be able to measure the mass for an isotope with a 65 ms half-life and a yield well below 2000 at/s. It should be noted that the mass of the next possible waiting-point nucleus for the rp process, ^{76}Sr, was also measured during the summer as a molecular ion ^{76}Sr^{19}F^{+}.

a) Mass of ^{72}Kr

During the summer 2000 mass measurements on $^{73-78}$Kr were performed at ISOLTRAP. It was not possible to measure the mass of ^{72}Kr due to limited time. Based on the previous experience we are confident that we are able to measure the mass of ^{72}Kr at ISOLTRAP within an accuracy of 5-10 keV provided that the measured yield from the December-2000 test can be reproduced.

b) Mass of ^{68}Se

In a recent CSS2 mass measurement at GANIL, the mass of ^{68}Se could be determined within an uncertainty of the order of 100 keV [24]. However, the value differs about 1.8 MeV from the value of the latest mass tabulation [25]. Based on the previous experience on measuring masses of molecular ions and the needed production rate of about 1000 at/s we are confident that, after proposed development work, we are fully capable of measuring the mass of ^{68}Se at ISOLTRAP within an uncertainty of 5-10 keV. Naturally, along the experiment, the masses of $^{69-71}$Se will be determined as well.

5) Summary and beamtime request

Measurement	Shifts	Beamline/Setup	Separator	Target/Ion source
Masses of $^{68-71}$Se	1 + 6	ISOLTRAP	GPS/HRS	thin Nb foil or ZrO$_2$ + Mk5 + CO$_2$ or CO addition
Mass of ^{72}Kr	1 + 3	ISOLTRAP	GPS/HRS	(thin) Nb foil + Mk7
Decay of ^{69}Kr	1 + 10	LA1/LA2 & βp array	GPS/HRS	thin Nb foil + Mk7
Decay of ^{73}Sr	1 + 10	LA1/LA2 & βp array	HRS	thin Nb foil + WSI(or RILIS) + CF$_4$
On-line calibrations	2	LA1/LA2 & βp array		
Total	**4 + 31**			

We propose to complete the experimental information for the nuclear mass surface around the waiting point nuclei ^{68}Se and ^{72}Kr using β-decay measurements and Penning trap mass spectroscopy at ISOLDE. The extended experimental database for masses would allow a more reliable adjustment of the nuclear mass models and modelling of the astrophysical rp process beyond A = 64. The beamtime request is given in the following table. The needed shifts for the stable beam tuning for the ISOLTRAP mass measurements and the tuning for the target and ion source parameters for the decay experiments are given separately. In total, we ask for 4 shifts with stable beams and 31 shifts with radioactive beams.

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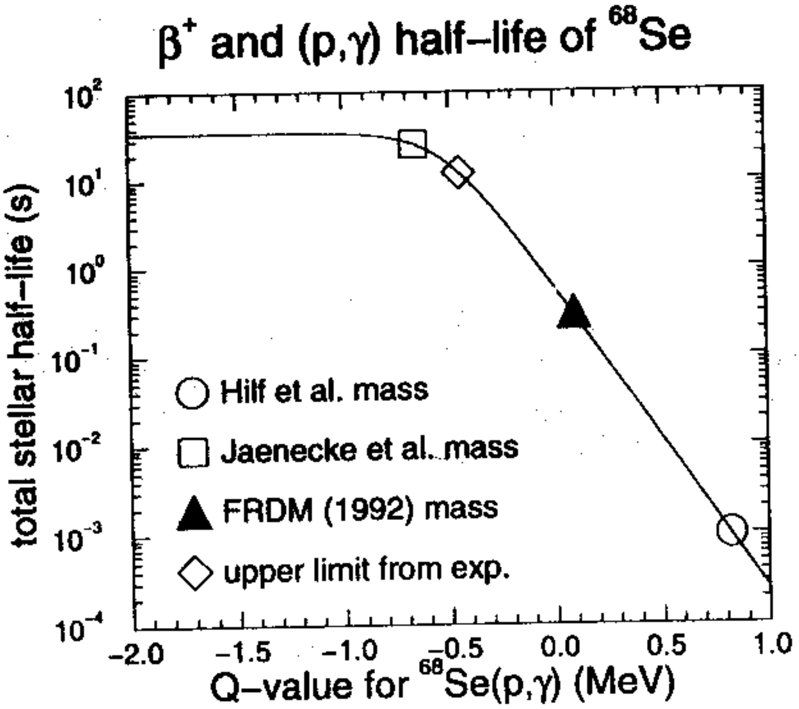

Figure 1. The stellar half-life of a waiting-point nucleus ^{68}Se as a function of the proton-capture Q value for the reaction ^{68}Se(p,γ)^{69}Br [3].

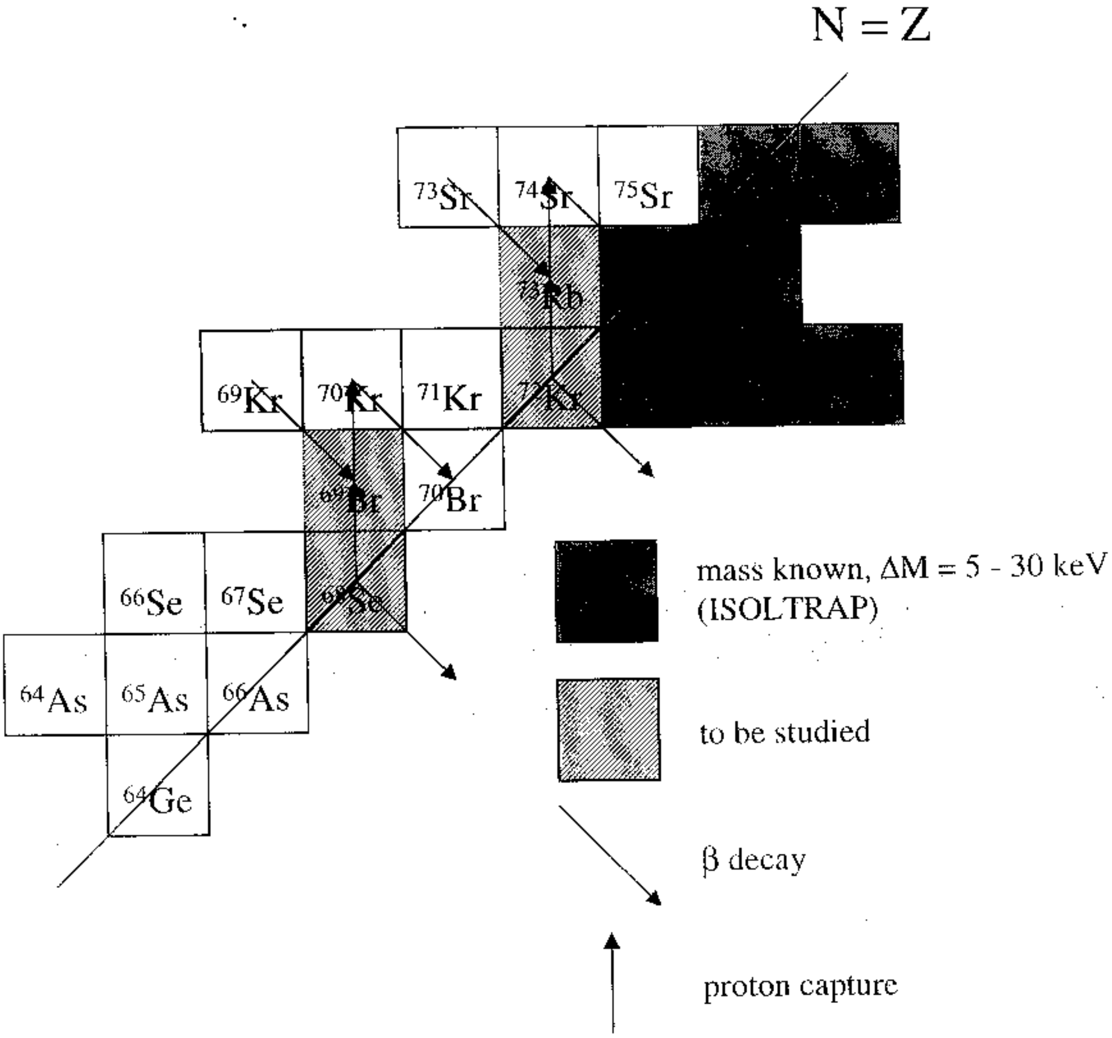

Figure 2) A part of the nuclide chart showing the region of interest. Full squares show the isotopes with known mass values studied at ISOLTRAP recently. The shaded squares show the isotopes to be studied in this work.

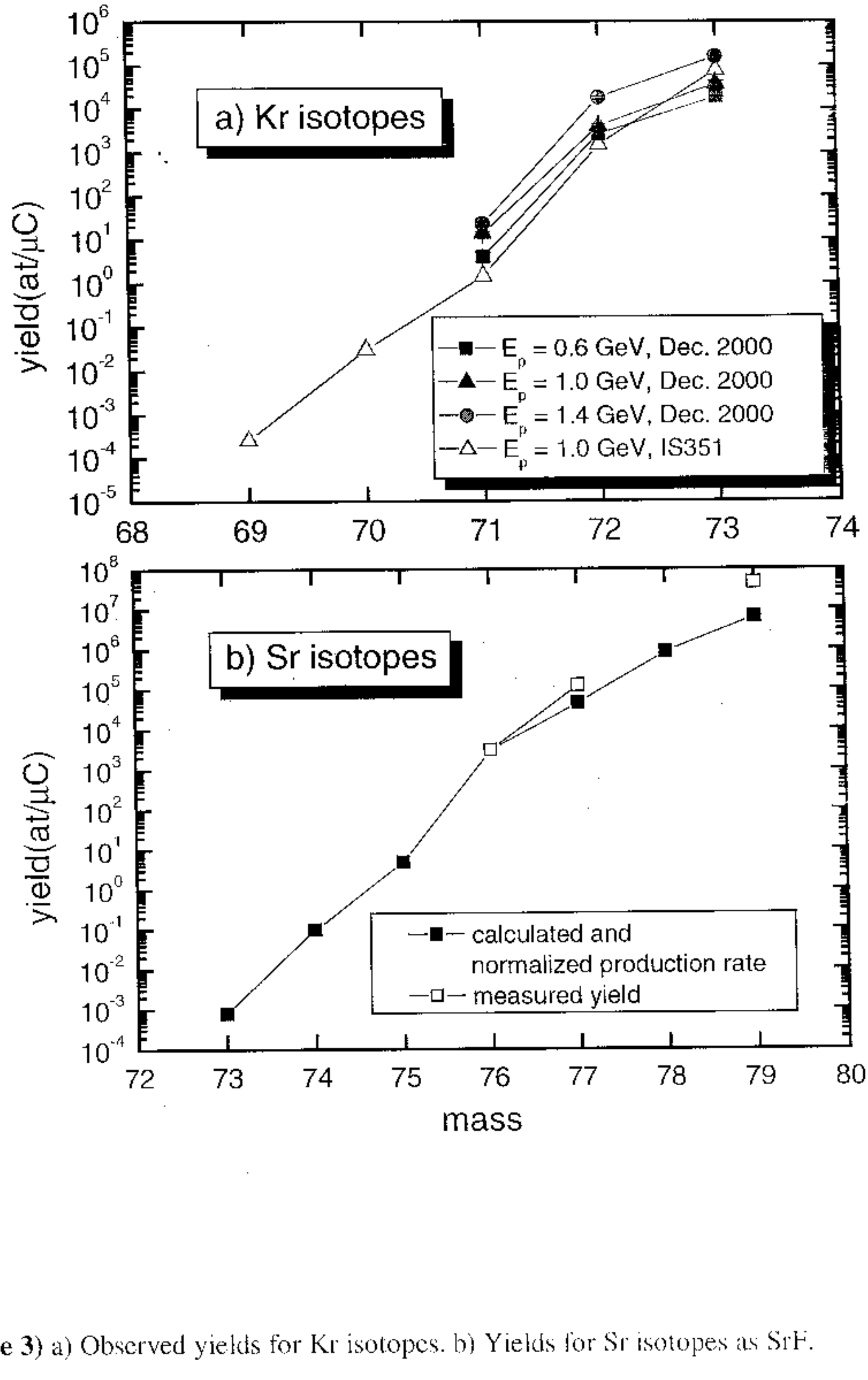

Figure 3) a) Observed yields for Kr isotopes. b) Yields for Sr isotopes as SrF.

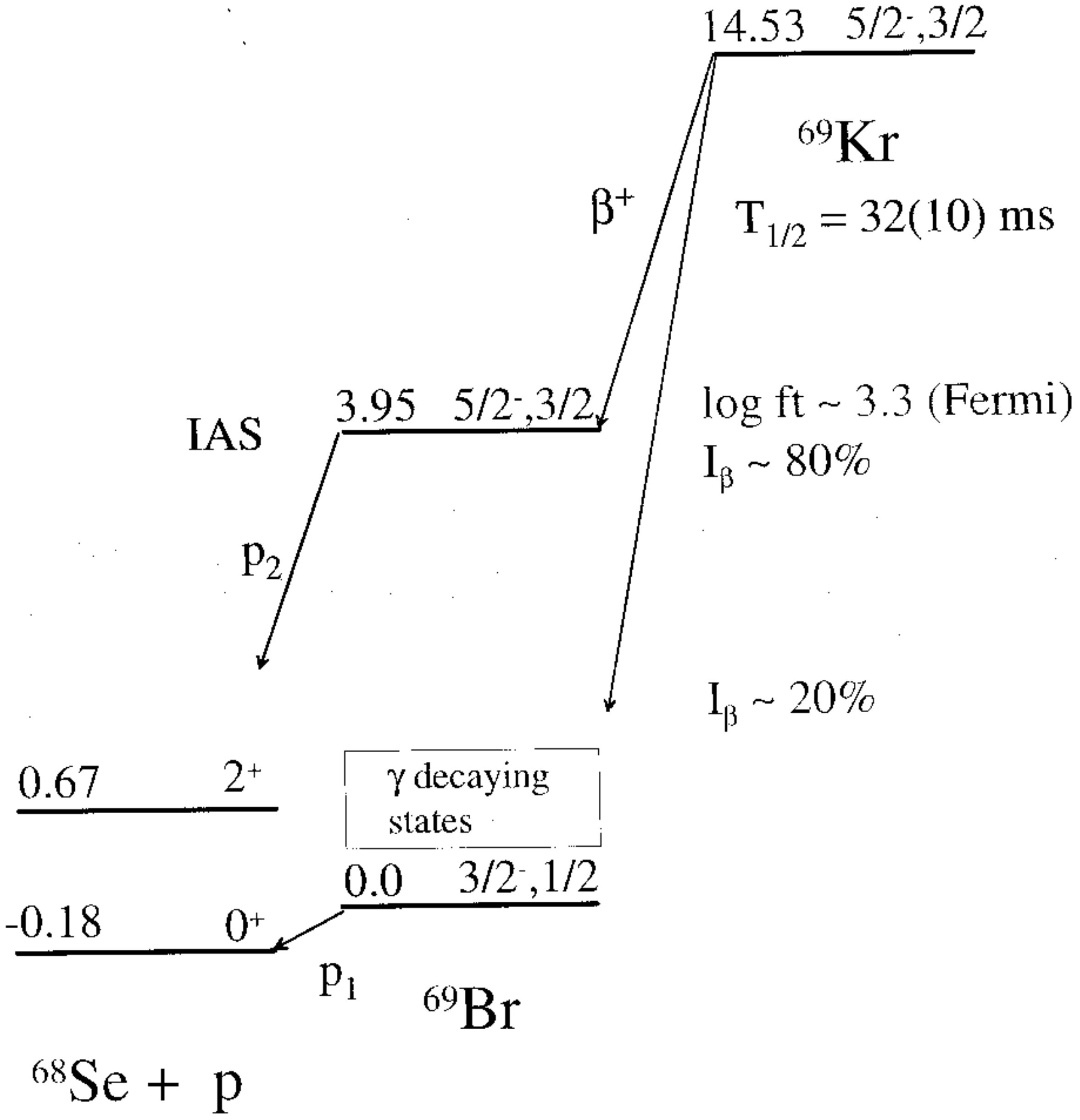

Figure 4) Estimated decay scheme of ^{69}Kr based on the measurement of Xu et al. [20] and assumed log ft values for Fermi and GT transitions. Note that the decay scheme of ^{73}Sr would be more or less equal.