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Günther Sinapius^{a)} and Helge L. Ravn^{b)}

a) Fakultät für Physik, Universität Bielefeld
D-4800 Bielefeld, Fed. Rep. of Germany

b) CERN, CH-1211 Geneva, Switzerland

and

the ISOLDE Collaboration, CERN, Geneva, Switzerland

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Günther Sinapius^a and Helge L. Ravn^b

^aFakultät für Physik, Universität Bielefeld
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INTRODUCTION

In all fields where low-energy positrons are employed, high intensities are desirable. The low-energy positrons originate from high-energy positrons that are moderated in solids. During the last decades the intensity of moderated positron beams has risen from less than one to 10^9 e⁺/s. There are two ways to increase the intensity, either by having a higher flux of high-energy positrons hit the moderator or by using more efficient moderators. In this text we will only deal with the first option.

POSITRON SOURCES PRESENTLY IN USE

The β^+ emission rate of commercially available long lived radioactive sources (⁵⁸Co and ²²Na) does not exceed 5 GBq. For the brightness of the positron beam not only the source activity but also its geometrical size and the end-point energy of the β^+ spectrum are crucial. The lower the end-point energy of a source, the more positrons thermalise in a given unit thickness of a moderator and can emerge as low-energy positrons.

High-intensity positron beams are available at electron accelerators^{1,2,3} and reactors.⁴ Because of their pulse structure present beams at electron accelerators are not useful for applications where coincidences between individual primary

positrons and outgoing particles are measured. So far these beams are magnetically guided and for most atomic physics experiments they would have to be extracted out of the guiding field. With a tungsten moderator 200 pA of moderated positrons have been reported.¹ It might be difficult to employ solid neon moderators⁵ in close proximity of a converter heated by the primary beam. At the high-flux reactor at the Brookhaven National Laboratory (BNL) ^{64}Cu sources are activated in 48 hour cycles (12.6 h half-life). From $10 \times 10 \times 0.1 \text{ mm}^3$ sources with 550 GBq β^+ emission rates positron beams of about 25 pA are obtained. About the same current is expected with a solid neon moderator, electrostatic beam transport and one remoderation stage.

The activity of long-lived radioactive sources is rather limited. All these sources are far from pointlike, the reason being the isotope composition and source self absorption. The specific β^+ emission rates reach about 1 GBq/mm^2 . Recently, two approaches to produce strong or pointlike radioactive sources have been studied. Before describing the results let us make some general remarks on the production of radioisotopes in nuclear processes.

PRODUCTION OF RADIOISOTOPES

The activity of a source, $A(t)$, that can be collected during an activation time t depends on its decay constant λ . For a production rate R one obtains:

$$A(t) = R (1 - \exp(- \lambda t)).$$

In order to collect high activities the activation time t should be in the order of the half life. If t is sufficiently long, the achievable activity equals the production rate R . Except for parasitic operation, when beam time is no limitation, one is restricted to short-lived isotopes.

In a nuclear rearrangement process like a (p,n) reaction the production rate depends on the cross section for the

process, σ , the intensity of the projectiles, I , the density of the target atoms, n , and the penetration depth, l :

$$R \approx \sigma n l I.$$

At a proton energy of about 10 MeV the cross sections have the highest value and come close to 10^{-24} cm^2 , they are higher for thermal neutrons. The beam intensity is mainly limited by cooling requirements, let us assume it to be 20 μA . If the source is to be used without further processing, self absorption limits the useful thickness to 100 mg/cm^2 which corresponds to $\approx 100 \text{ }\mu\text{m}$ Cu. With these values the upper limit for the production rate in (p,n) reactions is less than 100 GBq. The choice of the isotope then will be guided by the magnitude of the cross section σ , the β^+ decay fraction, the β^+ end-point energy and the half life.

The minimum diameter of the active area of this kind of sources is limited either by cooling considerations for charged projectiles or the lack of focussing for neutrals. The penetration depths of the projectiles reduces the intensity or the brightness. This can be overcome by isotope separation and selection of the isotope of interest or more easily by brightness enhancement schemes for the moderated positron beam. Now let us look at an example for a (p,n) reaction.

PRODUCTION OF ^{48}V

At Karlsruhe the process $^{48}\text{Ti}(p,n)^{48}\text{V}$ was investigated.⁶ ^{48}V is a positron emitter with a half live of 16 d, a β^+ fraction of 56 % and an end-point energy of 700 keV. A $13 \times 15 \times 1 \text{ mm}$ titanium sample was irradiated with 20 μA of 35 MeV protons for 15 minutes. From the γ -spectrum analysed some days later, the produced activity was determined to $A(15\text{min}) \approx 11 \text{ MBq}$. This agrees well with the calculated production rate of $R \leq 25 \text{ GBq}$. With 12 MeV protons a value of $R \approx 380 \text{ GBq}$ (210 GBq β^+ emission rate) is expected. Due to the self absorption in the sample, however, not all the positrons are available for moderation. If the sample is cut into 20 slices of $50 \text{ }\mu\text{m}$ each to arrange them in a matrix, the specific β^+ emission rate will be less than 50 MBq/mm^2 .

ON-LINE MASS SEPARATORS

Another approach is to employ on-line isotope separators. In these machines various isotopes are produced simultaneously by spallation, fragmentation and fission through the impact of ions, neutrons or high-energy particles on various targets. The experimental problem is the separation of the produced atoms from the target and the formation of ion beams. Whereas selectivity in the atomic mass can be achieved electromagnetically, the atomic number Z has to be selected chemically. Worldwide 83 elements are available at on-line mass separators.⁷ At the isotope separator on-line ISOLDE at CERN radioactive beams of 66 elements can be produced with protons beams.⁸ Because of their long range high-energy protons are favorite projectiles for high yields. When a $1\text{ }\mu\text{A}$ beam of 600 MeV protons passes a 100 g/cm^2 thick target, up to 10^{11} atoms of a given species can be produced.

Fig. 1. Lay-out of the ISOLDE on-line mass separator.⁷

The intensity at the experiment is reduced due to the efficiencies for release from the target, ionisation and transport from target to ioniser and finally to the experiment. Overall efficiencies may be as low as 0.01% but reach 80% for

elements with high vapour pressure and low ionisation potential like Rb and Cs.⁷ The ideally pure isotope beam can be deposited on diameters well below 1 mm. With a transport energy of 60 keV the penetration depths is several Å only.

COLLECTIONS AT ISOLDE

The first experiment to employ this method for production of strong positron sources was performed at ISOLDE.⁹ In this experiment ¹³⁰Cs and ⁸¹Rb were studied. These nuclei were chosen because an 1 μ A 600 MeV proton beam and a 50 g/cm² thick target yield isotope beams with intensities of above 10¹⁰ particles/s.¹⁰ Their half-lives of 29 min and 4.7 h and β^+ decay branches of 50 % and 27 %, respectively, allow sufficiently strong sources to be produced. Their endpoint energies are 2 and 1.1 MeV.

Thirteen samples were collected on 6 and 25 μ m thick annealed tungsten foils. Their activity was calculated from the beam intensity and the collection time. The activity obtained in a five hours collection later was measured with a Ge-Li γ -detector. It turned out to be 15% less than calculated. This may be due to instabilities in the proton current or sputtering of the sample. In this run 14 GBq of ⁸¹Rb were collected on an 1.5 x 3 mm spot, corresponding to a β^+ production rate of $R \approx 7$ GBq.

After collection the samples were moved out of the beam-line into a separate apparatus (Fig. 2) to study the low-energy positron yield. In different configurations either a separate 6 μ m tungsten foil was used as moderator, or the foil with implanted source itself served as moderator. The latter configuration gave maximum yields. Probably due to its lower end-point energy ⁸¹Rb showed superior results than ¹³⁰Cs. The normalised yield, $1.3 \cdot 10^{-5} \text{ e}^+ (\text{s Bq}_\beta)^{-1}$, was comparable to the value obtained with a ²²Na source and a 6 μ m W moderator in the same apparatus.

With improved beam optics the spot size can be reduced to 1 mm diameter. A conservative estimate shows that with a proton current of 2.8 μ A and a 300 g/cm² target β^+ production rate of 70 GBq can be achieved.

Fig. 2. Sketch of the apparatus for the test of positron sources.⁹

FUTURE DEVELOPMENTS

The synchro-cyclotron that provides the proton beam for ISOLDE can deliver a maximum current of 5 μA . So far the collection of very high activities has not been the major idea and lower currents are employed. With redesigned target containers and modified targets most of them could withstand higher currents. Energy dissipation calculations show that up to 100 μA are feasible without additional cooling.¹¹ There is only one on-line mass separator at an accelerator that can deliver such proton currents: at TRIUMF in Vancouver.¹² At present this device utilises only about 1 μA proton current, it needs further investment to operate with the maximum current. With a proton current of 100 μA from ^{81}Rb a β^+ production rate of about 3.5 TBq should be feasible. For such activities the source diameter increases, because about 10^{15} atoms will be collected during a collection time of one half-life. Sputtering losses will be a severe problem.

The advantage of producing positron source at on-line mass separators lies in the fact that only one specific isotope is collected. Thus intensity losses due to self absorption in the source or large source diameters can be avoided. If operated outside the collection site these source can be easily used in

conjunction with high-yield moderators like solid neon. The main disadvantage is the rather limited beam-time at on-line mass-separators. Because of the frequent switching between different isotope beams the collection of a specific isotope can not be done continuously in a parasitic operation over longer periods.

COMPARISON OF DIFFERENT METHODS TO PRODUCE HIGH β^+ ACTIVITIES

The choice between different ways to produce positrons so far has been mainly guided by the availability of an accelerator or a reactor. No device has been built for this purpose. Thus a comparison can only outline the (dis)advantages of different approaches, the choice will mainly be determined by the technical infrastructure. There is a break-even point between a poor source that works all year and an optimal source with very limited access ("A bird in the hand is worth two in the bush").

Positrons produced via bremsstrahlung and pair-production can be used at the electron accelerator only. The strong radiation background requires a long (magnetic) beam transport. The beam structure is determined by the duty cycle of the accelerator. Suitable LINACS exist at various sites.

At devices where "carry-away" sources can be made, the selection of the specific isotope is a compromise between the achievable activity and parameters relevant for the low energy positron beam. Probably there still are various isotopes worth trying. Worldwide there are several suitable proton accelerators, few on-line mass separators and fewer high-flux reactors. The highest activities are obtained at the BNL high flux reactor. If isotope separation is employed the usable activity still can be drastically increased. From proton accelerators operated at about 10 MeV strong but rather extended sources can be obtained. On-line mass separators are most suitable to produce pointlike sources of virtually every isotope. Due to the limitation on beam time they will be employed mainly where pointlike and short-lived sources are required.

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