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The upgraded ISOLDE yield database - A new tool to predict beam intensities

J. Ballof[a,b,*], J.P. Ramos[a,e], A. Molander[a,c,d], K. Johnston[a], S. Rothe[a], T. Stora[a], Ch.E. Düllmann[b,f,g]

[a] *CERN, 1211 Geneva 23, Switzerland*
[b] *Johannes Gutenberg - Universität Mainz, Institut für Kernchemie, Fritz-Strassmann-Weg 2, 55128 Mainz, Germany*
[c] *University of Helsinki, FI-00014 Helsinki, Finland*
[d] *Helsinki Institute of Physics, P. O. Box 64, FI-00014 Helsinki, Finland*
[e] *KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*
[f] *GSI Helmholtzzentrum für Schwerionenforschung, 64291, Darmstadt, Germany*
[g] *Helmholtz-Institut Mainz, 55099 Mainz, Germany*

Abstract

At the CERN-ISOLDE facility a variety of radioactive ion beams are available to users of the facility. The number of extractable isotopes estimated from yield database data exceeds 1000 and is still increasing. Due to high demand and scarcity of available beam time, precise experiment planning is required. The yield database stores information about radioactive beam yields and the combination of target material and ion source needed to extract a certain beam along with their respective operating conditions. It allows to investigate the feasibility of an experiment and the estimation of required beamtime. With the increasing demand for ever more exotic beams, needs arise to extend the functionality of the database and website not only to provide information about yields determined experimentally, but also to predict yields of isotopes, which can only be measured with sophisticated setups. For the prediction of yields, in-target production and information about release properties of target materials must be known. While the former were estimated in a simulation campaign using FLUKA and ABRABLA codes, the latter is available from measurement data as already stored in the database. We have compiled the information necessary to predict yields, and made available a yield prediction tool as web application. This currently undergoes extensive testing and will be available as powerful tool to the ISOLDE user community.

Keywords: CERN, ISOLDE, Radioactive Beams, Database, Yields, Yield Prediction, Cross sections, FLUKA, ABRABLA, Release efficiency, Production Yield, In-target production
PACS: 29.25.Ni, 29.25.Rm, 29.27.a, 29.50.+v, 13.85.Lg, 07.05.Tp

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1. Introduction

The ISOLDE facility is one of the oldest experiments at CERN and has been continuously upgraded over the years [1]. Today, it offers online production, extraction and separation of more than 1000 radioisotopes of 74 different chemical elements from thick targets, which are typically made of pressed powders, metallic foils, or molten materials. Within the target and ion source unit, the target materials are enclosed in a tantalum container, and are coupled to a transfer line and ion source, which are also selected out of a variety of different types of sources and lines.

In earlier days, a comprehensive collection of yield data was available in the ISOLDE Users' guide compiled by H.-J. Kluge [2]. Later, an online yield database was developed to provide information about yields to users and technical teams [3, 4, 5]. It is now fully redesigned, upgraded using state-of-the-art technologies, extended in its functionality and new yield data were included. The database and web application [6] not only store experimental yield information, but also provide release properties, in-target production cross sections estimated by means of time consuming and computationally expensive Monte-Carlo simulations and algorithms to predict yields of isotopes which have not yet been measured.

2. Beam Production at ISOLDE

The isotope extraction and beam production from thick targets is a multistage process. The radioisotopes are produced upon impact of the primary 1.4-GeV proton beam on a target material. The atoms then need to diffuse out of the target material and into the ion source,where they are ionized, extracted electrostatically and transported ion optically to an electromagnetic dipole for separation by mass to charge ratio..

An efficiency is associated to each step of the process. The first factor contributing to the radioactive ion beam yield Y is the in-target production N_0. Efficiencies for beam transport to the focal plane of the magnet, ioniza-

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*Corresponding author
Email address: `Jochen.Ballof@cern.ch` (J. Ballof)

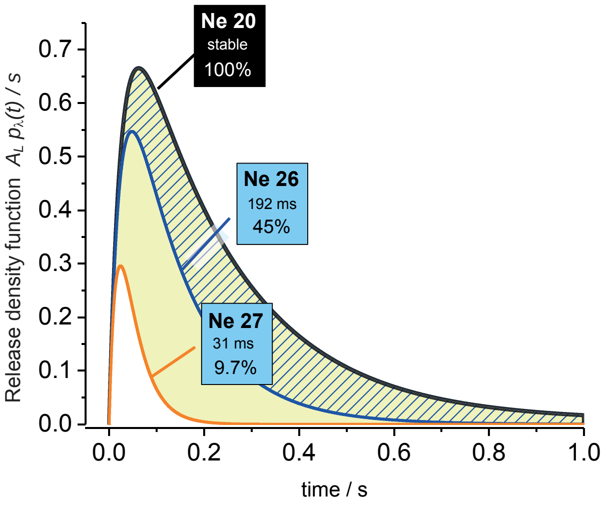
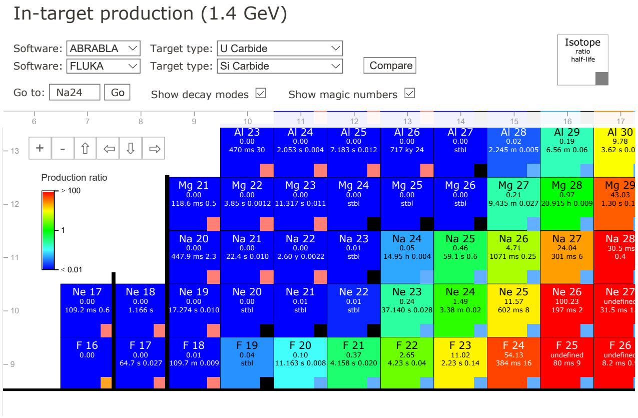


Figure 1: Typical non-normalized release curves $A_L\ p(t)$ of stable neon, and release curves $A_L\ p_\lambda(t) = A_L\ p(t)\ \mathrm{e}^{-\lambda t}$ of radioactive isotopes. The release efficiencies are given in percent and have been calculated according to Eq. 1. Parameters t_{rise}, t_{fall1}, t_{fall2} and α (cf. Eq. 2) taken from Ref. [10]. The normalization parameter A_L has to be chosen such, that $\int_0^\infty p(t)\ \mathrm{d}t$ computes to unity.



In-target production (1.4 GeV)

Software: ABRABLA Target type: U Carbide
Software: FLUKA Target type: Si Carbide Compare

Go to: Na24 Go Show decay modes ☑ Show magic numbers ☑

	6	7	8	9	10	11	12	13	14	15	16	17
13					Al 23 0.00 470 ms 30	Al 24 0.00 2.053 s 0.004	Al 25 0.00 7.183 s 0.012	Al 26 0.00 717 ky 24	Al 27 0.00 stbl	Al 28 0.02 2.245 m 0.005	Al 29 0.19 6.56 m 0.06	Al 30 9.78 3.62 s 0.0
12				Mg 21 0.00 118.6 ms 0.5	Mg 22 0.00 3.85 s 0.0012	Mg 23 0.00 11.317 s 0.011	Mg 24 0.00 stbl	Mg 25 0.00 stbl	Mg 26 0.00 stbl	Mg 27 0.21 9.435 m 0.027	Mg 28 0.97 20.915 h 0.009	Mg 29 43.03 1.30 s 0.1
11				Na 20 0.00 447.9 ms 2.3	Na 21 0.00 22.4 s 0.010	Na 22 0.00 2.60 y 0.0022	Na 23 0.01 stbl	Na 24 0.05 14.95 h 0.004	Na 25 0.46 59.1 s 0.6	Na 26 4.71 1071 ms 0.25	Na 27 24.04 301 ms 6	Na 28 30.5 ms 0.4
10		Ne 17 0.00 109.2 ms 0.6	Ne 18 0.00 1.166 s	Ne 19 0.00 17.274 s 0.010	Ne 20 0.00 stbl	Ne 21 0.01 stbl	Ne 22 0.01 stbl	Ne 23 0.24 37.140 s 0.028	Ne 24 1.49 3.38 m 0.02	Ne 25 11.57 602 ms 8	Ne 26 100.23 197 ms 2	Ne 27 undefine 31.5 ms 1
9		F 16 0.00	F 17 0.00 64.7 s 0.027	F 18 0.01 109.7 m 0.009	F 19 0.04 stbl	F 20 0.10 11.163 s 0.008	F 21 0.37 4.158 s 0.020	F 22 2.65 4.23 s 0.04	F 23 11.02 2.23 s 0.14	F 24 54.13 384 ms 16	F 25 undefined 80 ms 9	F 26 undefine 8.2 ms 0.

Figure 2: Cut-out of the interactive nuclide chart, which is used in the web application to visualize in-target production and radioactive beam yields. The example is meant to demonstrate the capabilities of the software and shows the relative in-target production rates of two different target materials estimated by simulations using two different codes. The background color represents the production ratio, and the inset rectangle the decay mode of the isotope. In addition, half-life information is given.

tion and chemical efficiency can be summarized in an overall efficiency parameter ϵ_{f}. The half-life dependent release efficiency ($\epsilon_{\text{release}}$) is governed by diffusion and effusion processes and takes into account the time passing between production and release. A more detailed discussion of efficiency parameters can be found e.g. in Ref. [7].

Each atom follows its individual path to reach the ion source, and the distribution function for the time needed to follow these trajectories is defined by the release density function $p(t)$ [8, 9] The release efficiency of an isotope with decay constant λ is obtained by folding the release density function $p(t)$ with a factor to account for decay losses.

$$\begin{aligned} Y &= N_0\ \epsilon_{\text{release}}\ \epsilon_{\text{f}},\ \text{where} \\ \epsilon_{\text{release}} &= \int_0^\infty p(t)\ e^{-\lambda t}\ \mathrm{d}t \end{aligned} \tag{1}$$

The release density function is normalized such, that $\int_0^\infty p(t)\ \mathrm{d}t = 1$. The efficiency parameter ϵ_{f} and the distribution function $p(t)$, which describes the release of a stable nuclide, depend on the chemical element, operating conditions and typically only to negligible extend on the isotope. Hence, it is only required to experimentally determine the parameters ϵ_{f} and $p(t)$ once for each chemical element in a defined target and ion source system at given operating conditions. Knowing the two parameters and the in-target production rates of isotopes, allows to predict yields for the full isotopic chain (cf. Eq. 1). The isotope for the measurement of $p(t)$ must be chosen such, that the tail of the experimentally obtained radioactive release curve $p_\lambda(t) = p(t)\ \mathrm{e}^{-\lambda t}$ is not governed by radioactive decay.

From elementary diffusion and effusion processes, expressions for the delay function $p(t)$ have been obtained, e.g. by Kirchner et al. [8]. However, these expressions depend on numerous parameters, such as target material properties, target geometry and operation conditions. In addition, the expressions are often difficult to fit to experimental data. For practical purposes, the experimental data is often fitted to the three exponential function given in Eq. 2 [12], where A_L is a normalization parameter, t_{rise}, t_{fall1} and t_{fall2} are time constants describing the curve shape, and α is a weighting coefficient.

$$\begin{aligned} p(t) = &\frac{1}{A_L}\left(1 - \mathrm{e}^{-t\ \ln(2)/t_{\text{rise}}}\right) \\ &\cdot \left(\alpha\ \mathrm{e}^{-t\ \ln(2)/t_{\text{fall1}}} + (1-\alpha)\ \mathrm{e}^{-t\ \ln(2)/t_{\text{fall2}}}\right) \end{aligned} \tag{2}$$

A typical release curve of stable neon is shown in Fig. 1, along with calculated release efficiencies for short-lived radioisotopes. At the time of writing, release curves for 427 yield entries are available in the yield database.

A common procedure to assess a yield, is based on the measurement of a release curve, as shown in Fig. 1. ISOLDE is supplied with protons from the proton synchrotron booster (PSB), which arrive as narrow pulses of only a few microseconds length and typically contain up to 3×10^{13} protons. The proton pulse impinges on the target at $t = 0$. After a certain delay time $t = t_{\text{delay}}$, electrostatic deflectors allow the radioactive beam emitted from the ion source to pass downstream the beamline and to the tape of the tape station, in which it is implanted for a defined collection time t_{collect}. After the end of the collection ($t = t_{\text{delay}} + t_{\text{collect}}$), the radioactive ion beam transport is prevented by electrostatic deflectors, and the tape is forwarded to move the collected activity to the measurement position, where it is counted by calibrated detectors. Taking into account the decay during tape transport, the number of ions per second extracted at $t = t_{\mathrm{delay}} + 0.5\ t_{\mathrm{collect}}$ is obtained. Repeating the procedure whilst varying the delay time t_{delay} allows to sample a full release curve of the radioactive beam. The yield in the focal center of the separation magnet is obtained by integration of the non-normalized release curve, and correcting for losses by beam transport from magnet to tape station. Beam losses are estimated by measurement of stable beam with Faraday Cups placed along the beamlines. The procedure is summarized in Ref. [3], and more detail about pulse shapes, yield calculation and efficiencies is given in Lit. [27].

3. In-Target Production

The in-target production rates N_0 of all common target materials were assessed by means of an extensive simulation campaign. High statistics of up to 1×10^9 primary particles are needed to achieve reliable production rates also for exotic nuclides. Two simulation codes have been used to investigate the production rates. The ABRABLA code [13] is commonly used at ISOLDE and was already used and benchmarked for 600 MeV and 1.0 GeV proton beam [14]. Per each simulation run, the code yields radionuclide production cross sections at a defined driver beam energy and target nuclide, and is therefore ideally suited for simple geometries and a beam directly impinging on the target, where secondary reactions do not contribute significantly. The cross section estimates are obtained at the initial energy of the proton beam, not taking into account energy losses in the target. The particle transport code FLUKA [15, 16] allows the definition of complex geometries and calculates multiple particle interactions with matter using various integrated physics models. The definition of a geometry has especially proven useful for target units equipped with a neutron spallation source, the so called proton-to-neutron converter [17, 18].

The codes were used to simulate isotope production with common and prospective target materials at proton beam energies of 0.6, 1.0, 1.4 and 2.0 GeV, to take into account historic driver beam energies delivered by the Synchrocyclotron (SC) along with the early, present and future beam energies of the Proton Synchrotron Booster (PSB), which supplies ISOLDE [19]. Besides the prediction of exotic nuclide yields, the simulation data allows the estimation of release efficiencies if experimental yields of several isotopes of the same chemical element are available. Thus, it gives insight into release properties of targets and ion sources used for the past 60 years at ISOLDE. The data enabled us to conduct a systematic study of isotope production at the planned upgraded driver beam energy of 2.0 GeV, for beams delivered after the upgrade.

4. Technical Implementation

All software components have been developed compatible to the CERN centrally provided IT infrastructure services to ensure reliability and long-term support. The Oracle Database 11g [20], which is widely used at CERN, serves as underlying data provider for all high-level applications.

4.1. Database

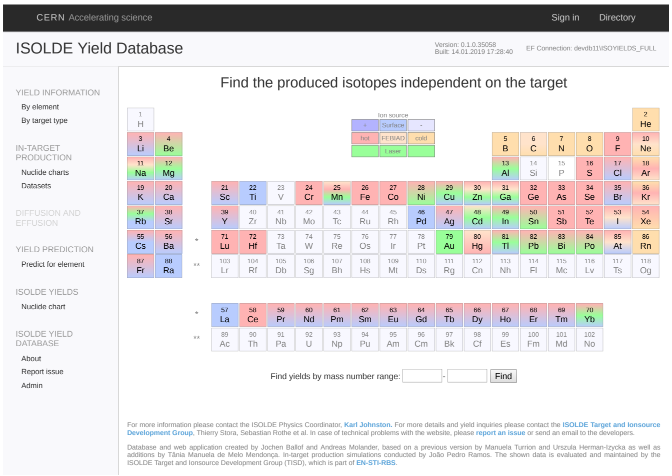
The database stores experimentally obtained radioactive ion beam yields which were typically measured using the ISOLDE tapestation and taken from publications. The yields are stored along with information about the used target-unit, such as type of ion source, target material, thickness and operational conditions, and are given as yield in the focal plane of the magnet. Within this work, the structure of the database was completely redesigned and further normalized to ease maintenance and allow data storage for the upgraded functionality. A measured yield is linked to a defined target unit, which in turn is associated with a target material, made up of a nuclide mixture in defined stoichiometry. A set of new tables was added to store in-target production data obtained in sumulations. For each target material nuclide, one ABRABLA run is necessary. The total in-target production cross section of a target material is then calculated by combining the estimated cross sections obtained in multiple ABRABLA runs and the thickness (areal density) of the target unit. In addition, FLUKA simulation results are available. Here the full target geometry and nuclide inventory is covered by one simulation. Release curve parameters are required to calculate release efficiencies (cf. Eq. 2) and are available in a table linked to the table holding information about measured yields. At the time of writing, ca. one million production cross sections estimated by simulation codes are available, also indicating the production channel (like fission or spallation) for ABRABLA data. Besides storing published yield information, the database was extended to maintain data of yield measurements, typically taking place before each physics run. Within the 2018 operating period, new yields have been introduced, which are now available to advanced users.

4.2. User and Application Programming Interfaces

Two new user-interfaces have been developed. One interface is implemented as website and displays data to users. For fast data manipulation, a rich client solution is under development. A prototype application implemented using Microsoft Access is already provided to users as RemoteApp by Microsoft Remote Desktop services (RDS) [21] to allow a rich client experience but avoiding at the same time the need of local software installation on client computers.

4.2.1. Web Application

In contrast to earlier versions, the new web application [6] is not based on Oracle integrated web solutions and Java applets, but implemented in C# under Microsoft



For more information please contact the ISOLDE Physics Coordinator, **Karl Johnston.** For more details and yield inquiries please contact the **ISOLDE Target and Ionsource Development Group**, Thierry Stora, Sebastian Rothe et al. In case of technical problems with the website, please **report an issue** or send an email to the developers.

Database and web application created by Jochen Ballof and Andreas Molander, based on a previous version by Manuela Turrion and Urszula Herman-Izycka as well as additions by Tânia Manuela de Melo Mendonça. In-target production simulations conducted by João Pedro Ramos. The shown data is evaluated and maintained by the ISOLDE Target and Ionsource Development Group (TISD), which is part of **EN-STI-RBS**.

Figure 3: The web frontend of the ISOLDE yield database, showing available beams in the periodic table of elements. The frontend is available at http://cern.ch/isolde-yields.

ASP.NET [22] to gain a higher degree of flexibility in development. User authentication is accomplished by Single Sign On (SSO) services, widely used at CERN. The Microsoft Entity Framework [23] allows object-relational mapping and rapid development of data driven applications. With the new application, further details about production conditions of yields are given, which include among other attributes, target and ion-source temperatures and release curves. The latter are provided as parameters (cf. Eq. 2) and plot to visualize the time structure of the release. Besides adding yield details, an interactive nuclide chart was developed using the JavaScript library D3.js [24], which is capable of displaying an overview chart of all beams at ISOLDE as well as in-target production yields for each target material [25]. For easy comparison between target materials or different driver beam energies, the plotting of ratios between different data sets is also available (cf. Fig. 2). The functionality to predict yields for not yet measured isotopes is also included in the web application. It allows the user to predict yields for the full chain of isotopes of a certain element. The desired target material, proton beam energy and simulation software are selected by the users. The application then searches for reference point candidates in the database, which serve as source for the calculation of the efficiency parameter ϵ_f. The actual reference point is selected by the user, and prediction results are displayed as table and plot. A typical plot is shown in Fig. 4. Half-life data of nuclides is necessary to calculate release efficiency. An import function for NUBASE evaluation data [26] allows to continuously update the data with new and modified entries.

4.2.2. Rich Client Application

The prototype desktop application allows fast and direct access to the data layer. It is intended to be used for data manipulation and queries by advanced users. Functionality has been included to calculate yields obtained during routinely performed measurements for each unit, which are either conducted at the ISOLDE tape station or derived from Faraday Cup readings. The tape station is equipped with scintillation counter and high purity germanium detector and used as reference method to determine yields.

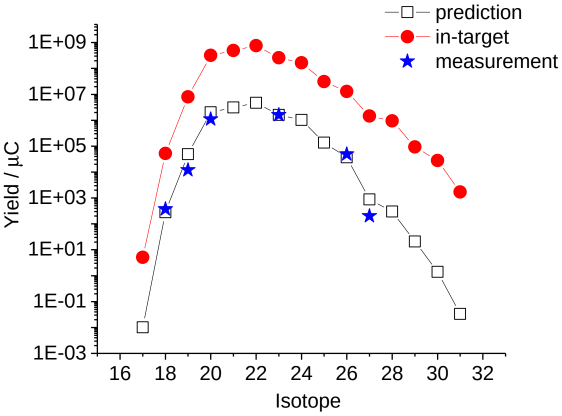


Figure 4: Exemplary plot showing measured yields, in-target production along with yield predictions of neon isotopes from a uranium carbide target [10, 6].The experimental yield for ^{23}Ne was used as reference point to calculate ϵ_f. The in-target production yields were taken from ABRABLA.

4.2.3. Application Programming Interface

Following user requests to link their own systems to the yield database, a REST-interface based on the ASP.NET Web API is available. The solution integrates nicely into Entity Framework and enables us to rapidly develop programming interfaces. The data is delivered as JSON or XML data. The interface is also used to provide data to the CRIBE (Chart of Radioactive Ion Beams in Europe) project, which aims at providing an overview of available and future radioactive ion beams at all facilities in Europe [28].

5. Conclusions and Outlook

Within a complete redevelopment of the website and restructuring of the underlying database we have added a set of new functions to the ISOLDE yield database application. Now, it does not only provide available yield information, but is also capable to predict yields at the prospective proton beam energy of 2.0 GeV, which is an option of the driver beam upgrade under consideration. Yield predictions for exotic isotopes, which could only be measured with sophisticated setups, are now available. To achieve the latter, a comprehensive simulation campaign was conducted. The results of the simulation data are made available to users. At the time of writing the application is available to advanced users and undergoes extensive testing before release on the ISOLDE web page. In the future, we plan to further extend the functionality of the database and develop interfaces for data exchange between asset management and control applications. The inclusion of yields reported by facility users and an extension of the simulation campaign are in preparation. The added simulation data will cover cross sections of materials which have not yet been used at ISOLDE, and will also be verified against new versions of the simulation codes.

6. Acknowledgments

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