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PHOTODISINTEGRATION OF LIGHT AND MEDIUM-WEIGHT NUCLEI AT INTERMEDIATE ENERGIES - III

SPALLATION OF VANADIUM, MANGANESE, IRON AND COBALT(*)

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ABSTRACT

Cross sections per equivalent quantum, in the energy range 0.3 GeV - 1.0 GeV, have been measured for spallation residuals from ^{51}V, ^{55}Mn, natural Fe, and ^{59}Co targets. Mean cross sections per photon have been deduced in this energy range and the data analysed in terms of charge-dispersion curves and mass-yield distributions. The mean cross sections per photon have also been compared with a semiempirical Rudstam's formula. A satisfactorily good agreement has been found with the calculated yields within a factor of two.

INTRODUCTION

Several electron- and photon-induced spallation studies for light, medium-weight, and heavy nuclei have been made at energies

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up to 16 GeV [1-26]. The experimental results, however, are not yet sufficient to permit deriving good systematics of these reactions, in a way similar to that found for proton-induced spallation [27-29], also in consideration of some discrepancies which there exist among them. Moreover, most of the available data are bremsstrahlung yields per equivalent quantum and only a relatively little number of absolute cross sections (per photon) can be found in the literature.

An attempt to systematize intermediate- and high-energy photon-induced spallation yields has been made by Jonsson and Lindgren [30], but, in some cases, the empirical five-parameter formulae deduced do not seem to reproduce satisfactorily enough the experimentally determined yields. Suitable modifications of the parameters have been proposed to fit better the experimental data [26].

The aim of the present work was to study in detail the photon-induced spallation and to give further information about the spallation of medium-weight elements at intermediate energies.

We have chosen natural vanadium, manganese, iron and cobalt as target elements for two reasons. Manganese and cobalt are monoisotopic in nature and vanadium is practically monoisotopic (99.76% ^{51}V); in addition, vanadium and iron allow to compare the present work results with measurements from other laboratories [10,26].

In this work, the yields of spallation residuals from the four targets were measured by the induced activity method and γ-spectroscopy, and the results analysed in terms of charge-dispersion parameters and mass-yield distributions. We believe that such data will help, to a certain degree, the understanding of the mechanism of spallation and deriving more successfully its systematics.

EXPERIMENTAL

High purity (> 99.9%) natural vanadium, iron and cobalt foils, and manganese powder (the latter in thin lucite containers) were exposed to uncollimated bremsstrahlung beams from the Frascati 1-GeV electron synchrotron, at bremsstrahlung end-point energies E_0 between 0.3 GeV and 1 GeV.

The target thicknesses were, as an average, 10^{21} nuclei per square centimetre. The target samples were positioned in air about 1.5 m from the beam exit window. After irradiation the γ-activity was measured with 70 cm^3 and 30 cm^3 (nominal volumes) Ge(Li)-detectors. Technical details concerning bremsstrahlung intensity, dose measurements and counting technique and efficiencies were already described in our previous papers [19-21] .

The relevant nuclear properties of the produced radionuclides have been selected from the recent literature [31-34]. For most of the radionuclides studied the half-lives, identifying γ-ray energies and branching ratios are those quoted in Refs. [26] and [35]; the others are listed in Table 1.

RESULTS

The measured yields, expressed as cross sections per equivalent quantum σ_Q, are listed in the Tables 2-5 for the different end-point energies E_0 chosen. The quoted errors include both statistical and systematic components, the latter dominating. They are comprehensive of counting statistics, fit errors (the area under the photopeaks was evaluated by fitting a gaussian function to the γ-lines) and systematic errors,estimated to about 10%, due to uncertainties in the decay data, the absolute detection efficiency of the detectors and the monitor system. These two latter components do not affect seriously the relative magnitude of the yields and, consequently, the calculated mean cross sections, as they are almost the same for all the measured yields. In some cases, several irradiations at the same E_0 were needed for better statistics. In conclusion, it seemed reasonable to assume that the cumulative significant errors ranged between 12 and 20% (in a few cases 30 to 50%); for most points, however, they are 6 to 12%.

Mean cross sections per photon, $\bar{\sigma}_k$, were deduced from the σ_Q values by assuming a 1/k dependence of the bremsstrahlung spectra on the photon energy k, in the region 0.3-1 GeV. In the case of reactions with a threshold higher than 0.3 GeV, has this region been restricted from the threshold up to 1 GeV. Table 6 reports the $\bar{\sigma}_k$ values thus obtained. Tables 2-6 also report the results of different authors for the sake of comparison.

It should be noted, at this point, that some of the yields measured (Tables 2-5) are cumulative ones, but in the largest majority of the cases, contributions from precursors are not too relevant, due to the smallness of their formation cross sections and the long half-lives.

From the cross sections σ_Q at $E_0 = 1$ GeV, N/Z charge-dispersion (CD) curves were derived (Figs. 1 and 2) for the mass region $42 \leq A \leq 48$ in the following way. A gaussian function has been used to fit the measured cross sections and the total isobaric yields have been deduced by interpolating a certain number of unmeasured cross sections. From the experimental data and the total isobaric yields, fractional yields were obtained. By successive iterations, a gaussian-shaped curve has been fitted to the fractional yields. A total of three iterations only was needed, since the third iteration gave results very close to those of the second one. Table 7 lists the N/Z dispersion parameters for the 1-GeV σ_Q data.

The same method has been adopted to obtain the N/Z CD curves from the mean cross sections per photon (Figs. 3-5). For iron and cobalt, CD curves have been calculated for the two different mass regions $42 \leq A \leq 48$ and $48 \leq A \leq 54$. Table 8 reports the N/Z dispersion parameters deduced from the $\bar{\sigma}_k$ values together with those obtained in the bombardment of vanadium by Bülow et al. [26] with photons in the energy range 0.25-0.80 GeV and by Husain and Katcoff [35] with 3- and 29-GeV protons. As one can see, the values of the maximum of the dispersion curves, the peak abscissa and the full width at half maximum are in excellent agreement with each other, although the data taken from Ref. [35] were obtained at very different experimental conditions for both the type and kinetic energy of the incident particles.

The mass-yield distributions for the mean cross sections per photon are represented in graphical form in Figs. 6-9. The mass distribution parabolas at fixed Z, in the semilog plot, were drawn by least-squares fitting the mass distributions of the mean cross sections of the scandium isotopes (Fig. 10) and by using the same curve to fit the experimental points at the different Z values for each target element. We wish to point out that , after a suitable adjustment, the curves of Fig. 10 have the same shape and FWHM. In Table 9 the values are reported of the slope K of the yield-surface ridges.

Finally, mass distributions of the cross sections per equivalent quantum at 1-GeV bremsstrahlung have been drawn in a similar way for vanadium and iron targets (Figs. 11 and 12).

DISCUSSION

As has already been said at the very beginning of this paper, there have been recent measurements of photospallation yields from vanadium and iron made at approximately the same energy as in the present work. Kumbartzki et al. [10] measured the cross sections per equivalent quantum of spallation products from aluminium, vanadium, manganese, iron, cobalt and arsenic at E_0 = 1.5 GeV, but only for vanadium and iron a large number of spallation residuals have been reported. Bülow et al. [26] , more recently, have determined the cross sections per equivalent quantum of spallation products from vanadium at different bremsstrahlung end-point energies from 75 MeV up to 0.8 GeV and deduced the mean cross sections per photon in the energy range 0.25--0.80 GeV; moreover, their analysis of the results is quite similar to that used in the present work.

From the Tables 2, 4 and 6, it is easily seen that the general trend of the yields measured agrees quite well with those of the papers quoted above.

The agreement is all the same satisfactory for the ratios of the cross sections of potassium isotopes [26,35] (Table 10), even if the ratios given by Kumbartzki et al. [10] differ considerably from the others.

The N/Z dispersion analysis shows complete agreement among the parameters deduced from the present work measurements and those reported in Refs. [26] and [35] (see Tables 7 and 8).

The values of the slope K of the yield-surface ridges listed in Table 9 are almost identical, within the limits of the experimental error, despite of the difference in the mass number of the targets used. As an average, we may say that for target mass numbers between 51 and 59, K is 1.32. This value compares very favourably with K = 1.37 which can be deduced from the work of Bülow et al. [26].

Very different K values are obtained, instead, when plotting mass-yield distributions for the cross sections per equivalent quantum at 1 GeV. In Figs. 11 and 12 such distributions are shown for vanadium and iron, respectively. The calculated slopes are, in fact, 1.7 for vanadium and 1.8 for iron. It is of some interest to compare these values with 1.7 [19] and 2.0 [9] for ^{27}Al at 1 GeV, 1.7 for ^{51}V at 1 GeV and 1.6 for natural Fe at 1.5 GeV [10], and with 1.7 for ^{45}Sc and 1.5 for natural Cu at 2 GeV [24].

The steeper slope which is generally obtained for the σ_Q cross sections at energies E_0 between 1 and 2 GeV gives rise to some discrepancies among the trends of the spallation pattern for produced radionuclides very far from the target nucleus. Both the present work results and those of Bülow et al. [26] seem to indicate, indeed, that the mean cross sections per photon of the light products ^{29}Al, ^{28}Al, ^{28}Mg, ^{27}Mg, ^{24}Na, ^{22}Na and ^{24}Ne follow the spallation trend (see Figs. 6-9). On the contrary, the cross sections per equivalent quantum at 1 GeV for these nuclides lie above the calculated trends (Figs. 11 and 12), well beyond the experimental error. Such a discrepancy has also been found [10] for ^{51}V and natural Fe irradiated with bremsstrahlung of

E_0 = 1.5 GeV. Fulmer et al. [9] found yields of ^{32}P and ^{24}Na larger than expected from a simple spallation mechanism for Fe irradiated with 1.5-, 3-, 5- and 16-GeV electrons. The same was also observed by Butement et al. [12] for ^{59}Co irradiated with 4-GeV electrons and by Bachschi et al. [24] for ^{45}Sc and Cu with 2-GeV bremsstrahlung. One could infer that for target nuclei having masses between 45 and 65 the cross sections per equivalent quantum of the photoproduction of light nuclei is larger than expected from spallation. Of course, no conclusions can be drawn about what kind of process is involved in the observed effect from the type of experiments described here. One must consider, though, that in the energy region around 1 GeV double and multiple pion production can play a relevant role in increasing these yields, through the mechanisms of fission and/or fragmentation. On the other hand, we wish to underline that the significant physical quantity we are dealing with is the cross section per photon and not the bremsstrahlung yield normalised to the number of equivalent quanta. In the introductory part of this paper enough stress has been put on the circumstance that, unfortunately, only little data there exist, thus far, in the literature on the cross sections per photon.

A few words must be spent about the systematics of photospallation residuals. Following the charge-distribution-mass-distribution (CDMD) Rudstam's formula [27], the mean cross section of photoproduction of the nuclide (A,Z) from the target nucleus (A_t,Z_t) is written as

$$\bar{\sigma}_k(A,Z) = \left\{\bar{\sigma}_0 A_t P R^{2/3} / \left[1.79(e^{PA_t}-1)\right]\right\} \exp\left[PA - R|Z-SA+TA^2|^{3/2}\right] \qquad (1)$$

where the parameters P and R define the slope and the width, res pectively, of the mass-yield curve, and S and T the position of the charge distribution. The quantity $\bar{\sigma}_0 A_t$ represents [30] the mean total inelastic cross section per nucleus, $\bar{\sigma}_0$ being the mean total inelastic cross section per nucleon.

We chose the following set of parameters [30] in calculating the $\bar{\sigma}_k$ values in the range 0.3-1 GeV

$$\begin{cases} \bar{\sigma}_0 = 260\ \mu b\ [36] \\ P = 5.22 A_t^{-0.89} \\ R = 2.0 \\ S = 0.486 \\ T = 0.00038. \end{cases} \qquad (2)$$

By using Eqn. (1) with the set (2), mean cross sections have been calculated for almost all the nuclides whose cross section has been experimentally determined. We did not calculate the cross section of photoproduction of ^{49}Cr from ^{51}V in view of the fact that for such a reaction, for which only two nucleons and a negative pion are emitted from the struck nucleus, direct processes may contribute to a large extent.

By way of comparison, the ratios have been determined of experimentally measured cross sections to the calculated ones and the results obtained are summarized in Table 11. A total of 98 experimental cross sections have thus been compared with the values deduced from Eqn. (1). Of these, 69% agree within a factor 2 with those of Eqn. (1), 82% within a factor 2.5, and 89% within a factor 3. Taking into consideration the large error involved in the measurements, it can therefore be concluded that our experimental data are approximated a good deal by the CDMD formula (1). The largest deviations have been met for product nuclei far from the β-stability valley (i.e., for those nuclei which lie at the wings of the mass-yield parabolas). The best agreement is found for the ^{55}Mn, natural Fe, and ^{59}Co targets. For ^{51}V the agreement is somewhat poorer (only 43.5% within a factor 2 and 65% within a factor 3). Bülow et al. [26] have deduced for ^{51}V a set of parameters slightly different from (2), by using a method of multiple linear regression; in this way they calculated cross sections from (1) which agree very well with their measured cross sections in the range 0.25-0.80 GeV.

In the present case too, an excellent agreement is met with the CDMD formula, when using for ^{51}V the set of parameters deduced by Bülow et al. [26] (see Table 11); 65% of the experimental mean cross sections are reproduced within a factor 1.2, 83% within a factor 1.5, 87% within a factor 2, and 96% within a factor 2.5. Only for ^{48}Cr we found a deviation larger than a factor 2.5, but, by reasoning similar to that given before for ^{49}Cr, we can likewise disregard this latter and conclude that all the cross sections measured for ^{51}V are reproduced within a factor 2.5.

A larger number of spallation studies is clearly called for to draw more precise and quantitative conclusions about such a remarkable component of the total inelastic yield of the interaction of intermediate- and high-energy photons with nuclei. For the present we shall be content with this rather qualitative discussion only. It is to be hoped that future work in this field will permit a better systematics of the phenomenon.

Further papers will be devoted to the study of the trend of the photoproduction of light elements from different targets and to a deeper discussion on the spallation mechanism, taking into account the results of Monte Carlo calculations on the cascade and evaporation steps which will also consider the double pion photoproduction.

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Table 1. Decay data of spallation residuals ($Z > 24$).

Nuclide	Half-life	Identifying γ-ray energy	Branching ratio
^{51}Mn	45.2 m	0.511 ($\gamma^{\pm}$)	1.94
$^{52}Mn^{m}$	21.1 m	1.434	1.00
$^{52}Mn^{g}$	5.6 d	0.744	0.82
		0.935	0.84
		1.434	1.00
^{54}Mn	303 d	0.835	1.00
^{52}Fe	8.2 h	0.165	1.00

Table 2. Yields of radionuclides in units of μb per equivalent quantum. Vanadium target.

NUCLIDE	E_0 (GeV)^a						
	0.30	0.40	0.50	0.60	0.75	0.90	1.00
$^{24}_{10}$Na	1.4 ± 0.3	2.0 ± 0.4	2.5 ± 0.4	2.6 ± 0.4	3.4 ± 0.4	3.5 ± 0.4	3.8 ± 0.4
$^{22}_{11}$Na	10 ± 3	20 ± 4	25 ± 4	25 ± 4	28 ± 4	32 ± 4	30 ± 4
$^{24}_{11}$Na	2.0 ± 0.4	8.0 ± 1.2	15.0 ± 1.8	20 ± 2	25 ± 2	32 ± 2	34 ± 2
$^{27}_{12}$Mg	3.0 ± 0.6	10 ± 1	15 ± 2	20 ± 2	25 ± 2	28 ± 2	30 ± 2
$^{28}_{12}$Mg	1.5 ± 0.5	2.5 ± 0.8	3.8 ± 0.8	5.0 ± 0.8	6.5 ± 0.9	7.5 ± 0.9	8 ± 1
$^{28}_{13}$Al	12 ± 4	25 ± 5	35 ± 5	50 ± 6	60 ± 7	75 ± 9	80 ± 10
$^{29}_{13}$Al	10 ± 3	17 ± 4	20 ± 5	25 ± 3	34 ± 4	37 ± 4	40 ± 5
$^{34}_{17}$Cl^m	1.0 ± 0.3	5.2 ± 1.3	9.0 ± 1.8	12.0 ± 1.4	15.0 ± 1.8	18 ± 2	20 ± 3
$^{38}_{17}$Cl	40 ± 10	60 ± 9	80 ± 12	90 ± 13	110 ± 13	120 ± 14	130 ± 16
$^{39}_{17}$Cl	15 ± 5	25 ± 7	35 ± 6	40 ± 6	50 ± 6	55 ± 6	60 ± 6
$^{41}_{18}$Ar	20 ± 4	40 ± 6	50 ± 6	65 ± 6	80 ± 8	90 ± 8	100 ± 10
$^{42}_{19}$K	200 ± 30	250 ± 40	350 ± 42	420 ± 50	417 ± 40	500 ± 50	540 ± 55
$^{43}_{19}$K	50 ± 7	83 ± 12	120 ± 18	150 ± 18	176 ± 20	200 ± 30	190 ± 30
$^{44}_{19}$K	35 ± 10	45 ± 14	50 ± 15	60 ± 15	65 ± 15	72 ± 12	75 ± 12
$^{45}_{19}$K	1.0 ± 0.3	4 ± 1	7 ± 2	9 ± 2	11 ± 2	13 ± 2	15 ± 3
$^{47}_{20}$Ca	10 ± 3	13 ± 4	15 ± 5	18 ± 4	19 ± 4	25 ± 5	23 ± 5
$^{43}_{21}$Sc	20 ± 3	44 ± 7	80 ± 10	100 ± 12	107 ± 10	130 ± 10	150 ± 10
$^{44}_{21}$Sc^m	214 ± 20	300 ± 30	350 ± 40	400 ± 40	475 ± 40	500 ± 40	525 ± 40
$^{44}_{21}$Sc^g	250 ± 20	320 ± 30	350 ± 40	410 ± 40	470 ± 40	490 ± 40	530 ± 40
$^{46}_{21}$Sc	714 ± 70	950 ± 76	1000 ± 100	1100 ± 100	1200 ± 100	1400 ± 100	1430 ± 100
$^{47}_{21}$Sc	1100 ± 100	1300 ± 100	1300 ± 100	1400 ± 110	1500 ± 110	1600 ± 100	1700 ± 100
$^{48}_{21}$Sc	120 ± 10	200 ± 16	200 ± 16	250 ± 15	260 ± 15	300 ± 15	346 ± 15
$^{48}_{23}$V	470 ± 40	630 ± 50	630 ± 50	650 ± 50	690 ± 50	740 ± 50	760 ± 50
$^{48}_{24}$Cr	56 ± 10	63 ± 12	65 ± 13	70 ± 10	75 ± 10	77 ± 10	80 ± 10
$^{49}_{24}$Cr	15 ± 3	20 ± 4	23 ± 4	25 ± 5	28 ± 5	30 ± 5	31 ± 5

Table 2. Yields of radionuclides in units of μb per equivalent quantum. Vanadium target (continued)

NUCLIDE	E_0 (GeV)						
	0.250^b	0.325^b	0.400^b	0.500^b	0.640^b	0.800^b	1.5^c
$^{24}_{11}$Na	0.7 ± 0.2	3.1 ± 0.3	5.8 ± 0.3	10.5 ± 0.4	16.4 ± 0.5	24.0 ± 0.4	51 ± 8
$^{27}_{12}$Mg			4 ± 2	6 ± 1	11 ± 2	17 ± 2	42 ± 7
$^{28}_{12}$Mg			0.8 ± 0.4	1.9 ± 0.5	3.1 ± 0.7	4.6 ± 0.5	9 ± 3
$^{28}_{13}$Al		10 ± 3	18 ± 3	30 ± 3	48 ± 4	64 ± 4	86 ± 15
$^{29}_{13}$Al	2 ± 2	8 ± 2	13 ± 3	23 ± 3	32 ± 3	37 ± 3	41 ± 9
$^{34}_{17}$Cl^m		2.6 ± 0.5	5.0 ± 0.5	8.8 ± 0.6	12 ± 1	14.4 ± 0.7	21 ± 4
$^{38}_{17}$Cl	13 ± 2	30 ± 2	58 ± 3	83 ± 4	99 ± 4	122 ± 4	147 ± 21
$^{39}_{17}$Cl	7 ± 2	12 ± 2	24 ± 2	31 ± 3	40 ± 3	39 ± 3	71 ± 12
$^{41}_{18}$Ar	16 ± 1	31 ± 1	44 ± 1	55 ± 2	73 ± 2	83 ± 1	124 ± 23
$^{42}_{19}$K	93 ± 3	163 ± 6	241 ± 6	298 ± 7	367 ± 9	393 ± 5	620 ± 90
$^{43}_{19}$K	50 ± 1	91 ± 1	120 ± 1	150 ± 1	185 ± 1	206 ± 1	310 ± 40
$^{44}_{19}$K	19 ± 7	28 ± 7	28 ± 7	39 ± 6	41 ± 6	57 ± 5	170 ± 130
$^{45}_{19}$K	4.2 ± 0.7	6.4 ± 0.5	7.7 ± 0.6	9.9 ± 0.5	12.4 ± 0.8	14 ± 0.6	20 ± 5
$^{47}_{20}$Ca	9 ± 2	12.5 ± 0.9	13.6 ± 0.8	18.4 ± 0.9	20 ± 1	25.5 ± 0.8	
$^{43}_{21}$Sc	39 ± 3	77 ± 3	101 ± 3	132 ± 4	161 ± 4	174 ± 4	180 ± 20
$^{44}_{21}$Sc^m	112 ± 1	196 ± 2	249 ± 2	302 ± 2	362 ± 2	406 ± 2	520 ± 70
$^{44}_{21}$Sc^g	124 ± 2	207 ± 2	255 ± 2	312 ± 2	368 ± 2	374 ± 2	520 ± 80
$^{46}_{21}$Sc	583 ± 18	815 ± 7	917 ± 10	1080 ± 10	1236 ± 14	1331 ± 12	1940 ± 330
$^{47}_{21}$Sc	693 ± 3	867 ± 5	957 ± 7	1062 ± 8	1246 ± 10	1389 ± 12	1820 ± 270
$^{48}_{21}$Sc	115 ± 1	159 ± 6	188 ± 4	227 ± 6	258 ± 4	281 ± 4	349 ± 43
$^{48}_{23}$V	581 ± 3	692 ± 3	750 ± 4	802 ± 4	896 ± 6	942 ± 4	1090 ± 130
$^{49}_{24}$Cr	10.0 ± 0.8	16.4 ± 0.9	20.4 ± 0.8	21.6 ± 0.8	27 ± 2	25.6 ± 0.9	77 ± 9

[a] Present work

[b] Data taken from Ref. [26]

[c] Data taken from Ref. [10]

Table 3. Yields of radionuclides in units of μb per equivalent quantum. Manganese target.

NUCLIDE				E_0(GeV)			
	0.30	0.40	0.50	0.60	0.75	0.90	1.00
$^{24}_{11}\mathrm{Na}$	3.0 ± 0.3	6.0 ± 0.6	8.0 ± 0.8	10.0 ± 1.0	12.0 ± 1.0	14.0 ± 1.0	15.0 ± 1.0
$^{27}_{12}\mathrm{Mg}$	5 ± 1	6 ± 1	9 ± 1	11 ± 1	13 ± 1	14 ± 1	15 ± 1
$^{28}_{12}\mathrm{Mg}$		0.5 ± 0.2	1.0 ± 0.3	1.5 ± 0.4	2.2 ± 0.5	2.8 ± 0.5	3.0 ± 0.5
$^{28}_{13}\mathrm{Al}$	15 ± 3	25 ± 5	30 ± 4	35 ± 4	45 ± 4	45 ± 4	50 ± 4
$^{29}_{13}\mathrm{Al}$	6 ± 1	10 ± 2	12 ± 2	15 ± 3	16 ± 2	18 ± 2	20 ± 2
$^{34}_{17}\mathrm{Cl}^{m}$	34 ± 7	42 ± 5	50 ± 4	55 ± 4	60 ± 4	67 ± 4	70 ± 4
$^{38}_{17}\mathrm{Cl}$	16 ± 4	28 ± 6	38 ± 8	47 ± 8	57 ± 8	65 ± 8	70 ± 8
$^{39}_{17}\mathrm{Cl}$	20 ± 4	23 ± 3	25 ± 2	28 ± 2	31 ± 2	33 ± 2	34 ± 2
$^{41}_{18}\mathrm{Ar}$	18 ± 5	28 ± 4	36 ± 4	42 ± 4	50 ± 4	56 ± 5	60 ± 5
$^{42}_{19}\mathrm{K}$	50 ± 15	76 ± 15	100 ± 17	115 ± 17	135 ± 16	150 ± 16	165 ± 17
$^{43}_{19}\mathrm{K}$	5 ± 2	15 ± 5	25 ± 6	35 ± 7	45 ± 7	50 ± 7	53 ± 7
$^{44}_{19}\mathrm{K}$	17 ± 5	19 ± 4	21 ± 4	24 ± 4	26 ± 4	28 ± 4	30 ± 4
$^{45}_{19}\mathrm{K}$	1.0 ± 0.5	1.0 ± 0.5	1.2 ± 0.5	1.4 ± 0.5	1.7 ± 0.5	2.0 ± 0.5	2.0 ± 0.5
$^{47}_{20}\mathrm{Ca}$	10 ± 3	12 ± 3	13 ± 3	15 ± 2	16 ± 2	17 ± 2	18 ± 2
$^{43}_{21}\mathrm{Sc}$	16 ± 5	17 ± 5	40 ± 7	60 ± 7	75 ± 7	90 ± 7	92 ± 7
$^{44}_{21}\mathrm{Sc}^{m}$	135 ± 15	170 ± 15	200 ± 15	215 ± 15	245 ± 15	265 ± 16	273 ± 16
$^{44}_{21}\mathrm{Sc}^{g}$	140 ± 20	170 ± 20	200 ± 20	220 ± 20	250 ± 20	270 ± 20	275 ± 20
$^{46}_{21}\mathrm{Sc}$	190 ± 40	210 ± 40	290 ± 40	350 ± 45	420 ± 45	460 ± 46	465 ± 47
$^{47}_{21}\mathrm{Sc}$	170 ± 40	180 ± 40	260 ± 45	300 ± 45	340 ± 45	380 ± 45	384 ± 45
$^{48}_{21}\mathrm{Sc}$	1.0 ± 0.5	2 ± 1	15 ± 4	24 ± 5	35 ± 5	50 ± 6	53 ± 6
$^{48}_{23}\mathrm{V}$	410 ± 50	470 ± 50	520 ± 50	550 ± 50	600 ± 60	630 ± 60	650 ± 60
$^{48}_{24}\mathrm{Cr}$	12 ± 3	13 ± 3	15 ± 3	17 ± 3	18 ± 3	19 ± 3	20 ± 3
$^{49}_{24}\mathrm{Cr}$	132 ± 15	144 ± 15	153 ± 15	160 ± 15	170 ± 16	176 ± 18	180 ± 18
$^{51}_{24}\mathrm{Cr}$	2000 ± 150	2150 ± 150	2250 ± 150	2340 ± 150	2450 ± 150	2530 ± 150	2580 ± 160

Table 4. Yields of radionuclides in units of μb per equivalent quantum. Iron target.

NUCLIDE	E_0(GeV)							
	0.30	0.40	0.50	0.60	0.75	0.90	1.00	1.5[a]
$^{24}_{11}\mathrm{Na}$		3.0 ± 0.3	6.0 ± 0.6	8 ± 1	10 ± 1	12 ± 1	13 ± 1	29 ± 4
$^{27}_{12}\mathrm{Mg}$	3 ± 1	6 ± 1	8 ± 1	10 ± 1	12 ± 1	14 ± 1	15 ± 1	18 ± 4
$^{28}_{12}\mathrm{Mg}$			0.7 ± 0.2	1.2 ± 0.4	1.8 ± 0.5	2.2 ± 0.5	2.5 ± 0.5	3 ± 1
$^{28}_{13}\mathrm{Al}$	8 ± 3	18 ± 4	26 ± 4	32 ± 4	40 ± 4	45 ± 4	50 ± 4	78 ± 12
$^{29}_{13}\mathrm{Al}$	2 ± 1	6 ± 2	10 ± 2	12 ± 2	16 ± 2	18 ± 2	20 ± 2	28 ± 8
$^{34}_{17}\mathrm{Cl}^{m}$		8 ± 4	15 ± 4	20 ± 4	27 ± 4	32 ± 4	35 ± 4	
$^{38}_{17}\mathrm{Cl}$		15 ± 4	25 ± 5	35 ± 7	45 ± 8	55 ± 8	60 ± 8	48 ± 9
$^{39}_{17}\mathrm{Cl}$		5 ± 2	10 ± 3	13 ± 3	18 ± 3	21 ± 3	23 ± 3	16 ± 4
$^{41}_{18}\mathrm{Ar}$		2 ± 1	8 ± 2	13 ± 3	20 ± 3	25 ± 3	20 ± 3	26 ± 4
$^{42}_{19}\mathrm{K}$	20 ± 8	40 ± 10	60 ± 15	70 ± 15	90 ± 15	105 ± 15	115 ± 15	240 ± 50
$^{43}_{19}\mathrm{K}$		2 ± 1	5 ± 2	15 ± 5	24 ± 5	30 ± 5	34 ± 5	51 ± 8
$^{44}_{19}\mathrm{K}$	8 ± 4	11 ± 4	13 ± 4	15 ± 4	17 ± 4	19 ± 4	20 ± 4	
$^{45}_{19}\mathrm{K}$	1.6 ± 0.5	1.9 ± 0.5	2.2 ± 0.5	2.4 ± 0.5	2.7 ± 0.5	2.9 ± 0.5	3.0 ± 0.5	
$^{47}_{20}\mathrm{Ca}$	3.0 ± 1.0	4.0 ± 1.0	6.0 ± 2.0	7.0 ± 2.0	8.5 ± 2.0	9.4 ± 2.0	10.0 ± 2.0	
$^{43}_{21}\mathrm{Sc}$	30 ± 8	55 ± 8	80 ± 8	85 ± 8	100 ± 8	100 ± 8	140 ± 8	190 ± 30
$^{44}_{21}\mathrm{Sc}^{m}$	140 ± 12	170 ± 12	180 ± 12	204 ± 12	230 ± 12	250 ± 12	260 ± 13	380 ± 40
$^{44}_{21}\mathrm{Sc}^{g}$	145 ± 16	170 ± 16	180 ± 16	200 ± 16	230 ± 16	245 ± 16	250 ± 16	410 ± 50
$^{46}_{21}\mathrm{Sc}$	100 ± 30	100 ± 30	170 ± 35	220 ± 35	260 ± 37	330 ± 38	324 ± 40	480 ± 70
$^{47}_{21}\mathrm{Sc}$	70 ± 20	80 ± 20	154 ± 30	180 ± 30	210 ± 30	235 ± 30	246 ± 30	163 ± 20
$^{48}_{21}\mathrm{Sc}$	2 ± 1	2 ± 1	15 ± 3	20 ± 3	28 ± 3	32 ± 3	34 ± 3	34 ± 6
$^{48}_{23}\mathrm{V}$	490 ± 45	540 ± 45	580 ± 45	620 ± 45	660 ± 45	690 ± 45	710 ± 45	1280 ± 140
$^{48}_{24}\mathrm{Cr}$	24 ± 4	27 ± 4	28 ± 4	30 ± 4	31 ± 4	33 ± 4	34 ± 4	46 ± 6
$^{49}_{24}\mathrm{Cr}$	142 ± 25	160 ± 25	175 ± 25	187 ± 25	200 ± 25	212 ± 25	220 ± 25	590 ± 60
$^{51}_{24}\mathrm{Cr}$	2700 ± 130	2900 ± 150	3000 ± 150	3100 ± 150	3200 ± 200	3350 ± 200	3400 ± 200	3900 ± 400
$^{51}_{25}\mathrm{Mn}$	20 ± 5	28 ± 5	35 ± 5	38 ± 5	45 ± 5	47 ± 5	50 ± 5	
$^{52}_{25}\mathrm{Mn}^{m}$	410 ± 40	430 ± 40	450 ± 40	460 ± 40	480 ± 40	490 ± 40	500 ± 40	910 ± 100
$^{52}_{25}\mathrm{Mn}^{g}$	390 ± 40	415 ± 40	435 ± 40	450 ± 40	475 ± 40	490 ± 40	500 ± 40	790 ± 90
$^{54}_{25}\mathrm{Mn}$	4670 ± 300	4900 ± 300	5150 ± 300	5300 ± 300	5500 ± 300	5700 ± 300	5800 ± 300	7200 ± 900

[a] Data taken from Ref. |10|