EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the
ISOLDE and Neutron Time-of-Flight Experiments Committee
for experiments with HIE-ISOLDE

Masses of r-process waiting-point nuclides

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Abstract

The regions around possible waiting-point nuclei need to be studied to obtain valuable information for r-process models. In particular, masses around ^{80}Zn and ^{130}Cd need to be determined with high precision. Thanks to a sustained program of efficiency improvements, the mass measurements of ISOLTRAP have reached the region around the exotic waiting-point nuclides ^{80}Zn and ^{130}Cd. We intend to benefit from the complementary features of the HIE-ISOLDE energy upgrade – namely intensity and purification improvements of the ISOLDE facility – in order to determine the neutron-separation energies and shell gaps of these critical waiting points.

1. Introduction

The synthesis of over half of the heavy elements has its origin in the rapid neutron-capture process (r-process) [1]. However, it has yet to be determined where in the universe and under which astrophysical conditions this process occurs. Reliable nuclear data are needed to compare competing models with astronomical data and to allow for separating r-process from other nucleosynthesis components [2]. At neutron-shell closures the r-process is slowed down by so-called waiting-point nuclei, which have comparatively long half-lives with regard to β-decay. In addition to its importance for fundamental nuclear structure, the strength of these shell closures has a strong influence on the r-process path and hence, the heavy-element abundances. The determination of neutron separation energies (from direct mass measurements) is thus of capital importance for constraining r-process models. The isotopes ^{80}Zn and ^{130}Cd are prominent waiting points for which shell gaps are still missing.

2. Physics case

Recently, ISOLTRAP mass measurements of ^{80,81}Zn constrained the astrophysical waiting-point conditions resulting in a defined region of neutron density and temperature as a reliable input guiding r-process models [3]. The largest uncertainty, however, arises from the strength of the N=50 shell closure due to the unknown mass of ^{82}Zn. The uncertainty of the ^{82}Zn-mass extrapolation in [3] still governs the matter flow through ^{80}Zn.

Similarily, the waiting point ^{130}Cd is of special importance since the strength of the N=82 shell gap has been shown to have a strong influence on the number of neutrons available for fission – and subsequent re-cycling of the r-process [4]. This question is particularly interesting since the hypothesis of a quenched N=82 shell has long been cited as a possible cure for the heavy-element-abundance deficits of models [5]. For ^{130}Cd, β- and γ-spectroscopic decay studies have already been performed at ISOLDE with the highest achievable isotopic selectivity [6]. This nuclide was also the subject of the ISOLTRAP proposal INTC-P-160. The mass of ^{130}Cd together with its more neutron-rich neighbors ^{131,132}Cd needs to be measured precisely to derive the shell gap and hence, the dynamics of this waiting point.

The HIE-ISOLDE upgrade will improve the yields on the nuclides of interest [7]. Together with high-resolution mass separation improvements at ISOLDE as well as further improvements of ISOLTRAP, these important measurements will become feasible.

3. Experimental setup

Precision mass measurements with a relative uncertainty reaching 10^{-8} are routinely achieved with the pioneering Penning trap mass spectrometer ISOLTRAP – permanently installed at ISOLDE. It consists currently of three parts: a radio-frequency quadrupole (RFQ) ion trap for beam preparation and two Penning traps [8]. The linear, gas-filled RFQ ion trap cools the 60 keV continuous ISOLDE beam via buffer gas cooling. Furthermore, the ions are accumulated and leave the so-called buncher as ion bunches towards the preparation Penning trap where contaminants are removed with a resolving power of up to 10^5. The ions are then transferred to the second, precision Penning trap for the mass measurement. The time-of-flight detection technique is employed to determine the frequency of an ion stored in a Penning trap, from which the mass can be extracted in conjunction with a reference mass measurement. ISOLTRAP has studied nuclides with half-lives below 100ms and production yields of only a few hundred ions per second and can be used without major modifications or change in infrastructure to measure the mass of ^{82}Zn.

Currently, a fourth trap is implemented into the experimental setup of ISOLTRAP. This complements the developments of HIE-ISOLDE with regard to the ^{130}Cd measurements by better coping with Cs contamination. Located between the buncher and the preparation Penning trap, the electrostatic-mirror trap aims at further purifying the ISOLDE beam before it reaches the preparation trap. First tests have demonstrated a mass resolving power of more than 80,000 [9].

4. Beam requirements

In the past, ISOLDE could deliver a yield of about 10 ions/µC (PSB, 50 g/cm^2 UC_x target) for ^{82}Zn ($t_{1/2} \approx 100$ ms) [10]. Since 2005, developments were made to suppress contamination by isobaric Rb, which has a yield of over 10^7 ions/µC. A neutron converter reduces direct nuclear reactions of protons with the actinide material and a 700 °C quartz transfer line freezes out Rb and Ga isobars [11,12]. Furthermore, the ions of interest are selectively ionized by a laser. With these developments, yields of 80 ions/µC (^{82}Zn), 2000 ions/µC (^{82}Ga), and 5×10^6 ions/µC (^{82}Rb) were measured. However, the spectrometer ISOLTRAP could not yet cope with the delivered ^{82}Zn because of a still too high contamination ratio combined with a too low production yield. Here, HIE-ISOLDE is primarily needed to improve the yield on ^{82}Zn, where an improvement of a factor of six is expected, i.e. 480 ^{82}Zn particles per second [13]. However, ISOLTRAP would also benefit from a further suppression of rubidium contaminants.

Test measurements involving a neutron converter and a colder (300 °C) quartz line yielded values for ^{128}Cd, from which the values for ^{130,132}Cd can be extrapolated [13]. For ^{130}Cd ($t_{1/2}$ = 162 ms), the yield lies around 10^3 ions/µC, for ^{132}Cd ($t_{1/2}$ = 97 ms) 1 ion/µC with ^{131}Cd ($t_{1/2}$ = 68 ms) lying somewhere in between. The ^{130}Cs contamination measured was almost 10^6 ions/µC. Other isobars are estimated at <10 ions/µC (^{130}In), << 1 ion/µC (^{132}In), and >10^6 ions/µC (^{132}Cs) [13]. In this case, the expected increase of a factor of 6 for going from yields to particles per second needs to be combined with mechanisms to further suppress isobaric contaminants. Here, developments such as the GdB_6 low-work-function cavity and the LIST trap should be pushed towards implementation.

5. Safety aspects

There are no further safety aspects to be considered than the once currently installed at ISOLTRAP.

6. References

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