Radionuclide production and activation studies for the MICE target in ISIS

The Sheffield Target Team

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Introduction

Titanium targets are being used by the MICE collaboration for producing high intensity muon beams. The target interacts with protons in the ISIS synchrotron and will become activated via spallation. As a consequence a radiological study is desirable. FLUKA 2006 has been used to study radionuclide production in the titanium target and estimates of activation have been made assuming several irradiation and cooling scenarios.

FLUKA

FLUKA[1][2] is a general purpose Monte Carlo designed to model the transport and interaction of hadrons, heavy ions and electromagnetic particles in matter. It is widely used in a variety of fields including accelerator shielding, target design, calorimetry, activation studies and dosimetry and is capable of spanning a large energy range from a few KeV up to the TeV scale. Radionuclide production is calculated directly from inelastic hadronic interaction models therefore FLUKA can be used for arbitrary particle-target configurations and energies and is well suited for the purposes of this study.

Target Description

The MICE target is a thin slab of titanium with dimensions 35mm × 10mm × 1mm attached to the end of a cross shaped shaft 565mm long. The target is dipped into the beam at a rate of 1.0 Hz where it is assumed to interact with 1.4×10^{12} incident protons per pulse. The beam is assumed to be incident on the target 15mm from the base on the narrow face as indicated in Fig. 1 and to consist of 800 MeV protons only.

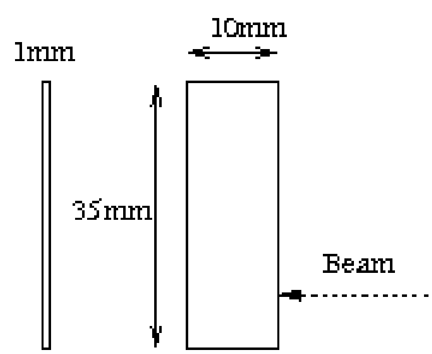


Figure 1. The geometry used for the target - beam interaction.

In the actual experiment the target was operated at 0.4 Hz and the total number of incident protons was far lower than this initial assumption. The value of 1.4×10^{12} protons on target was originally estimated to be the number required to give ~600 good muons and as such must be regarded as an aspirational value. During MICE shifts over the 2008 period the target was pulsed for a total of 185207 times in ISIS corresponding to less than 3 days full running. As a consequence the total target exposure and activation for 2008 was far less than it would be under full operational conditions. In this study radionuclide production per p-p is given and the activation values were calculated assuming full run periods and can be scaled appropriately.

Radionuclide production

The Table 1 below shows some of the significant radionuclide production per proton incident on the target. A full table of radionuclides is included at the end of the report.

Nuclide	Half-life	Production per p-p
^{48}V	16d	5.95×10^{-6}
^{45}Ti	3.08h	6.84×10^{-5}
^{48}Sc	43.7h	2.28×10^{-5}
^{47}Sc	3.35d	2.44×10^{-4}
^{46}Sc	83.81d	7.17×10^{-5}
^{44}Sc	2.44d	5.47×10^{-5}
^{43}Sc	3.9h	3.15×10^{-5}
^{47}Ca	4.54d	1.64×10^{-6}
^{41}Ca	10300y	6.48×10^{-5}
^{43}K	22.3h	1.20×10^{-5}
^{28}Mg	21.0h	1.02×10^{-6}
^{24}Na	14.95h	3.93×10^{-6}

Table 1. Some of the significant radionuclide species produced per incident proton.

Activation

No significant activation is expected for the target as operated during the 2008 run period as the total number of p-p interactions was limited. However if we assume a normal ISIS run schedule and further assume that MICE runs for 2 shifts per day then various activation scenarios can be explored. The original proposed ISIS run schedule for 2008 is given in Table 2 below.

Period	Beam on (days)	Beam off (days)
1	38	25
2	38	39
3	38	39
4	38	25
5	38	Cooling

Table 2. The proposed ISIS 2008 run schedule.

We investigate two irradiation scenarios, the first where we remove the target after one 38 day irradiation period and the second where the target is exposed to the full cycle of operations as given above. Activation is then calculated for several cooling times; one hour, one day, one week, one month, one year and ten years.

The activation for a single 38 day irradiation period is given in Table 3 below.

	Dominant activities (Bq) in the target					
Radionuclide	1 hour	1 day	1 week	1 month	1 year	10 years
^{48}V ^{47}V	4.79×10^6 1.15×10^6	4.59×10^6 -	3.54×10^6 -	1.30×10^6 -	- -	- -
^{45}Ti	5.46×10^7	3.09×10^5	-	-	-	-
^{48}Sc ^{47}Sc ^{46}Sc ^{44}Sc ^{43}Sc	2.25×10^7 2.48×10^8 3.86×10^7 9.98×10^7 2.65×10^7	1.56×10^7 2.00×10^8 3.83×10^7 4.43×10^7 4.40×10^5	1.59×10^6 5.82×10^7 3.65×10^7 7.96×10^6 -	249 5.42×10^5 3.01×10^7 3.66×10^4 -	- - 1.89×10^6 2.47×10^4 -	- - - 2.18×10^4 -
^{43}K	1.17×10^7	5.74×10^6	6.53×10^4	-	-	-
^{24}Na	8.04×10^6	2.77×10^6	3500	-	-	-

Table 3. Activation after a 38 day irradiation period.

The activation for the full 2008 ISIS run schedule is given in Table 4 below.

	Dominant activities (Bq) in the target					
Radionuclide	1 hour	1 day	1 week	1 month	1 year	10 years
^{48}V ^{47}V	5.11×10^6 1.15×10^6	4.90×10^6 -	3.78×10^6 -	1.39×10^6 -	- -	- -
^{45}Ti	5.46×10^7	3.09×10^5	-	-	-	-
^{48}Sc ^{47}Sc ^{46}Sc ^{44}Sc ^{43}Sc	2.25×10^7 2.48×10^8 8.39×10^7 9.99×10^7 2.65×10^7	1.56×10^7 2.00×10^8 8.33×10^7 4.44×10^7 4.40×10^5	1.59×10^6 5.82×10^7 7.92×10^7 8.06×10^6 -	249 5.42×10^5 6.55×10^7 1.36×10^5 -	- - 4.10×10^6 1.23×10^5 -	- - - 1.08×10^5 -
^{43}K	1.17×10^7	5.74×10^6	6.53×10^4	-	-	-
^{24}Na	8.04×10^6	2.77×10^6	3500	-	-	-

Table 4. Activation after the full ISIS run schedule.

Uncertainties in predictions

In order to give confidence in the accuracy of the results obtained with FLUKA two experimental studies of protons on titanium were examined and compared with FLUKA. The first of these studies[3] investigated the spallation yields from 590 MeV protons on titanium, the second [4] investigated 1.1 GeV protons on titanium.

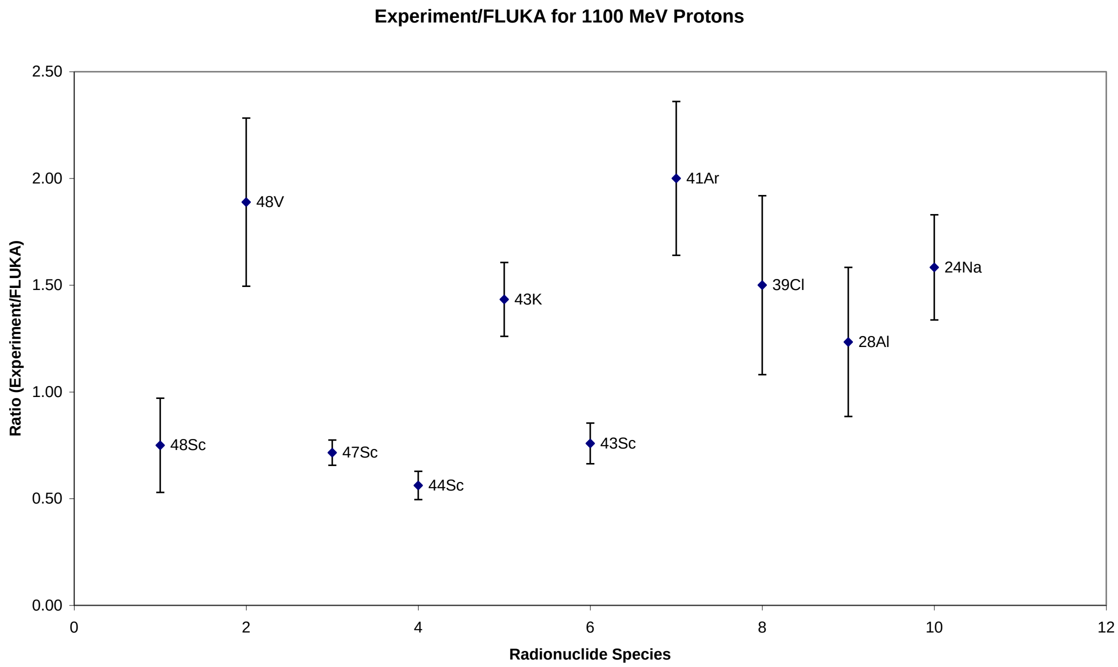
Nuclide	Experiment	Calculations	This work
^{48}V	1.22 ± 0.40	1.02 ± 0.35	1.46 ± 0.09
^{44}Ti	1.42 ± 0.40	0.62 ± 0.21	3.05 ± 0.33
^{43}Sc	6.94 ± 1.00	-	6.44 ± 0.25
^{44}Sc	16.80 ± 2.50	-	21.55 ± 0.69
^{46}Sc	29.50 ± 3.50	17.50 ± 5.60	24.23 ± 0.73
^{47}Sc	22.90 ± 3.50	17.40 ± 5.60	41.27 ± 1.71
^{48}Sc	2.80 ± 0.50	1.62 ± 0.52	4.02 ± 0.51
^{47}Ca	0.27 ± 0.09	-	0.30 ± 0.10
^{42}K	9.20 ± 1.20	6.00 ± 1.90	4.96 ± 0.21
^{43}K	3.70 ± 0.50	2.11 ± 0.68	1.85 ± 0.12
^{41}Ar	1.60 ± 0.60	-	0.35 ± 0.11
^{28}Mg	0.25 ± 0.08	0.10 ± 0.03	0.23 ± 0.06
^{22}Na	0.86 ± 0.15	0.64 ± 0.21	1.45 ± 0.12
^{24}Na	1.46 ± 0.21	0.87 ± 0.28	1.11 ± 0.09
^{7}Be	2.40 ± 0.40	1.22 ± 0.40	2.82 ± 0.33

Table 5. Beam Energy E=590GeV, Units (mb)

Nuclide	Experiment	Calculations	This work
^{48}Sc	0.42 ± 0.12	0.36 ± 0.10	0.56 ± 0.04
^{48}V	0.17 ± 0.03	0.14 ± 0.04	0.09 ± 0.01
^{47}Sc	4.02 ± 0.32	4.18 ± 0.39	5.62 ± 0.13
^{46}Sc	2.23 ± 0.67	0.36 ± 0.10	0.56 ± 0.04
^{45}K	0.07 ± 0.02	0.05 ± 0.02	0.03 ± 0.01
^{44}Sc	1.28 ± 0.15	1.04 ± 0.21	2.28 ± 0.03
^{43}K	0.43 ± 0.05	0.51 ± 0.12	0.30 ± 0.01
^{43}Sc	0.44 ± 0.04	0.38 ± 0.09	0.58 ± 0.05
^{41}Ar	0.20 ± 0.03	0.25 ± 0.09	0.10 ± 0.01
^{39}Cl	0.12 ± 0.03	0.16 ± 0.05	0.08 ± 0.01
^{38}S	0.10 ± 0.03	0.07 ± 0.02	0.01 ± 0.01
^{38}Cl	0.23 ± 0.07	0.27 ± 0.09	0.22 ± 0.01
^{29}Al	0.22 ± 0.07	0.16 ± 0.05	0.19 ± 0.03
^{28}Mg	0.09 ± 0.03	0.08 ± 0.02	0.56 ± 0.04
^{28}Al	0.58 ± 0.16	0.61 ± 0.14	0.47 ± 0.03
^{27}Mg	0.94 ± 0.32	0.76 ± 0.17	0.11 ± 0.02
^{24}Na	0.38 ± 0.05	0.33 ± 0.12	0.24 ± 0.02

Table 6. Beam Energy E=1100 MeV, Units (10^{-4} g^{-1} cm^2)

In both studies the experimental and calculated values for the two proton energies were compared with the results obtained using FLUKA at that energy. It can be clearly seen that FLUKA gives reasonable estimates for nuclide production and is reliable in most cases within a factor of two if we reject results that have a combined statistical error of greater than 30%. The plot below shows the ratio of experiment/FLUKA for 1100 MeV protons with the 30% error cut applied to the data.



Conclusions

We have used the FLUKA Monte Carlo codes to produce an estimate of the radionuclide production in the MICE target and calculated the likely activation of the target under normal ISIS run conditions. The validity of these calculations was then tested using other experimental results and is shown to be in reasonable agreement within a factor of two giving us confidence in the reliability of the predictions.

	A	Production per p-p	Half Life	
Vanadium	49	1.28×10^{-6}	330.00	Days
	48	5.94×10^{-6}	16.00	Days
	47	4.12×10^{-6}	32.60	Minutes
Titanium	45	6.84×10^{-5}	3.08	Hours
	44	1.71×10^{-5}	67.00	Years
Scandium	49	1.45×10^{-5}	57.30	Minutes
	48	2.28×10^{-5}	43.70	Hours
	47	2.44×10^{-4}	3.35	Days
	46	7.17×10^{-5}	83.81	Days
	44	5.47×10^{-5}	2.44	Days
	43	3.15×10^{-5}	3.90	Hours
Calcium	47	1.64×10^{-6}	4.54	Days
	45	3.55×10^{-5}	162.70	Days
	41	6.48×10^{-5}	1.03×10^{5}	Years
Potassium	45	8.40×10^{-7}	17.80	Minutes
	44	2.80×10^{-6}	22.10	Minutes
	43	1.20×10^{-5}	22.30	Hours
	42	2.69×10^{-5}	12.36	Hours
	38	5.04×10^{-6}	7.63	Minutes
Argon	42	1.08×10^{-6}	33.00	Years
	41	3.90×10^{-6}	1.83	Hours
	39	3.47×10^{-5}	269.00	Years
	37	5.11×10^{-5}	35.00	Days
Chlorine	39	3.04×10^{-6}	55.60	Minutes
	38	4.17×10^{-6}	37.20	Minutes
	36	6.04×10^{-5}	3.01×10^{5}	Years
	34	5.47×10^{-6}	32.20	Minutes
Sulphur	38	3.40×10^{-7}	2.84	Hours
	37	7.00×10^{-7}	5.05	Minutes
	35	2.38×10^{-5}	87.20	Days
Phosphorus	33	2.37×10^{-5}	25.30	Days
	32	3.81×10^{-5}	14.28	Days
Silicon	32	3.58×10^{-6}	152.00	Years
	31	1.10×10^{-5}	2.62	Hours
Aluminium	29	8.46×10^{-6}	6.50	Minutes
	28	1.71×10^{-5}	2.25	Minutes
Magnesium	28	1.02×10^{-6}	21.00	Hours
	27	4.04×10^{-6}	9.45	Minutes
Sodium	24	3.93×10^{-6}	14.95	Hours
	22	1.14×10^{-5}	2.60	Years
Fluorine	18	5.74×10^{-6}	1.83	Hours
Nitrogen	13	1.62×10^{-6}	9.97	Minutes
Carbon	14	9.28×10^{-6}	5715.00	Years
	11	1.42×10^{-5}	20.30	Minutes
Beryllium	10	1.37×10^{-5}	1.50×10^{6}	Years
	7	2.34×10^{-5}	53.28	Days
Hydrogen	3	1.93×10^{-4}	12.26	Years

Table 7. The full radionuclide production list for 800 MeV protons on titanium.

References

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