Isotope production comparison at ISOLDE with 1 GeV and 1.4 GeV protons

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The difference in isotope production between 1 GeV and 1.4 GeV proton projectiles was investigated at ISOLDE/CERN during the year 1999. As target materials Uranium Carbide, Thorium Carbide, Lead and Lanthanum Oxide were used and the ratio of the measured production yields for the two different projectile energies were determined for isotopes of the elements Francium, Mercury, Thallium, Xenon, Cesium, Krypton, Rubidium and Neon. A comparison of these experimental results with the predictions from a two-step reaction model Monte-Carlo code shows good agreement.

Key words: Production cross sections, Yields, ISOL technique, Evaporation, Fission, Intranuclear Cascade Model
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1 Introduction

Radioactive Ion Beams may be produced in ISOL systems by proton spallation of thick targets, from which the radioactive species are released, ionized, mass

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separated and if needed post accelerated. The quantity of foremost interest is the yield related to the proton current at different kinetic energies for a requested isotope and given target and ion source combination.

After CERN's PS-BOOSTER has been upgraded in energy from 1 GeV to 1.4 GeV in 1998 it has become possible in 1999 to use protons with both energies for the isotope production at ISOLDE and first measurements have been performed for Uranium Carbide, Thorium Carbide, Lead and Lanthanum Oxide as target material. The production yields were determined for isotopes of the elements Francium, Mercury, Thallium, Xenon, Cesium, Krypton, Rubidium and Neon. A strait forward theoretical description of the measured yields is not easily accessible as not only the nuclear reaction cross sections have to be considered but also atomic processes in the target and ion source. Nevertheless, a reliable theoretical description is desirable in order to predict optimized technical scenarios for the production of radioactive ion beams for future radioactive beam facilities [1].

A common method to estimate cross sections and determine yields is the use of semiempirical formulae that work reasonably for isotopes not too far from the cases where measurements are available. However, for more exotic species the extrapolation often leads to a non satisfactory degree of uncertainty.

In this work, a systematic study of measured yields with protons of 1 GeV and 1.4 GeV is conducted. Ratios of the measured yields are compared with ratios of calculated production cross sections of the intranuclear cascade model CASCABLA, which has been successfully applied to projectile fragmentation of heavy nuclei, as discussed in chapter 2 below.

2 Survey of production yield ratios

2.1 Measurements

Cross section information being comparable with the results of theoretical calculations is not easily accessible from our yield measurements due to the fact that the measured yields should be unfolded with the diffusion and effusion in the target and the resulting decay losses as well as the ionization efficiencies of the ion source. Yield ratios , for the two different proton energies have been chosen instead where in a first order approximation all these effects cancel out:

$$, = \frac{\mathrm{Yield}_{1.4\,\mathrm{GeV}}}{\mathrm{Yield}_{1.0\,\mathrm{GeV}}}\Bigg|_{\mathrm{measured}} \approx \frac{\sigma_{1.4\,\mathrm{GeV}}}{\sigma_{1.0\,\mathrm{GeV}}}\Bigg|_{\mathrm{CASCABLA}} \qquad (1)$$

The production rate of the isotopes investigated here vary from a few ions per second far from β-stability up to several nA at the production peak. The measuring procedure was adapted accordingly:

- Beams down to 10^8 particles per second were measured in a Faraday-Cup during continuous proton bombardment of the target.
- For beams too weak for a Faraday-Cup measurement a release curve [2] was recorded after single proton pulses of up to 3.2×10^{13} protons by implanting the produced ions into a tape and counting their decay particles with a scintillator.
- For very weak beams of neutron emitters a neutron detector was used integrating the neutron counts over several hundred proton pulses.

All measurements for one target were performed for both energies consecutively so that target and ion-source parameters remained unchanged. Note, that the target materials weren't isotopically pure while for the calculations the most abundant isotope was used.

2.2 The CASCABLA Monte-Carlo code

The Monte-Carlo Code CASCABLA [3,4] has been successfully applied to describe production cross sections for peripheral collisions of relativistic heavy-ions and protons e.g. 800 $A \cdot MeV$ ^{197}Au projectiles impinging on a hydrogen target at GSI, Darmstadt [5]. The code considers a two-step process, first an intranuclear cascade [6] to calculate the number of nucleons removed from the target in the nuclear collision and the excitation energy of the remaining excited nucleus (prefragment) and then an ablation stage where these prefragments either evaporate neutrons, protons, or alpha particles or undergo fission. The description of the fission process is based on the saddle-point model described in [4] and evaporation from the fission fragments is included as well.

Prefragments are located around the mean line of constant Z/A in the chart mainly caused by the uncorrelated removal of either neutrons or protons in a sudden process reflecting the geometrical overlap between target and projectile in the collision. The general effect of going to higher proton energies is an extended population of the evaporation-residue corridor towards lighter nuclei which is situated on the neutron deficient side of the valley of β-stability, where evaporation of protons and neutrons is equally probable. This also leads to a depopulation of fission events on the neutron rich side for medium masses because the related number of fissioning nuclei decreases. The higher excitation energy of prefragments causes in addition an increase in the production of low mass nuclei in the evaporation-residue corridor. However, we anticipate that rather light reaction products ($A \leq 30$) are formed in more central collisions, where multifragmentation can be a significant reaction mechanism. Therefore, the description based on the intranuclear cascade might be only a crude approximation.

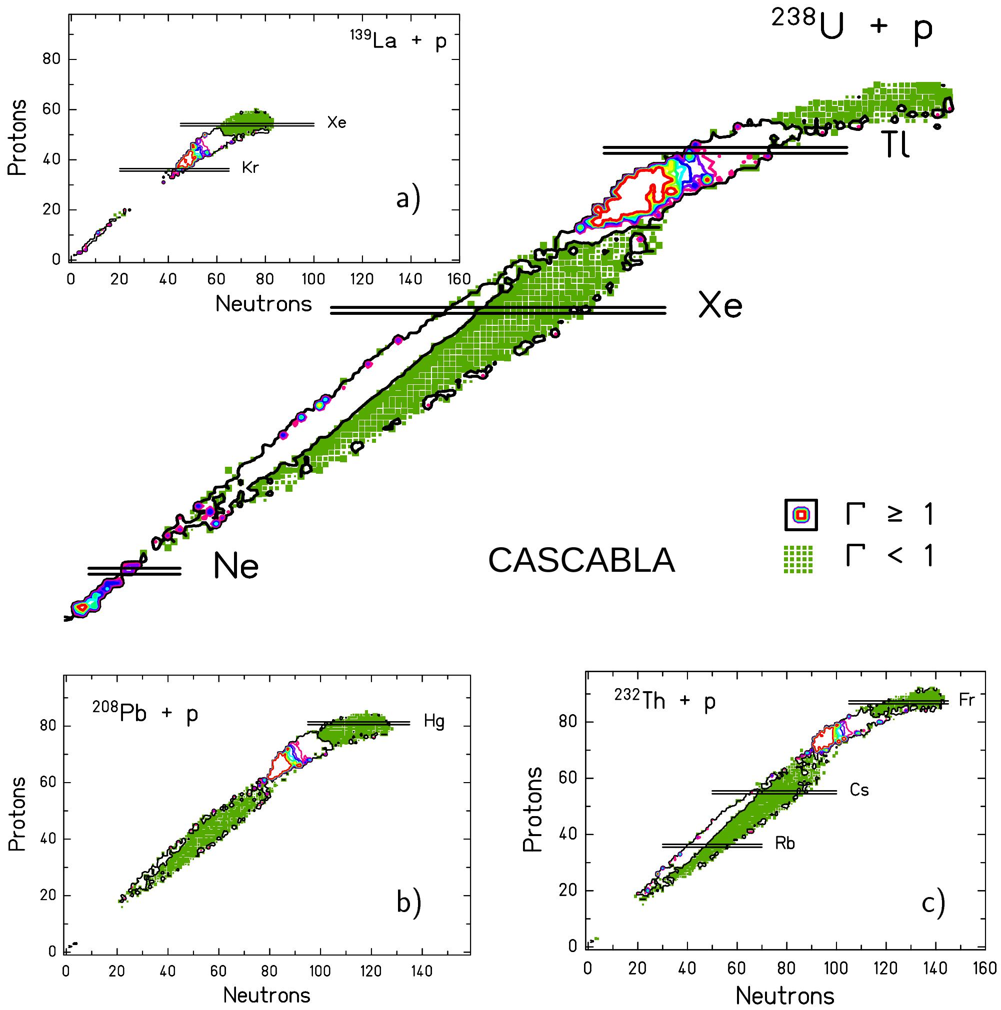

Fig. 1. Calculated cross section ratios for ^{238}U, ^{139}La (a), ^{208}Pb (b) and ^{232}Th (c) as target material are shown on a chart of nuclides. The dark area denotes ratios $\Gamma < 1$ where lower proton energies are favored in terms of production of these isotopes whereas the white areas with contour lines mark nuclides with Γ going from 1 to 8 and an increased yield should be expected. The black horizontal lines indicate the isotopic chains for which a direct comparison between the calculation and the available experimental yields from the ISOLDE mass separators was done. The results are discussed in the text.

The typical time needed for a CASCABLA run of about 5 *h* for 300.000 events on a state of the art workstation limits the calculation to a minimal cross section in the order of a few tenth of a *mb*. Fig. 1 shows nuclear charts with the calculated cross section ratios.

For the elements discussed, the range of isotopes for which CASCABLA results are statistically significant corresponds roughly to the range practically measurable at ISOLDE. Deviations from a otherwise smooth dependence in the calculation at these boundaries result from reaching the limit where a too small number of generated events was used to calculate the cross section ratios. However, the scope of both the model and the measurement could be extended by increased calculating and measuring time, respectively.

2.3 The Uranium target data

For the test measurements with Uranium as target material two different target/ion-source units were used: For the Thallium data target unit UC_2 #163 with a Tungsten surface ionizer and a target thickness of 46 g/cm^2 of Uranium

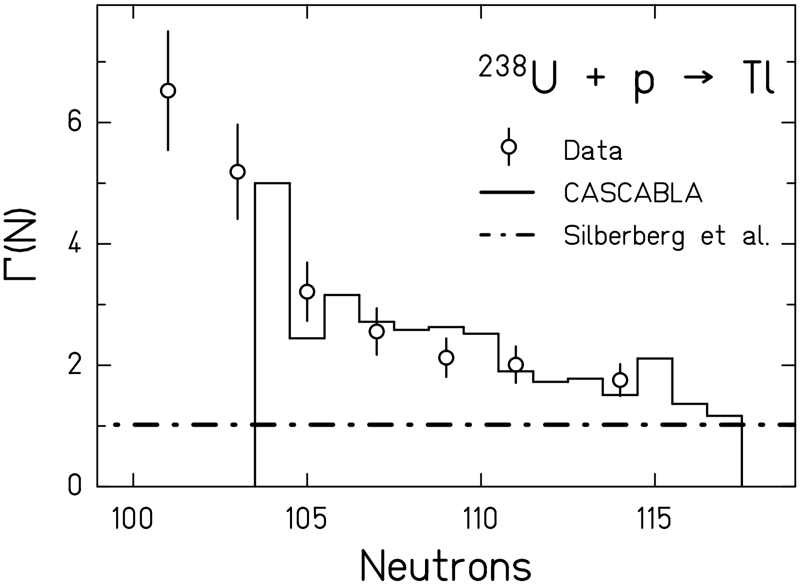

Fig. 2. Thallium isotope production yield ratios , obtained with a Uranium Carbide target (data points). The histogram shows the result of the CASCABLA code. The dashed-dotted line indicates the values for the cross section ratios obtained with the Silberberg and Tsao [7,8] calculation. The ratio remains constant at a value of 1.02 and is clearly in disagreement with the measured data.

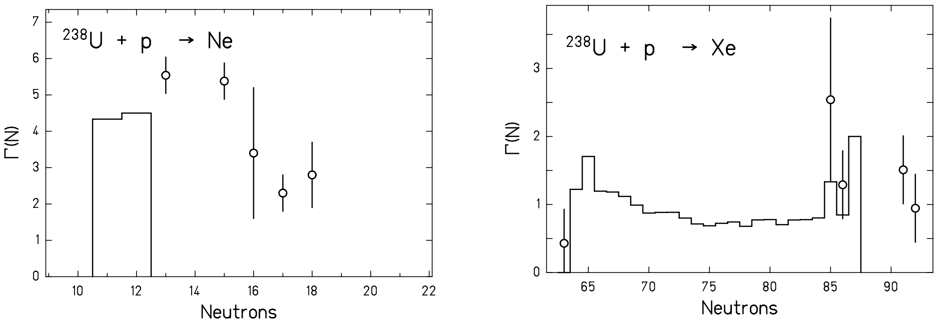

Fig. 3. Neon (left) and Xenon (right) isotope production yield ratios , from a Uranium Carbide target. The histogram shows the results of the CASCABLA calculation.

was used. For the noble gases unit UC_2 #159 was used with a cooled transfer line between the target container and the ion source, which allows a very efficient suppression of non gaseous isobaric beam contaminants. Here the target thickness was 52 g/cm^2 of Uranium.

The yield ratios for the production of Tl, Ne and Xe isotopes are shown in figs. 2 and 3. The Tl measurement was initiated by the results of the CASCABLA calculation. Thallium is the element closest to the region where the predicted increase should be highest, which unfortunately is not easily accessible due to the limited release of the elements Ta to Hg from UC_2 and ThC_2 targets. The agreement with the data is good and the calculation describes correctly the observed trends even if it does not cover the whole range of observed thallium isotopes. At both the neutron-deficient and neutron-rich side the cross sections drop nearly exponentially and require much longer computation time for CASCABLA to predict. The Silberberg & Tsao systematics [7,8] however does not at all reflect the observed dependency on neutron number.

For Ne and Xe the situation is less conclusive even if the general trends for the ratios are described satisfactorily, see fig. 3. Especially for the Ne isotopes it would be desirable to get hands on the production mechanism to improve the description for these processes that may not be assigned to pure evaporation or fission events.

2.4 The Thorium, Lead and Lanthanum target data

The Thorium Carbide target/ion-source unit ThC_2 #151 was of the same type as UC_2 #163 except that the target container was a factor 2 longer leading to a target thickness of 87.5 g/cm^2 of Thorium. The Lanthanum Oxide

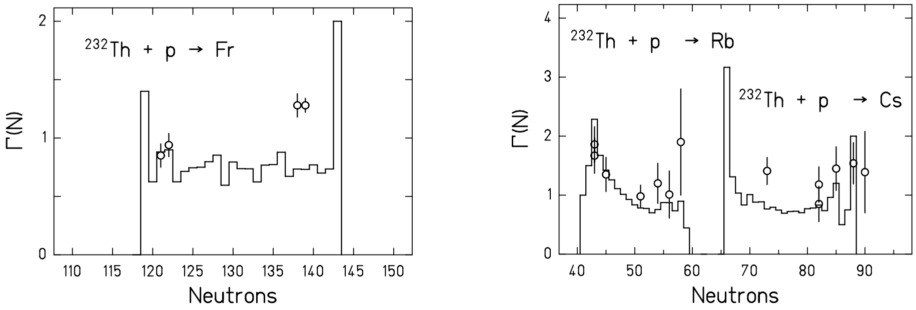

Fig. 4. Francium (left), Rubidium and Cesium (right) isotope production yield ratios , from a Thorium Carbide target. The histogram shows the result of the CASCABLA code.

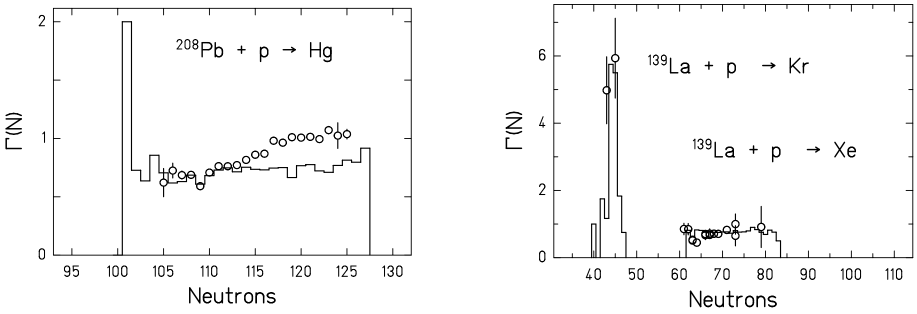

Fig. 5. Mercury from Lead (left), Xenon and Krypton from Lanthanum (right) isotope production yield ratios , . The histogram shows the result of the CASCABLA code.

target/ion-source unit La_2O_3 #161 which was equipped with a cooled transfer line like UC_2 #159 and also used for the production of noble gas beams, had a La thickness of 64.2 g/cm^2. The Lead target/ion-source unit Pb #116 is a different type compared to the other units already discussed as it is a liquid metal target. This gives a much higher density inside the target and leads to a thickness of 227 g/cm^2. The ion source is a hot plasma type connected via a special transfer line that inhibits droplets of the target material entering the ion source. The development of these units is described in [9]. The Lead is heated up to 600 °C, which is rather cold compared to other target materials. This combined with the high density of the target material leads to non negligible additional heating by the proton beam, which was compensated by ohmic heating since it is different for the two proton energies.

The ^{232}Th target calculation shows a behavior very similar to the ^{238}U case (see fig. 1 (c)), where both fission and evaporation residues can be observed.

The obtained results for ^{139}La and ^{208}Pb show cases where fission plays a minor role for the production process. These data can be used to check separately the evaporation code in the model. The isotopic chains in the mid-mass region reflect nicely the shuffling from the neutron-rich to the proton-rich reaction products as can be seen especially in fig. 4 for Rb. The calculations and the measured data are in agreement within the error bars. However, the Fr and Hg production yield ratios from the Th and Pb target respectively differ substantially from the model predictions in the vicinity of the target nuclei. This could be assigned either to the neglected energy loss in the target or to a drawback in the Cugnon cascade that shows systematically deviations for products close to the target nucleus. Further studies with a complete mapping of different isotope chains as shown in fig. 5 for the Hg isotopes would be needed to understand in more detail these deviations. Additionally the used thin target approximation could be replaced by an numerical integration over a set of calculations with different proton energies depending on the depth related energy loss within the target material.

3 Summary

The measured dependency of the isotope production on the energy of a primary proton beam are generally in very good agreement with predictions from the Monte-Carlo code CASCABLA. The results clearly show that a careful choice of the projectile energy is an important parameter for an optimized production yield of radioactive isotopes and that with CASCABLA a very powerful tool is available allowing reliable theoretical calculations of production cross sections for a wide range of the nuclear chart only lacking the region of light elements very far from the target nucleus, where central collisions dominate the production process.

At ISOLDE the measurements of the energy dependence will be continued for further target materials and isotopes. Also tests with a 600 MeV proton beam are foreseen as well as attempts to correct the CASCABLA calculations for the energy loss dE/dx of protons in thick ISOLDE targets.

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