The increasing significance of non-standard positron emission tomography (PET) nuclides in medicine is briefly outlined. The decay data of those radionuclides are generally well known, except for the positron emission intensity \( I_{\beta^+} \) in a few cases. The recent precise measurements on the \( I_{\beta^+} \) values for \(^{64}\text{Cu} \), \(^{76}\text{Br} \), \(^{120}\text{I} \) and \(^{124}\text{I} \) are described. Some general aspects of cyclotron production of radionuclides are discussed. The need of some fundamental nuclear chemistry research with regard to the development of a new production route is demonstrated. An accurate knowledge of the excitation function of a nuclear reaction is essential to optimize the production route. The yield of a product calculated from the excitation function of a reaction gives the maximum achievable yield. Such yields are given for 24 radionuclides presently attracting attention. The experimental yields are always lower than the theoretical values, calling upon constant improvements in targetry and chemical processing procedures. Many of the non-standard PET nuclides, like \(^{64}\text{Cu} \), \(^{86}\text{Y} \), \(^{93}\text{mTc} \), \(^{124}\text{I} \), etc. are produced in good yields at low energy cyclotrons while for production of some other radionuclides (e.g. \(^{52}\text{Fe} \), \(^{73}\text{Se} \), \(^{83}\text{Sr} \), etc.) an intermediate energy cyclotron is required.

KEY WORDS: Tomography, emission computed - Radiopharmaceuticals - Production, data.

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Although those radionuclides are still used in some special cases, the trend has somewhat shifted towards more purpose oriented longer-lived positron emitters.

Today, there are two major directions in which non-standard, i.e. non-conventional, positron emitters are used. The first one concerns the study of slow metabolic processes, like protein synthesis, cell proliferation, etc. where relatively long-lived positron emitters are required. The second one relates to quantitation aspects, both in diagnosis via single photon emission tomography (SPECT) and dosimetry in internal open source radiotherapy. If the SPECT radioisotope in a pharmaceutical could be substituted by a positron emitting homologue, the distribution kinetics could be determined quantitatively via PET. The results would then be of immediate use in quantification of the SPECT pharmaceutical. In internal radiotherapy, generally a pure β emitter like 88Sr or 90Y is preferred, but since the distribution of the radioactivity cannot be measured accurately from outside of the body, the dosimetry is rather empirical. On the other hand, if the radiotherapeutical could be mixed with a small amount of a positron emitting homologue, the distribution of the radioactivity could be easily determined via PET and the dose calculation would then be on a more firm footing.

In this article, the author is dwelling on the development of non-standard PET radionuclides with the above mentioned two motivations in mind. Several aspects of development work deserve attention. This contribution, however, deals with the basic nuclear data for production and application of some of the non-standard positron emitters.

Decay data

Decay data are the major criterion for the choice of a radionuclide for medical application. In general, the decay data are fairly well known. A problem with many of the non-standard relatively long-lived positron emitters, however, is that the positron emission intensity is often rather low and not exactly known, thereby causing some uncertainty in the quantitation of tomographic scans. For the more promising radionuclides it is therefore imperative to determine some of the relevant decay data with higher accuracy.

The decay data of most of the non-standard positron emitters were determined in the context of nuclear structure studies; the recent related works deal more with evaluations\(^1\) of older data rather than with new measurements. Since many of the radioactive samples used in older measurements were prepared without radiochemical separations, they were radionuclically not pure. Furthermore, β-ray spectroscopy has not attained the same precision as high-resolution γ-ray spectroscopy. The X-ray component, which is related to electron capture (EC) decay, was determined in older works generally using a gas counter. It appears, therefore, worthwhile to perform new measurements on some important radionuclides, especially on positron emission intensities, in cases where they appear to be rather uncertain.

The modern methodology of determination of positron emission intensity consists of preparation of a very clean thin source, accurate measurement of annihilation radiation (using both HPGe detector γ-ray spectroscopy and γγ-coincidence counting) and determination of EC component via high-resolution X-ray spectroscopy using a thin Ge or Si(Li) detector. The measurement of decay data of 64Cu (\(T_{1/2}=12.7\) h) constitutes a typical case. This radionuclide decays by three modes, viz. β emission, EC and β+ emission. According to the latest evaluation\(^1\) the positron emission intensity corresponds to 17.4%. The experimentally reported \(I_β\) values, however, range between 17.4% and 19%. With EC a very weak γ transition of energy 1 346 keV has also been reported. Its intensity could range between 0.47% and 0.6%. In a recent work,\(^2\) the radionuclide was produced either via the \(64Ni(p,n)\) or the \(66Zn(d,α)\) reaction using highly enriched (>99%) target material. The radioisotope was chemically separated and a thin sample on filter paper was prepared for radioactivity measurement via β counting, γγ-coincidence counting, and X-ray and γ-ray spectroscopy. From all the counting results and the literature knowledge a decay scheme of 64Cu was developed which is reproduced in Figure 1. The β- branching intensity of 38.4% deduced in that experiment is very close to the value of 38.1±0.3% measured via mass spectrometry.\(^3\) The β+ emission intensity was found to be 17.8±0.4%.

Similar to 64Cu, work on a few other important non-standard PET nuclides has also been performed in recent years.\(^2,4-6\) The results on β+ emission intensities are summarized in Table I. It is suggested that for the four investigated radionuclides, viz. 64Cu, 76Br, 120I and 121I the given \(I_β\) values should be adopted as
standard values. Regarding other non-standard PET nuclides, such measurements also need to be done.

Production data

General considerations

Production data are primarily related to the formation of a desired radionuclide under optimum conditions. In the choice of a production process for a non-standard PET nuclide, therefore, following points need to be given due attention.

Availability of a cyclotron

The desire to develop non-standard PET nuclides is generally prevalent at PET centers with low-energy cyclotrons (E_p ≤ 18 MeV, E_d ≤ 10 MeV). The nuclear reactions which could be applied are low-energy processes, e.g. (p,n), (p,α), (d,n), (d,α), etc. Occasionally a higher energy two particle cyclotron (with E_p ≤ 30 MeV, E_d ≤ 15 MeV) or a multiparticle intermediate energy cyclotron (accelerating p, d, 3He and α-particles) with E_p ≤ 70 MeV may be available. In those cases, several nuclear reactions, like (p,xn), (3He,xn), etc. may be suitable for production purposes.

Availability of highly enriched target material

Since many of the radionuclides can be produced via low-energy nuclear reactions only on isotopically enriched targets, the availability of suitable target material, which is usually rather expensive, may be absolutely necessary.

High current targetry

In order to be able to produce sufficiently large amounts of the desired radionuclide, it is absolutely necessary to develop target materials and target holders which would withstand high beam fluxes of charged particles. Furthermore, the radioactive product should be relatively easily separated from the matrix activity.

Efficient chemical processing

It is imperative that from the irradiated target material not only the desired radionuclide is separated in a clean form, but also the target material is efficiently recovered for reuse. Thus, the chemical processing may demand very skilful radiochemical work.

During all the above-mentioned considerations, the major criteria are the yield and the purity. Utmost attempts need to be made to get the product in high yield and with the highest possible purity.

Excitation functions

The probability of a nuclear reaction leading to the formation of a radionuclide is expressed in terms of “cross section”, and its energy dependence is called an “excitation function”. An accurate knowledge of the excitation function allows to calculate the production yield of a radionuclide via the well-known activation equation, provided the number of target nuclei and the projectile flux are exactly known.

Cross section data near reaction thresholds

As discussed above, many of the PET centers equipped with small cyclotrons have considerable

![Figure 1.—Decay scheme of 64Cu with intensities of emitted radiations. [From Qaim et al.2].](image-url)
interest in producing non-standard positron emitters. For the very decision whether an available low-energy cyclotron is suitable for production, an accurate knowledge of the excitation function of the nuclear reaction near the threshold is necessary. In the higher energy region, the cross section data help to optimize the production route. As an example, the cross section data for the production of $^{124}$I via the $^{124}$Te(p,n)$^{124}$I reaction are shown in Figure 2. An early measurement was limited to proton energies >10 MeV. As a consequence this reaction was considered to be unsuitable for production of $^{124}$I, and resort was made to the $^{124}$Te(d,2n)$^{124}$I reaction. The latter reaction needs higher deuteron energies than those available at PET centers: the production was therefore limited. After the publication of a more thorough study near the threshold, it became evident that the (p,n) process is quite suitable for use at a low-energy cyclotron. Thereafter, most of the laboratories shifted over to this reaction and today even some commercial companies are utilizing this method for $^{124}$I production. The accurate cross section database near the threshold allows the optimum use of even a very small cyclotron ($E_p \leq 11$ MeV) for production of $^{124}$I on a limited scale.

Regarding other nuclides, a recent accurate measurement of the $^{76}$Se(p,n)$^{76}$Br reaction cross section near the threshold confirmed that this radionuclide can be conveniently produced at a low-energy cyclotron. Other important radionuclides which are generated via the (p,n) reaction and whose excitation functions have been accurately measured near the thresholds are $^{64}$Cu, $^{86}$Y, $^{94}$mTc and $^{120}$I. All those radionuclides can be produced using a low-energy cyclotron available at a PET center.

Two other low-energy nuclear reactions which occasionally find application in the production of some non-standard PET nuclides are (p,α) and (d,n). They are generally used when a (p,n) reaction is not possible (due to non-availability of a suitable target material). Some of the examples are: $^{51}$Ni(p,α)$^{55}$Co, $^{54}$Fe(d,n)$^{58}$Co and $^{76}$Se(d,n)$^{74}$Br. For proper application of each method, the respective database near the threshold was strengthened through accurate measurements.

**COMPETING REACTION CHANNELS**

At projectile energies $>20$ MeV, several intermediate energy reactions like (p,xn), (p,pxn), etc. start competing and the demand on the needed nuclear data information increases. Several radionuclides can be produced only via such reactions because of lack of suitable target nuclides on which low-energy reactions could be induced. Another motivation for using an intermediate energy reaction may be to obtain higher yield of a product. However, the level of radionuclidic impurities is then also higher. The radionuclide $^{73}$Se, for example, is produced almost exclusively via the $^{75}$As(p,3n)$^{73}$Se reaction since no low-energy reaction is possible. The target window (or thickness), however, has then to be chosen such that the yield of the desired product is high and the levels of the long-lived impurities are low. If the range $E_p=40 \rightarrow 30$ MeV is chosen, then the yield of $^{73}$Se is 1406 MBq/µA⋅h and the levels of $^{72}$Se and $^{75}$Se impurities are limited to <0.2%.

In an attempt to increase the yield of $^{124}$I the $^{125}$Te(p,xn)-reactions were investigated in detail and the results are shown in Figure 3. The suitable energy range for $^{124}$I production via the $^{125}$Te(p,2n)$^{124}$I reaction is $E_p=21 \rightarrow 15$ MeV. The integral yield is about 5 times higher than that via the $^{124}$Te(p,n)$^{124}$I reaction, but the level of the $^{125}$I impurity is also considerably higher.

For production of nuclides in the intermediate energy region mostly proton beams are utilized. However, in certain special cases deuterons, $^3$He- and $\alpha$-particle beams have also proven to be useful. This is particularly true if targetry involving (p,xn) or (d,xn) reactions is difficult. The radionuclides $^{39}$P (T$_{1/2}$ = 2.5 min) and

![Figure 2.—Excitation function of the $^{124}$Te(p,n)$^{124}$I reaction. The high precision measurements near the reaction threshold done by Scholten et al. are now the basis of yield calculations for the production of $^{124}$I.](image-url)
38K (T1/2 = 7.5 min), for example, are advantageously produced via the 27Al(α,n)30P and 35Cl(α,n)38K reactions, respectively. Similarly, the radionuclide 75Br (T1/2 = 1.6 h) had been produced for a long time via the 75As(3He,3n)75Br reaction. In order to demonstrate the variety of nuclear processes which could be used for the production of a radionuclide, the case of 64Cu, one of the most important non-standard PET radionuclides, is considered in detail. Table II gives a summary of the methods suggested for its production in a no-carrier-added form. Originally the 64Zn(n,p)64Cu reaction was used27 which, however, does not have a high yield. Furthermore, the product is contaminated with 67Cu, unless enriched 64Zn is used as target material. The 64Ni(d,2n)64Cu reaction has a high yield, 28 but the deuteron energy needed for production is not available at cyclotrons in PET centers. The 64Ni(p,n)64Cu reaction gives high yield 17 and can be utilized at a small-sized cyclotron. The 66Zn(d,α)64Cu reaction has a relatively low yield29 and is thus not attractive. The natZn(d,x)64Cu process is, however, interesting30, 31 if about 25 MeV deuterons are available. The 68Zn(p,αn)64Cu reaction has a good yield, 32 but the upper energy limit is 35 MeV since at higher energies considerable amount of 67Cu is also formed as impurity. As far as practical production of 64Cu is concerned, small amounts have been generated via the reactions 68Zn(p,αn)64Cu33 and natZn(d,x)64Cu.34, 35 The reaction 64Ni(p,n)64Cu, originally suggested by the Jülich group, 36 has, however, become the method of choice, although the highly enriched 64Ni used as target material is rather expensive. The method has been developed to almost perfection at St. Louis36 and is also successfully used at Bethesda.37 This example demonstrates that the successful use of a suggested method is dependent on many factors, which are given above.

### FORMATION OF ISOMERIC STATES

A new feature of the non-standard PET nuclides in comparison to the standard PET nuclides is the occasional occurrence of isomeric states. In practice, one of the isomeric states is of interest and the other is merely an impurity. The ratio of their cross sections depends on the type of reaction through which they are produced. The production of 94mTc (T1/2 = 52 min) in the interaction of protons with enriched 94Mo constitutes a typical case. The excitation functions for the formation of various radionuclides 29 are shown in Figure 4. Through adjustment of the energy range in the target the products 93m,gTc are easily removed. However, the amount of undesired 94gTc in the desired 94mTc cannot be altogether eliminated. Over the energy range of E_p = 13 → 7 MeV, the 94gTc impurity in 94mTc amounts to 6%. In an attempt to decrease the level of the impurity, two other processes, namely 93Nb(3He,2n)94m,gTc and 92Mo(α,pn)94m,gTc, were also investigated. The level of the 94gTc impurity found was, however, 25% and 30%, respectively. Thus the 91Mo(p,αn)94m,gTc reaction is the best choice. It may be emphasized here that this type of fundamental nuclear investigations are mandatory to find the reaction giving the lowest level of the isomeric impurity, since the isomeric cross section ratio is difficult to

<table>
<thead>
<tr>
<th>Production route</th>
<th>Suitable energy range (MeV)</th>
<th>Calculated integral yield (MBq/µA·h)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>64Zn(n,p)64Cu</td>
<td>Fission spectrum</td>
<td>14.5*</td>
<td>27</td>
</tr>
<tr>
<td>64Ni(d,2n)64Cu</td>
<td>13 → 7</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>64Ni(p,n)64Cu</td>
<td>12 → 9</td>
<td>241</td>
<td>17</td>
</tr>
<tr>
<td>66Zn(d,α66Cu</td>
<td>13 → 7</td>
<td>6.6</td>
<td>29</td>
</tr>
<tr>
<td>natZn(d,x)64Cu</td>
<td>25 → 10</td>
<td>50</td>
<td>30, 31</td>
</tr>
<tr>
<td>68Zn(p,αn)64Cu</td>
<td>35 → 20</td>
<td>~100</td>
<td>32</td>
</tr>
</tbody>
</table>

*Activity/mg Zn at Φ_n = 8.7 × 10^{13} n cm^{-2} s^{-1} for 150 h. |
predict. Often even the most sophisticated nuclear model calculations reproduce the experimental data after considerable input parameter adjustments.\textsuperscript{38-40} Some of the important non-standard PET nuclides where isomeric states occur are $^{52m,g}$Mn, $^{82m,g}$Rb, $^{86m,g}$Y, $^{94m,g}$Tc, $^{120m,g}$I, etc.

**Integral yields**

The integral yield of a nuclear reaction product denotes the radioactivity achieved at the end of an irradiation. In charged particle induced reactions, it always refers to a definite projectile energy range effective within the target.

The integral yield can be calculated from the excitation function of a reaction. It can also be determined experimentally under production conditions. A comparison of the two values (\textit{i.e.} calculated and experimental yields) then reflects the quality of targetry and chemical processing related to large scale production of the radionuclide.

**Calculation of integral yield**

From a given excitation function, the expected yield of a product for a certain energy range, \textit{i.e.} target thickness, can be calculated\textsuperscript{41} using the expression:

$$Y = \frac{N_f H}{M} \int (1-e^{-\lambda t}) E \left( \frac{dE}{d\rho x} \right)^{-1} \sigma(E) dE$$

where $Y$ is the activity (in Bq) of the product, $N_f$ is the Avogadro number, $H$ is the enrichment (or isotopic abundance) of the target nuclide, $M$ is the mass number of the target element, $I$ is the projectile current, $dE/d(\rho x)$ is the stopping power, $\sigma(E)$ is the cross section at energy $E$, $\lambda$ the decay constant of the product and $t$ the time of irradiation. The limits of the integration give the energy range of the projectile effective in the target, and the yield is then valid for that energy range. The calculated yield value represents the maximum yield which can be expected from a given nuclear process. Such calculations are often done in radionuclide development programs. The assumptions made include: 1) specific energy range; 2) beam current of 1 $\mu$A; 3) irradiation time of 1 h.

Thus the calculated yield is given in the units MBq/$\mu$A·h.

As a typical example, the integral yields of $^{76}$Br, $^{75}$Br and $^{75}$Se calculated from the recently measured\textsuperscript{16} excitation functions of the reactions $^{76}$Se(p,xn)$^{75,76}$Br, $^{76}$Se(p,2n)$^{75}$Br and $^{76}$Se(p,pn)$^{75}$Se, respectively, are shown in Figure 5 as a function of proton energy. The shaded area gives the optimum energy range ($E_p=15\rightarrow 8$ MeV) for the production of $^{76}$Br: the $^{75}$Br is completely avoided and small amount of $^{75}$Se formed is removed chemically. The integral yield of $^{76}$Br over this energy range amounts to 360 MBq/$\mu$A·h.
and is obtained by subtracting the yield at 8 MeV from that at 15 MeV.

**CALCULATED YIELDS OF NON-STANDARD TOMOGRAPHY NUCLIDES**

The excitation functions of most of the non-standard PET nuclides have been relatively well investigated and, in general, therefrom the integral yields have been calculated. For the formation of some nuclides, a large number of reactions have been studied. For practical reasons, however, discussed above, only one or two nuclear routes have been developed for each nuclide to be produced in sufficient quantity and good quality. The production is done using an optimum energy range, i.e., a range giving the maximum yield of the product and the minimum amount of radionuclidic impurities.

An exhaustive documentation of calculated yields of various non-standard PET nuclides produced via all the routes is beyond the scope of this article. Instead attention was directed to one or two most commonly used production reactions for each radionuclide. For those reactions, then, the reported optimum energy range was adopted and the calculated yield of the radionuclide under study was deduced. Similarly, the major impurities and their magnitudes were estimated. The results are given in two tables. The short-lived radionuclides (with $T_{1/2} \leq 2$ h) are given in Table III. Those radionuclides have found only some limited applications. In Table IV are listed the longer lived non-standard PET nuclides which have been used in one way or the other for many years. It, however, does not include a few radionuclides like $^{45}$Sc and $^{74}$As for which (according to the judgement of this author) accurate excitation functions are not available, although those radionuclides have been practically produced in small quantities and used in a few studies.

**COMPARISON OF THEORETICAL AND PRACTICAL YIELDS OF NON-STANDARD POSITRON EMISSION TOMOGRAPHY NUCLIDES**

In order to demonstrate the feasibility of medical application of a radionuclide it has to be produced in sufficient quantity. This involves irradiation of a relatively thick target at a high beam current for a sufficiently long period, followed by its chemical processing to isolate the desired radionuclide from the matrix activity. The radionuclide activity extrapolated to the end of bombardment is called the “batch yield.” It is then normalized to beam current and time of irradiation. The result is then in units of MBq/µA and is denoted as “experimental thick target yield.” If now it is compared with the yield calculated from the excitation function of the radionuclide the difference is the yield of radionuclidic impurities.

### Table III.—Short-lived non-standard PET nuclides ($T_{1/2} \leq 2$ h).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$T_{1/2}$</th>
<th>Common production route</th>
<th>Energy range (MeV)</th>
<th>Calculated yield (MBq/µAh)</th>
<th>Radionuclidic impurity (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{30}$P</td>
<td>2.5 min</td>
<td>$^{27}$Al($\alpha$,n)</td>
<td>28 → 10</td>
<td>740</td>
<td>—</td>
<td>42</td>
</tr>
<tr>
<td>$^{38}$K</td>
<td>7.5 min</td>
<td>$^{35}$Cl($\alpha$,n)</td>
<td>22 → 10</td>
<td>270</td>
<td>—</td>
<td>43</td>
</tr>
<tr>
<td>$^{51}$Mn</td>
<td>46.2 min</td>
<td>$^{50}$Ca($\alpha$,n)*</td>
<td>16 → 12</td>
<td>777</td>
<td>—</td>
<td>44</td>
</tr>
<tr>
<td>$^{62}$Cu**</td>
<td>9.7 min</td>
<td>$^{62}$Ni($p$,n)*</td>
<td>14 → 10</td>
<td>$1.2 \times 10^3$</td>
<td>61, 64Cu (&lt;4)</td>
<td>45</td>
</tr>
<tr>
<td>$^{75}$Br</td>
<td>1.6 h</td>
<td>$^{75}$As($^{2}$He,3n)</td>
<td>10 → 4</td>
<td>700</td>
<td>—</td>
<td>46</td>
</tr>
<tr>
<td>$^{77}$Kr</td>
<td>1.2 h</td>
<td>$^{77}$Se($^{3}$He,3n)*</td>
<td>36 → 15</td>
<td>$3 \times 10^3$</td>
<td>$^{76}$Br (1.7)</td>
<td>47</td>
</tr>
<tr>
<td>$^{94m}$Tc</td>
<td>52 min</td>
<td>$^{91}$Mo(p,n)</td>
<td>9 → 7</td>
<td>$5 \times 10^3$</td>
<td>$^{94}$Tc (6)</td>
<td>48</td>
</tr>
<tr>
<td>$^{110m}$In</td>
<td>1.1 h</td>
<td>$^{111}$Cd(p,2n)*</td>
<td>23 → 16</td>
<td>$6 \times 10^3$</td>
<td>$^{110}$In (10)</td>
<td>51</td>
</tr>
<tr>
<td>$^{120}$I</td>
<td>1.3 h</td>
<td>$^{120}$Te(p,2n)</td>
<td>15 → 9</td>
<td>$2 \times 10^5$</td>
<td>$^{120}$I (1.8)</td>
<td>52</td>
</tr>
</tbody>
</table>

*Using highly enriched target isotope; **the preferred method of production of this radionuclide is the $^{62}$Zn-$^{62}$Cu generator route. The parent nuclide is produced via the $^{60}$Cu(p,2n)$^{60}$Zn reaction.
tation function over the same energy range as for the thick target, the ratio reflects the efficiency of the applied production methodology.

For all the non-standard PET nuclides listed in Tables III and IV both theoretical and experimental yields are available. The general result is that the experimental yield is always lower than the theoretical value. Some of the reasons may be: a) uncertainty in the thickness of the irradiated sample; b) inhomogeneity of the target; c) undefined chemical composition of the target; d) lower enrichment of the target. The theoretical yield calculation is generally for a 100% enriched metallic/element target; e) uncertainty in the projectile beam intensity. In production runs often defocused and wobbled beams are used, resulting in deflection of part of the beam from the target (which is not separately recorded to be able to introduce a correction); f) materials damage due to high current; g) loss of the product during irradiation; h) loss of the radioactive product during chemical processing.

The experimental yield is thus strongly dependent on high current targetty and chemical processing of the irradiated material. The yields often vary between 20% and 80% of the theoretical values. In the methodological development of a radionuclide, a relatively low yield may be sufficient to perform the feasibility tests. However, when real applications increase, the demands on the availability of the radionuclide increase. Out of all the non-standard PET nuclides listed in Tables III and IV, 7 of them, viz. $^{64}$Cu, $^{72}$As, $^{73}$Se, $^{76}$Br, $^{86}$Y, $^{94m}$Tc and $^{124}$I, have been receiving enhanced attention. The basic cross section data and calculated yields are available as standard data. Several laboratories around the world, and even a few commercial companies, are spending lot of efforts to enhance the batch yields as well as the thick target yields. The latter involves optimization work to obtain the experimental value as close to the theoretical value as possible.

### Conclusions

The decay data of most of the non-standard PET nuclides are generally well known, except for the positron emission intensity in a few cases. Using very pure radioactive samples and modern techniques of X-ray and $\gamma$-ray spectroscopy, it is possible to determine the $I_{\beta+}$ values accurately. The development of a non-standard PET nuclide for applications demands some fundamental nuclear chemistry research.

### Table IV. Non standard PET nuclides with intermediate half-lives ($T_{1/2} \geq 2\ h$).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$T_{1/2}$</th>
<th>Common production route</th>
<th>Energy range (MeV)</th>
<th>Calculated yield (MBq/µAh)</th>
<th>Radionuclidic impurity (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{52}$Mn</td>
<td>5.6 d</td>
<td>natCr(p,xn)</td>
<td>20 → 10</td>
<td>0.4</td>
<td>$^{54}$Mn (&lt;0.5)</td>
<td>45</td>
</tr>
<tr>
<td>$^{52}$Fe</td>
<td>8.3 h</td>
<td>$^{55}$Mn(p,4n)</td>
<td>100 → 60</td>
<td>22</td>
<td>$^{54}$Fe (&lt;2)</td>
<td>54</td>
</tr>
<tr>
<td>$^{52}$Fe</td>
<td>8.3 h</td>
<td>$^{52}$Cr(He,3n)</td>
<td>36 → 17</td>
<td>1.3</td>
<td>$^{54}$Fe (&lt;0.01)</td>
<td>53</td>
</tr>
<tr>
<td>$^{55}$Co</td>
<td>17.6 h</td>
<td>$^{50}$Ni(p,n)$^{54}$Fe</td>
<td>15 → 7</td>
<td>14</td>
<td>$^{57}$Co (0.5)</td>
<td>21</td>
</tr>
<tr>
<td>$^{61}$Cu</td>
<td>3.4 h</td>
<td>$^{64}$Ni(p,n)$^{54}$Fe</td>
<td>12 → 9</td>
<td>647</td>
<td>$^{61}$Cu (14.6)</td>
<td>17</td>
</tr>
<tr>
<td>$^{64}$Cu</td>
<td>12.7 h</td>
<td>$^{64}$Ni(p,n)$^{54}$Fe</td>
<td>12 → 9</td>
<td>236</td>
<td>$^{61}$Cu (0.4)</td>
<td>17</td>
</tr>
<tr>
<td>$^{66}$Ga</td>
<td>9.4 h</td>
<td>natGe(p,xn)</td>
<td>18 → 8</td>
<td>93</td>
<td>$^{61}$As (&lt;10)</td>
<td>56</td>
</tr>
<tr>
<td>$^{75}$Se</td>
<td>7.1 h</td>
<td>$^{75}$As(p,3n)</td>
<td>40 → 30</td>
<td>1.×10³</td>
<td>$^{72}$Se (&lt;0.2)</td>
<td>25</td>
</tr>
<tr>
<td>$^{82m}$Rb</td>
<td>6.2 h</td>
<td>$^{82}$Kr(p,n)$^{86}$Sr</td>
<td>18 → 10</td>
<td>11</td>
<td>$^{81}$Rb (1.6)</td>
<td>47</td>
</tr>
<tr>
<td>$^{85}$Sr</td>
<td>32.4 h</td>
<td>$^{85}$Rb(p,3n)</td>
<td>37 → 30</td>
<td>160</td>
<td>$^{85}$Sr (0.24)</td>
<td>58</td>
</tr>
<tr>
<td>$^{89}$Zr</td>
<td>14.7 h</td>
<td>$^{88}$Sr(p,n)$^{92}$Zr</td>
<td>14 → 10</td>
<td>400</td>
<td>$^{88m}$Y (3)</td>
<td>18</td>
</tr>
<tr>
<td>$^{92}$Nb</td>
<td>78.4 h</td>
<td>$^{92}$Sr(p,n)$^{95}$Nb</td>
<td>12 → 6</td>
<td>43</td>
<td>$^{89}$Zr (&lt;0.1)</td>
<td>59</td>
</tr>
<tr>
<td>$^{124}$I</td>
<td>4.18 d</td>
<td>$^{124}$Te(p,n)$^{128}$I</td>
<td>12 → 8</td>
<td>16</td>
<td>$^{124}$I (0.1)</td>
<td>11</td>
</tr>
</tbody>
</table>

*Using highly enriched isotope as target material.
Measurement of the excitation function of a nuclear reaction allows optimization of the production route. The theoretical yield of a radioactive product calculated from the excitation function gives always the maximum achievable yield. Efforts related to targetry and chemical processing are then constantly under improvement to get the experimental yield value as close to the theoretical value as possible. Many of the important non-standard PET nuclides (64Cu, 72As, 80Br, 86Y, 94mTc, 124I, etc.) can be produced in good yields at low energy cyclotrons (E_p<18 MeV), using highly enriched target materials. For production of some other radionuclides, e.g. 54Fe, 75Se, 85Sr and 125I (in large quantities), an intermediate energy cyclotron is required.

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