Excitation functions and thick-target yields for radioisotopes induced in natural Mg, Co, Ni and Ta by medium energy protons

F.J. HAASBROEK, J. STEYN, R.D. NEIRINCKX and G.F. BURDZIK
National Physical Research Laboratory, C.S.I.R., Pretoria, South Africa

and

M. COGNEAU and P. WANET
Laboratoire de Chimie Inorganique et Nucléaire, Université de Louvain, Louvain-la-Neuve, Belgium

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Laboratoire de Chimie Inorganique et Nucléaire, Université de Louvain, Louvain-la-Neuve, Belgium

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ABSTRACT

Excitation functions were determined with protons of energy up to 100 MeV for the production of Na-22 in natural magnesium; Fe-55, Co-55, Co-56, Ni-56, Co-57, Ni-57 and Co-58 in natural cobalt; Co-55, Co-56, Ni-56, Co-57, Ni-57 and Co-58 in natural nickel and Hf-175 in natural tantalum by the stacked-foil technique. Thick-target yields were calculated from the excitation functions and were also determined directly for Na-22 and Fe-55. 100 MeV protons yielded production rates of: 65 μCi.uAh⁻¹ for Na-22 in magnesium; 750 μCi.uAh⁻¹ for Co-56, 356 μCi.uAh⁻¹ for Co-57 and 310 μCi.uAh⁻¹ for Co-58 in nickel; 638 μCi.uAh⁻¹ for Hf-175 in tantalum. With 85 MeV protons the production rates were found to be: 31,6 μCi.uAh⁻¹ for Fe-55, 2,11 x 10³ μCi.uAh⁻¹ for Co-55, 19,5 μCi.uAh⁻¹ for Ni-56 and 1,47 x 10³ μCi.uAh⁻¹ for Ni-57 in cobalt; 1,28 x 10⁴ μCi.uAh⁻¹ for Co-55, 507 μCi.uAh⁻¹ for Ni-56 and 2,10 x 10⁴ μCi.uAh⁻¹ for Ni-57 in nickel.
EXCITATION FUNCTIONS AND THICK-TARGET YIELDS FOR RADIOISOTOPES INDUCED IN NATURAL Mg, Co, Ni and Ta BY MEDIUM ENERGY PROTONS

National Physical Research Laboratory, CSIR
Pretoria, South Africa

M. Cogneau and P. Wanet
Laboratoire de Chimie Inorganique et Nucléaire,
Université de Louvain, Louvain-la-Neuve, Belgium

INTRODUCTION
Routine production of radioisotopes in the Pretoria cyclotron for biological, industrial and medical applications started during 1964. Since then the demand for a greater variety and larger amounts of cyclotron isotopes has increased progressively. However, due to the relatively low maximum projectile energies obtainable with the current machine (protons: 14.5 MeV; deuterons: 17.5 MeV; helium-3-particles: 37 MeV and alpha-particles: 34 MeV) these increased demands can only be satisfied to a limited extent. A program was therefore initiated to investigate the potential of projectiles of higher energy for the commercial production of radioisotopes. These studies form part of a Feasibility Study for a National Accelerator Facility for the Republic of South Africa.

Excitation functions and cross-sections for large numbers of nuclear reactions by charged particles have already been reported in the literature. Progress has also been made with the estimation of excitation functions by semi-empirical procedures. Despite this, it is
often still difficult to find adequate information to make an accurate estimate of the potential production rates of specific radioisotopes. This applies in particular when targets of the natural elements, i.e. consisting of a number of stable isotopes, are to be bombarded with medium to high energy projectiles, because several different reactions can contribute to the production of a desired radioisotope. The possibilities of a concurrent production of undesirable radioisotopic impurities are also much higher under these circumstances. Against this background it was decided to determine experimentally the potential production rates of a number of radioisotopes in targets of the natural elements.

Excitator functions for the production of Na-22 in magnesium, Fe-55, Co-55, Co-56, Ni-56, Co-57 and Co-58 in cobalt, Co-55, Co-56, Ni-56, Co-57, Ni-57 and Co-58 in nickel and Hf-175 in tantalum were measured by the stacked-foil technique. A preliminary bombardment of a single stack of the four target elements, staggered in rotation, was made with 100 MeV protons in the Maryland cyclotron. Subsequent bombardments of three similar stacks were performed in the Louvain-la-Neuve cyclotron with 85 MeV protons. In addition, thick targets of magnesium and cobalt were bombarded for the direct measurement of thick-target yields of Na-22 and Fe-55. In these studies, special consideration was given to the production of radioisotopically pure cobalt isotopes.

EXPERIMENTAL PROCEDURE

Target preparation

Circular discs of the target elements were prepared by turning stacked sheets of the elements to a diameter of 29 mm on a lathe. The diameter was measured accurately before dismounting the stack of discs from the lathe. After cleaning, the individual discs were weighed accurately. In preparing the targets for bombardment the sequence of the four elements was changed in replicate stacks so as to
spread the experimental points more evenly over the energy range involved. Apart from the target discs no other degrader or catcher foils were employed in the stacks.

Thick targets of magnesium were made in the form of solid rods of diameter 29 mm while thick targets of cobalt were prepared by stacking 1 mm thick circular discs to the required thickness. All the targets were made thick enough to stop the proton beam completely; the relevant information on the target materials is presented in Table 1.

**TABLE 1 : PARTICULARS OF TARGET MATERIALS**

<table>
<thead>
<tr>
<th>Target elements</th>
<th>Thickness range (mg.cm(^{-2}))</th>
<th>Chemical purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discs in stacks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural magnesium</td>
<td>130 to 260</td>
<td>&gt;99.9</td>
</tr>
<tr>
<td>Natural cobalt</td>
<td>220</td>
<td>99.99*</td>
</tr>
<tr>
<td>Natural nickel</td>
<td>220</td>
<td>99.99*</td>
</tr>
<tr>
<td>Natural tantalum</td>
<td>250</td>
<td>99.95*</td>
</tr>
<tr>
<td>Thick targets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural magnesium</td>
<td>3800, 5700 and 7900</td>
<td>&gt;99.9</td>
</tr>
<tr>
<td>Natural cobalt</td>
<td>10 x 890</td>
<td>99.9*</td>
</tr>
</tbody>
</table>

* Information furnished by supplier: Goodfellow Metals Ltd., Cambridge, England

**Bombardments**

During bombardments the stacks and thick targets were clamped in a special water-cooled holder fitted in a Faraday-cup. The charge collected on the Faraday-cup was measured accurately with a calibrated current integrator having a sensitivity of one count per 10\(^{-6}\) coulombs. The complete system was checked with a standard current source prior to each bombardment. From the dimensions of the Faraday-cup and the size of the beam entrance aperture in the guardring, it was estimated that less than 1 % of the secondary charged particles could escape undetected.
Particulars of the bombardments are summarized in Table 2.

**TABLE 2: PARTICULARS OF BOMBARDMENTS**

<table>
<thead>
<tr>
<th>Target and cyclotron</th>
<th>Incident proton energy (MeV)</th>
<th>Average beam intensity (µA)</th>
<th>Approximate duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maryland Stack No 1</td>
<td>100 ± 2</td>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Louvain-La-Neuve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack No 2, 3 and 4</td>
<td>85 ± 0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Thick targets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium No 1 and 2</td>
<td>85 ± 0.5</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Magnesium No 3 and 4</td>
<td>70 ± 0.4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Magnesium No 5 and 6</td>
<td>55 ± 0.3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cobalt No 1 and 2</td>
<td>85 ± 0.5</td>
<td>1.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Radioactivity measurements**

Autoradiographs were prepared from the top and bottom discs of the bombarded stacks to determine the dispersion of the beam as it traversed the stack and also to verify that it was properly collimated and focused on the stack. The radioisotopes induced in the targets were identified and their activity in the individual discs measured directly by means of 4096-channel gamma-spectrometers fitted with Ge(Li)-detectors. Only Fe-55 was separated chemically from the cobalt discs before it was measured by an absolute standardization technique based on liquid scintillation counting. The Ge(Li)-detectors were calibrated by employing the accurately known relative intensities of the gamma-rays of a thin disc Mo-152g source together with thin disc Na-22, Co-57 and Cs-137 standard sources. The maximum uncertainties in the activities of the standard sources
are given as 2.5%.

The activity of the Na-22 produced in the magnesium rods was measured in an ionization chamber by comparing it with a standard Na-22 solution (maximum uncertainty 3%) of approximately similar dimensions.

Measurements on both the short-lived isotopes (Co-55, Ni-56 and Ni-57) and the longer-lived isotopes commenced 1.3 days after bombardment and were conducted in the Inorganic and Nuclear Chemistry Laboratory of the University of Louvain at Louvain-la-Neuve. This was followed 35 days later by a second set of measurements in the National Physical Research Laboratory (NPRL), Pretoria, which involved only the longer-lived isotopes. The samples of the preliminary bombardment in the Maryland cyclotron were measured in the NPRL only after the short-lived isotopes had decayed completely.

Chemical separations

The Fe-55 induced in the cobalt discs and thick targets was separated from its matrix by liquid-liquid extraction based on the use of di-isopropyl-ether. Prior to separation the amount of iron impurity in each matrix was determined and a known amount of carrier iron was added for the accurate determination of the chemical yield by atomic absorption spectrometry measurements.

Calculations

The gamma-ray photopeak areas were calculated with an adapted version of a computer program AUTSPAN designed for the automatic analysis of gamma-spectra. The decay parameters employed for calculating the activities of the individual radioisotopes induced in the targets are summarized in Table 3. Relative efficiency curves were calculated for both the Eu-152g gamma-rays whereby the efficiency of the 0.1218 MeV gamma was taken as unity and the gamma-rays of the

* Laboratoire de Métrologie des Rayonnements ionisants, Gif Sur Yvette, France.
TABLE 3: SUMMARY OF DECAY PARAMETERS USED IN THE CALCULATIONS 9,10

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Gamma-ray energy (MeV)</th>
<th>Fraction of total disintegrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-22</td>
<td>953 d</td>
<td>1.2745</td>
<td>1,000</td>
</tr>
<tr>
<td>Fe-55</td>
<td>959 d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-55</td>
<td>0.758 d</td>
<td>0.9311</td>
<td>0.73</td>
</tr>
<tr>
<td>Co-56</td>
<td>77.3 d</td>
<td>0.84675</td>
<td>1.000</td>
</tr>
<tr>
<td>Ni-56</td>
<td>6.1 d</td>
<td>0.1583</td>
<td>1.00</td>
</tr>
<tr>
<td>Co-57</td>
<td>270.9 d</td>
<td>0.12206</td>
<td>0.851</td>
</tr>
<tr>
<td>Ni-57</td>
<td>1.50 d</td>
<td>0.1273</td>
<td>0.15</td>
</tr>
<tr>
<td>Co-58</td>
<td>71.1 d</td>
<td>0.81075</td>
<td>0.99</td>
</tr>
<tr>
<td>Cs-137</td>
<td>11000 d</td>
<td>0.6616</td>
<td>0.855</td>
</tr>
<tr>
<td>Hf-175</td>
<td>70 d</td>
<td>0.3434</td>
<td>0.85</td>
</tr>
</tbody>
</table>

three standard sources whereby also the efficiency of the 0.1221 MeV gamma of Co-57 was taken as unity. Under ideal conditions these two curves should be almost identical. They therefore served to indicate how accurately the detectors could be calibrated including the variations that could be expected when both complex and simple gamma-spectra are involved.

The energy degradation of the proton beam in the stack was calculated with a computer program DEGRADE which is based on the formulae proposed by Williamson, Boujot and Picard. Corrections for the attenuation of the proton beam intensity were calculated by making use of experimentally determined total cross-sections ($\sigma_\tau$)12,13,14. Where necessary values for $\sigma_\tau$ were obtained by interpolation based on the approximately linear relationship14 between $\sigma_\tau$ and $A^2/3$ where $A$ is the mass number of the element concerned.

As most of the radioisotopes under study are produced via more than one nuclear reaction (Table 4), the excitation
functions were calculated in units of the radioactivity induced per unit target thickness and unit beam current (y expressed in \( \text{nCi.\mu A h^{-1}.mg^{-1}.cm^2} \)) rather than cross-sections. Thick-target yields (Y expressed in \( \mu \text{Ci.\mu A h^{-1}} \)) were calculated from the excitation functions by means of the relationship:

\[
Y = \frac{E_{\text{max}} \cdot I \cdot \sum y.I. \cdot \frac{dE}{d(P_x)}^{-1} \cdot \Delta E}{\text{Threshold}}
\]

where \( I \) is the calculated attenuation factor for the beam current in the stack,
\( \frac{dE}{d(P_x)} \) the stopping power (in \( \text{MeV.cm^{-1}.g^{-1}} \)) and \( \Delta E \) increments of 5 MeV.

RESULTS AND DISCUSSION

The autoradiographs indicated that the proton beam was properly focused on the targets and that the dispersion of the beam was too small to cause significant losses of protons from the stacks in a lateral direction. The calculated total attenuation of the 85 MeV beam current before it was stopped amounts to approximately 7.5%. The corrections for the calculated thick-target yields for protons of the same energy due to beam attenuation amount to approximately 3.5%.

The calculated relative efficiencies of the detectors for the gamma-rays of the Na-22 and Cs-137 standards agree to within ±2.5% with corresponding values obtained from the Eu-152g relative efficiency curve. The experimental points from the two independent relative efficiency curves were therefore pooled into a single curve (Fig. 1), which together with the known activities of the standard sources, was used to calculate the unknown activities of the radioisotopes induced in the bombarded discs.

The activities induced in the discs were such that more than \( 10^4 \) counts could be collected for most of the peak areas analyzed. Exceptions were Ni-56 in the cobalt discs for which the total counts ranged from \( 1 \times 10^3 \) to \( 2.5 \times 10^3 \) and Co-56 and Ni-57 in cobalt and Co-55, Co-56 and Co-57 in nickel for which the counts ranged from \( 3 \times 10^3 \) upwards for
TABLE 4: SUMMARY OF TARGET NUCLEI, SOME NUCLEAR REACTIONS INVOLVED, RADIOISOTOPES INDUCED AND THRESHOLD VALUES

<table>
<thead>
<tr>
<th>Target nuclei</th>
<th>Reactions</th>
<th>Product</th>
<th>Threshold* (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24}$Mg (78.7 %)</td>
<td>Several possibilities leading directly or indirectly to $^{22}$Na: $(p,xn); (p,ypxn); (p,αxn)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{25}$Mg (10.1 %)</td>
<td></td>
<td>$^{22}$Na</td>
<td>17.1</td>
</tr>
<tr>
<td>$^{26}$Mg (11.2 %)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{59}$Co (100.0 %)</td>
<td>$(p,4n)$; $(p,2p3n)$; $(p,xn)$</td>
<td>$^{55}$Co</td>
<td>41.2</td>
</tr>
<tr>
<td>$^{60}$Ni (67.8 %)</td>
<td>$(p,xn)$; $(p,2p2n)$</td>
<td>$^{56}$Ni</td>
<td>33.9</td>
</tr>
<tr>
<td>$^{58}$Ni (26.2 %)</td>
<td>$(p,pn)$; $(p,p3n)$; $(p,α)$</td>
<td>$^{57}$Ni</td>
<td>19.4</td>
</tr>
<tr>
<td>$^{181}$Ta (100.0 %)</td>
<td>$(p,7n)^{175}$W $^{34}$ min $^{175}$Ta $^{175}$Hf</td>
<td></td>
<td>48.5</td>
</tr>
<tr>
<td>$^{175}$Ta $^{10}$ min $^{175}$Hf</td>
<td>$^{175}$Hf</td>
<td></td>
<td>44.8</td>
</tr>
<tr>
<td>$^{175}$Hf</td>
<td>$^{175}$Hf</td>
<td></td>
<td>13.3</td>
</tr>
</tbody>
</table>

the Louvain-la-Neuve measurements. The Ni-57 activities calculated from the 0.1273 MeV peak were from 5 % to 8.5 % higher than those obtained from the 1.3776 MeV peak, and this discrepancy is most probably due to uncertainties in the
branching ratios (Table 3). The average of the two values was used. The results of the measurements in the two laboratories compared favourably. For instance, the activities of Co-57 in the cobalt and nickel discs as measured at the NRCRL and Louvain-la-Neuve agreed within 2.5% and 5% respectively. The Louvain-la-Neuve results consist of the sum of the directly measured Co-57 activity and the contribution calculated from the measured Ni-57 precursor. In the case of the nickel discs from 36% to 45% of the Co-57 was produced by the decay of Ni-57.

Activity lost from the discs by recoils being ejected in the forward direction was estimated from the measured activities of radioisotopes transferred between adjacent target discs as being less than 0.3%. No corrections were therefore made for these losses.

The results of the preliminary bombardment in the Maryland cyclotron agreed fairly well with those of the final experiment conducted at Louvain-la-Neuve. The results of the former could therefore be used to extrapolate the thick-target yield curves of the Louvain-la-Neuve experiment from 85 MeV to approximately 100 MeV. This applies to the longer-lived isotopes only. The overall uncertainties in the calculated excitation functions, on the basis of estimated systematic errors, reproducibility of the results and uncertainties in the various parameters used for the calculations, are estimated to be between 6% and 9%.

**Magnesium target**

The excitation function and thick-target yield curve for Na-22 in Mg are presented in Fig. 2. Table 5 shows that there is good agreement between the directly measured and calculated thick-target yields. With 100 MeV protons a thick-target yield of approximately 65 μCi.μAh⁻¹ seems possible which is approximately twentyfold higher than the current production rate of Na-22 obtained in the Pretoria cyclotron by bombardment of magnesium with 16 MeV deuterons. Our excitation function agrees within the limits of the
stated errors with the excitation functions made up by De Lassus St-Genies and Tobailem from the results of Bimbot and Gauvin, Furukawa, Shizuri, Komura, Sakamoto and Tanaka, Korteling and Caretto and others. The maximum of our total cross-section calculated from Fig. 2 is 82 mb as compared with a value of 79 mb reported by Furukawa et al. The value reported by Meadow and Holt is approximately 40% lower.

**TABLE 5: CALCULATED AND DIRECTLY MEASURED THICK-TARGET YIELDS OF Na-22 IN NATURAL Mg**

<table>
<thead>
<tr>
<th>Proton energy (MeV)</th>
<th>Thick-target yield (in µCi.µAh⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
</tr>
<tr>
<td>55</td>
<td>19.0</td>
</tr>
<tr>
<td>70</td>
<td>33.8</td>
</tr>
<tr>
<td>85</td>
<td>49.0</td>
</tr>
</tbody>
</table>

**Cobalt target**

The excitation functions and thick-target yield curves for the radioisotopes induced in the cobalt discs are presented in Figures 3 to 7. From a comparison of the Fe-55 and Co-55 thick-target yield curves (Figures 3 and 4) it was deduced that only a small fraction of Fe-55 is formed via the $^{59}$Co(p,p₄n)$^{55}$Co reaction and that the $^{59}$Co(p,αn)$^{55}$Fe and $^{59}$Co(p,2p3n)$^{55}$Fe reactions apparently predominate. Figure 3 indicates a potential production rate of 31 µCi.µAh⁻¹ for Fe-55 in cobalt with 85 MeV protons. The directly measured thick-target yield of 31.9 ± 1.6 µCi.µAh⁻¹ is in close agreement. The current production rate obtained in the Pretoria cyclotron with 16 MeV deuterons on manganese is 4.5 µCi.µAh⁻¹. From the thick-target yield curves in Figures 5, 6 and 7 it was calculated that the (p,4n)$^{56}$Ni and (p,3n)$^{57}$Ni reactions contribute very little to the total amounts of Co-56 and Co-57 induced in the cobalt discs. This excludes the possibility of obtaining useful amounts of carrier-free and radioisotopically pure Co-56 and Co-57 from proton-bombarded cobalt targets by a selective chemical
separation of the nickel isotopes shortly after bombardment.

The maxima of the total cross-sections for the production of Co-55, Ni-56 and Ni-57 in cobalt as reported by Sharp, Diamond and Wilkinson agree, within the limits of the stated errors, with the current results. This is not the case for Co-56, Co-57 and Co-58, however, for which considerable differences exist. These differences are most probably attributable to the less accurate measuring techniques employed by Sharp et al. The positions of the maxima, however, agree with each other to within 1 MeV.

Nickel target

The results for the nickel discs are presented in Figures 8 to 11. Figure 8 shows a potential production rate of \(1.3 \times 10^4\) \(\mu\text{Ci.\mu Ah}^{-1}\) for Co-55 in natural nickel bombarded with 85 MeV protons. With 100 MeV protons relatively high production rates of Co-56 (750 \(\mu\text{Ci.\mu Ah}^{-1}\)), Co-57 (356 \(\mu\text{Ci.\mu Ah}^{-1}\)) and Co-58 (310 \(\mu\text{Ci.\mu Ah}^{-1}\)) are achievable (Fig. 9). If this mixture is left to decay for approximately 800 days a sample with an effective production rate for Co-57 of approximately 45 \(\mu\text{Ci.\mu Ah}^{-1}\) and containing 1 % Co-56 and 0.3 % Co-58 would be obtained. Krasnov and Dmitriev obtained a Co-57 yield of 35 \(\mu\text{Ci.\mu Ah}^{-1}\) containing 0.9 % Co-58 for nickel bombarded with 22 MeV protons. From the thick-target yields (Figures 10 and 11) it was calculated that 7 % of the Co-56 activity is formed via Ni-56 and 40 % of Co-57 via Ni-57. However, further calculations showed that a chemical separation of the directly produced cobalt isotopes from the nickel target followed by a second separation 1,5 days later would render a Co-57 sample with an effective production rate of only 58 \(\mu\text{Ci.\mu Ah}^{-1}\) containing 11 % Co-56. This is worse than the first possibility where use is made of a long decay period only.

The maxima of the total cross-sections for the formation of Co-55, Co-56, Co-57, Ni-56 and Ni-57 in nickel obtained from Figures 8, 9, 10 and 11 agree, within the stated overall
errors, with the results of Tanaka, Furukawa and Chiba. The maximum cross-section for Co-58, however, is more than 40% higher than the value reported by Tanaka et al. The positions of the various maxima of the cross-sections are also up to 5 MeV higher than those of the same authors.

**Tantalum target**

The results presented in Fig. 12 show that protons of energy higher than 70 MeV are required for the production of Hf-175 and that 100 MeV protons would yield a production rate of approximately 640 μCi·μAh⁻¹. The cross-sections derived from Fig. 12 at 64, 74 and 84 MeV for the formation of Hf-175 in tantalum agree, within the limits of the overall errors, with the results of Rao and Yaffe. Traces of Hf-172 were detected in tantalum discs which were bombarded with protons of energy higher than 75 MeV.

**ACKNOWLEDGEMENTS**

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REFERENCES


6. AUBIN, G., BARETTE, J., BARETTE, M. and MONARO, S. Precision measurements of gamma-ray intensities and energies in the decay of 152Eu, 154Eu, 56Co, 110mAg and 125Sb. Nucl. Instr. and Meth. 76, 93, 1969.


11. WILLIAMSON, C.P., BOUJOT, J.P. and PICARD, J. Tables of range and stopping power of chemical elements for charged particles of energy 0.05 to 500 MeV. Rep. CEA-R3042, Saclay, 1966.


15. RÖHM, H.P., VERWEY, C.J., STEYN, J. and RAUTENBACH, W.L. Excitation functions for the $^{24}\text{Mg}(d, a)^{22}\text{Na}$, $^{26}\text{Mg}(d, a)^{24}\text{Na}$ and $^{27}\text{Al}(d, a)^{24}\text{Na}$ reactions. J. inorg. nucl. Chem. 31, 3345, 1969.


18. FURUKAWA, M., SHIZURI, K., KOMURA, K., SAKAMOTO, K. and TANAKA, S. Production of $^{26}\text{Al}$ and $^{22}\text{Na}$ from proton bombardment of Si, Al and Mg. Nucl. Phys. A. 174, 539, 1971.
Figure 2.

Excitation function (A) and thick-target yield curve (B) for Na-22 induced by protons in natural magnesium.
Figure 2.
Excitation function (A) and thick-target yield curve (B) for Fe-55 induced by protons in natural cobalt.
Excitation function (A) and thick-target yield curve (B) for Co-55 induced by protons in natural cobalt.
Figure 8.
Excitation functions (A) and thick-target yield curves (B) for Co-56, Co-57 and Co-58 induced by protons in natural cobalt.
Figure 6.
Excitation function (A) and thick-target yield curve (B) for Ni-56 induced by protons in natural cobalt.
Figure 7.
Excitation function (A) and thick-target yield curve (B) for Ni-57 induced by protons in natural cobalt.
Figure 8.
Excitation function (A) and thick-target yield curve (B) for Co-55 induced by protons in natural nickel.
Figure 9.
Excitation functions (A) and thick-target yield curves (B) for Co-56, Co-57 and Co-58 induced by protons in natural nickel.
Figure 10.
Excitation function (A) and thick-target yield curve (B) for Ni-56 induced by protons in natural nickel.
Excitation function (A) and thick-target yield curve (B) for Ni-57 induced by protons in natural nickel.

Figure 11.
Figure 12.
Excitation function (A) and thick-target yield curve (B) for Hf-175 induced by protons in natural tantalum.