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Abstract: The activation of air in the tunnel of the proposed Linear Collider (e^+ and e^- beams 250 GeV, 8 MW each) is calculated. A beam loss of 20 % from unshielded collimators near the interaction point is assumed. The nuclides ^{3}H, ^{7}Be, and ^{11}C produced by photospallation and ^{41}Ar produced by capture of thermal neutrons are transported in the ventilated air to one end of the tunnel and exhausted. The resulting exposure of persons living near the ventilation shaft is calculated taking into account submersion, surface radiation, inhalation, and ingestion via the exposure pathes plants-person, plants-cow-milk-person and plants-cow-meat-person. The sum of all effective doses is about 10 to 1 μSv/a at distances 30 m - 1000 m which is less than 1 % of the natural radiation background.

1. Introduction

It is proposed to build a Linear Collider which collides electron and positron beams with beam energy of 250 GeV each and a beam power of 8 MW. Scientific aspects and accelerator techniques are described in a Conceptual Design Report [1]. A tunnel of 33 km length houses two linear accelerators, beginning at the DESY site, directed towards north-west, and ending near the village Westerhorn. The interaction point and the large detector is at the midpoint of the tunnel. After having passed this region each beam is dumped into an absorber. The absorption of an 8 MW elektron beam produces an enormous amount of secondary radiation and radioactivity, therefore each dump will be installed probably not in the tunnel but in a separate room beside of it. An addition, the dump is shielded by thick concrete walls in order to keep the activations of soil and groundwater as low as possible [2]. The activation of air in that room is also low and will not be considered in the present paper.

The next largest source of secondary radiation is the system of distributed collimators downstream the interaction point. They shield the components of the incoming beamline against the low energy tail of the deflected beam and against beamstrahlung produced in the interaction point. The fraction of the beam which is absorbed by these collimators can be as high as 10-20 %. We assume that they will not be surrounded by thick shielding, so they present the principal source of air activation in the tunnel.

The tunnel will be ventilated continuously with an air speed of 0.6 m/s, see the Design Report [1]. So a continuous air flow passes the collimator region which is assumed to be 200 m long. This gives an activation time of a few minutes. A decay time of 7 h is given by the time during which the air reaches the north end of the accelerator where it is exhausted through a ventilation shaft.

In reports on air radioactivity usually the nuclides ^{15}O and ^{13}N are considered which are produced most copiously. Despite the larger cross sections we can neglect them in our case because of their short half-life. We will calculate the production of ^{11}C (half-life 20 min), ^{41}Ar (1.8 h), ^{7}Be (53 d), and ^{3}H (12 a). These nuclides in the exhausted air produces a certain exposure to persons living in the neighbourhood of the ventilation shaft. Effective doses will be calculated produced by the following effects: submersion, inhalation, dose by γ-emitters deposited on the earth surface (surface radiation), and ingestion. For the latter effect the exposure-pathes plants-person, plants-cow-milk-person, and plants-cow-meat-person are considered.

2. Production of radioactive nuclides in air

2.1 Production by photons

The cross sections of the spallation reactions producing ^{7}Be, ^{3}H, or ^{11}C from ^{16}O and ^{14}N are not well known. The cross sections for ^{16}O (γ, x) ^{7}Be, ^{16}O (γ, x) ^{3}H, and ^{16}O (γ, x) ^{11}C were measured from threshold to 60 MeV [3, 4, 5] and are displayed in fig. 1; they are extrapolated to 200 MeV. We could not find these cross sections for ^{14}N. The reaction thresholds for ^{16}O and ^{14}N are rather similar, and we assume that the dependence on γ-energy is the same but the ^{14}N cross section is enhanced by the ratio of the integrated total neutron cross sections σ (γ, n_{tot}) which are known: $\int \sigma_{\gamma,ntot}(^{14}N) \; / \; \int \sigma_{\gamma,ntot}(^{16}O) = 2.4$ [6].

The distributed collimators are simulated by a single aluminium target placed in the axis of the concrete tunnel (5 m inner diameter) and hit centrally by the electron beam. The number of produced photons is calculated by the MC program FLUKA 97 [7] as a function of photon energy and angle. Two target dimensions are tested: 1 m * 20 cm Ø and 2 m * 5 cm Ø. The first one gives the higher flux in the forward direction 0°-5°, at all larger angles the production from the thinner target is larger. We take the respective higher yields at all angles, so these unshielded targets may represent the worst case regarding air activation. The results (number of photons per one 250-GeV electron) are given in tab. 1 for 6 angular bins and for 4 energy intervalls selected according to the cross section curves. Also given are mean flight pathes in air within the tunnel for each angular bin.

The number of produced nuclides per primary electron is

$$N = n \sum_{\Theta} l(\Theta) \sum_{k} \Gamma(\Theta, k)\sigma(k)$$

n = number of atoms per cm^3 in air

l (Θ) = flight path (cm) in air as a function of angle

Γ (Θ, k) = number of photons in one angular and energy bin

σ (k) = production cross section (cm^2)

This is true if the attenuation of photon flux along the flight path is small ; it can be verfied by calculating, e.g., the pair production. The used l (Θ) value are also indicated in tab. 1.

We calculate activity concentrations for an 8 MW operation with 250 GeV beam energy and assume a beam loss of 20 % at the collimators, this gives $4 \cdot 10^{13}$ e/s. The saturation activity concentration is

$$\overline{A}_s = \frac{4 \cdot 10^{13}\ N}{V}$$

V = interaction volume = $0.7\ \pi\ r^2 L$, r = tunnel radius and L = lenght of interaction volume.

The activation time t_1 is L/v (v = velocity of the ventilated air = 0.6 m/s) and the decay time t_2 is 15 km/v. The activity concentration at the exhaust shaft is

$$\overline{A} = \overline{A}_s\ (1-e^{-\lambda t_1})e^{-\lambda t_2}$$

λ = decay constant. Since $1 - \exp(-\lambda t_l) \approx \lambda t_l$ for all nuclides considered, the results are independent of L. With a ventilation rate of $3 \cdot 10^4$ m³/h [1] and an assumed operation of 5000 h/a, the emitted activity per year, A, can be calculated. The numbers are doubled for two operating linacs. The results are part of tab. 2.

2.2. Production by high energy neutrons and protons

At electron accelerators the production of radioactive nuclides in air by secondary medium-energy neutrons is known to be small compared with the production by photons. In order to check if this is true also at very high energies we made a rough estimate by calculating neutron- and proton-induced spallation reactions giving ^{7}Be or ^{3}H. The sparse information on spallation of ^{16}O is collected in [2]. Here we assume that these cross sections also apply to ^{14}N. The number of neutrons and protons per angular bin and with energies above the spallation thresholds, *N* and P, are also calculated by the FLUKA 97 code. An aluminium target 5 m * 20 cm Ø is chosen. The results are also entered into tab. 1. Then the number of produced nuclei in air can be calculated in the same way as above. The result is that the number of produced ^{7}Be and ^{3}H is smaller than the number calculated in section 2.1 by a factor of 10. Despite the crude assumptions on cross sections this proves that neutron- and proton-induced spallation can be neglected.

2.3. Production of ^{41}Ar

^{41}Ar is produced by capture of thermal neutrons. We assume the same target as in section 2.2 and a tunnel section of 30 m length as the activation volume. In this air volume the total track length of thermal neutrons (energy < 0.4 eV) is calculated by means of FLUKA 97, the result is 39 m per one 250-GeV electron. The cross section is 0.64 barn. With these values and the same procedure and data as in section 2.1 one receives the released activity per year which is entered into tab. 2.

3. Effective doses in the environment

3.1. Methods of calculation

The annual release of ^{3}H, ^{7}Be, ^{11}C, and ^{41}Ar is calculated in the preceding chapter, the resulting figures are rather low. Nevertheless it is the duty to calculate effective doses received by people living in the vicinity of the north end of the accelerator. A number of exposure pathes are to be considered: submersion in a cloud of γ-emitters or β-emitters, inhalation, doses by γ-emitters deposited on earth surface due to dry fall-out and wash-out by rainfall („surface radiation"), and doses by ingestion via the exposure pathes plants-person, plants-cow-milk-person, and plants-cow-meat-person.

Methods and formulae are entirely taken from the official direction entitled „Ascertainment of radiation exposure due to release of radioactive nuclides from nuclear installations“ [8], the respective nuclide-specific data are collected in [9]. Effective doses are calculated in all cases except for β-submersion where the skin dose is estimated (the contribution of skin dose to effective dose is 1 % [10]). The used formulae are presented in the following, symbols are explained only once. Distance-dependent propagation factors are given in tab. 3, isotope-specific constants in tab. 4. Effective doses are calculated for an adult and for a child of age 1 year.

Detailed meteorological data for our site near the village Westerhorn are not available at present. From [11] we got the long-term mean of the amount of rainfall near the neighbouring town Itzehoe, 817 mm/a, and the mean wind velocity at airport Fuhlsbüttel of Hamburg, 4.2 m/s. We assume that the wind is directed towards the point of interest during 20% of the operation time (5000 h). These data are sufficient for using simplified formulae which are also presented in [8] for official use. In view of the resulting very low doses we believe that more detailed calculations are unnecessary.

- γ-submersion

$$H_a = A g_s^\gamma \chi_\gamma$$

H_a = annual effective dose (Sv/a)
A = released activity per year (Bq/a)
g_s^γ = dose rate factor (Sv m² Bq^{-1} s^{-1}) for γ radiation
χ_γ = long-term propagation factor for γ submersion (s m^{-2}), 20 m height of exhaust shaft, wind direction probability 0.2.

- β-submersion

$$H_a = A g_s^\beta \chi p$$

g_s^β = dose rate factor (Sv m^3 Bq^{-1} s^{-1}) for β radiation
χ = long-term propagation factor (s m^{-3}), 20 m height of exhaust shaft
p = wind direction probability = 0.2

- Inhalation

$$H_a = A g_h \chi \dot{V} p$$

g_h = dose factor (Sv/Bq) for inhalation
$\dot{V}$ = breathing rate = $2.32 \cdot 10^{-4}$ m^3 s^{-1} (adult)
= $6.03 \cdot 10^{-5}$ m^3 s^{-1} (child)

Fall-out factor F^G

$$F^G = \chi v_g p$$

F^G (m^{-2})
v_g = velocity of deposition = $1.5 \cdot 10^{-3}$ ($m\ s^{-1}$)

Wash-out factor W^G

$$W^G = \frac{cJ}{2\pi x u}$$

c = wash-out coefficient ($a\ mm^{-1}\ s^{-1}$) (tab. 4)
J = amount of rainfall =817 mm a^{-1}
x = distance (m)
u = mean wind velocity = 4.2 m s^{-1}

- Surface radiation

$$H_a = A\,(F^G + W^G)\,K\,g_f\,b$$

$K = \frac{1}{\lambda}\,(1 - e^{-\lambda t_b})$; λ = physical decay constant of nuclide (tab. 4)
t_b = time of deposition = 50 a

g_f = dose rate factor ($Sv\ m^2\ s^{-1}\ Bq^{-1}$) for γ surface radiation
b = correction factor for penetration in deeper earth layers = 0.5

- Ingestion

$$H_a = g_g\,(U^{Pf} C^{Pf} + U^{Bl} C^{Bl} + U^{Mi} C^{Mi} + U^{Fl} C^{Fl})$$

g_g = dose factor ($Sv\ Bq^{-1}$) for ingestion
U^{Pf}, U^{Bl}, U^{Mi}, U^{Fl} = consumption per year of plants without green foliage plants, green foliage plants, milk, meat. (tab. 5)

Specific activities C ($Bq\ kg^{-1}$) for all nuclides except ^3H

$$C^{Pf} = a_p\,A\,\Big[(F^S + f_w W^S)\frac{1 - \exp(-t_e{}^{Pf}(\lambda_V + \lambda))}{Y^{Pf}(\lambda_V + \lambda)}$$
$$+ (F^G + W^G)T^{Pf}\frac{1 - \exp(-t_b(\lambda_M + \lambda))}{P^A(\lambda_M + \lambda)}\Big]e^{-\lambda t_v^{Pf}}$$

a_p = conversion factor = $3.2 \cdot 10^{-8}\ s^{-1}$
F^S = fall-out factor for summer = 2 F^G
W^S = 2 W^G

f_W = fraction of activity deposited by rain on plants = 0.3
t_e^{Pf} = time of exposition = $5.2 \cdot 10^6$ s (=60 d)
λ_V = residence time constant of nuclide on plants = $5.7 \cdot 10^{-7}$ s^{-1} (≙ 14 d)
Y^{Pf} = crop of plants = 2.4 kg m^{-2}
T^{Pf} = transfer factor earth → plant = $5 \cdot 10^{-4}$
t_b = deposition time of nuclide on earth = $1.57 \cdot 10^9$ s (= 50 a)
λ_M = residence time constant of nuclide on earth surface = $1 \cdot 10^{-9}$ s^{-1} (≙ 22 a)
P^A = effective mass of earth = 280 kg m^{-2}
t_V^{Pf} = waiting time between harvest and consumption = $5.2 \cdot 10^6$ s (= 60 d)

C^{Bl} : same formula as for C^{Pf}, but with
Y^{Bl} = 1.6 kg m^{-2}
$t_V^{Bl} = 0$

$$C^{Mi} = C^{Fu} M_{Fu} T^{Mi}$$

$$C^{Fl} = C^{Fu} M_{Fu} T^{Fl} e^{-\lambda t_V^{Fl}}$$

M_{Fu} = consumption of cow fodder per day = 65 kg d^{-1}
T^{Mi} = transfer factor fodder → milk = $1 \cdot 10^{-4}$ d kg^{-1}
T^{Fl} = transfer factor fodder → meat = $1 \cdot 10^{-3}$ d kg^{-1}
t_V^{Fl} = waiting time between slaughtering and consumption = $1.7 \cdot 10^6$ s (=20 d)

C^{Fu} = specific activity of fodder
$= f_p C^{Wd} + (1 - f_p) C^{Lf}$
f_p = fraction of year which is grazing time = 0.5
C^{Wd} = specific activity of pasture plants, same formula as for C^{Pf}, but with
$t_e^{Wd} = 2.6 \cdot 10^6$ s(= 30d)
Y^{Wd} = 0.85 kg m^{-2}
P^{Wd} = 120 kg m^{-2}
$t_V^{Wd} = 0$
C^{Lf} = specific activity of stored fodder
$= C^{Wd} e^{-\lambda t_V^{Lf}}$
$t_V^{Lf} = 7.8 \cdot 10^6$ s(= 90d)

Specific activities C (Bq kg^{-1}) for ^3H

$$C^{Pf} = C^{Bl} = C^{Wd} = C^{Lf} = C^{Fu} = C_{H3}$$

$$C_{H3} = A\ f_H^{Pf} \left(f_L a_\rho \frac{\chi^S}{\Psi^S} + f_N \frac{W^S}{J^S \rho_w} \right)$$

f_H^{Pf} = fraction of water in plants = 0.8
f_L = fraction of ^3H in plants absorbed from air humidity = 0.3
f_N = fraction of ^3H in plants absorbed from rain = 0.7
$\chi^S = 2\chi$ (tab. 3)
$W^S = 2\ W^G$; W^G calculated with above formula and c from tab. 4.

Ψ^S = mean air humidity during growth period = 0.009 kg m^{-3}
J^S = amount of rainfall during sumer assumed to be 0.5 J = 408 l m^{-2}
ρ_w = density of water = 1 kg l^{-1}

3.2. Results

The effective doses per year are calculated for the 4 nuclides ^3H, ^7Be, ^{11}C and ^{41}Ar by using the formulae of the preceding section and the data on released activities of tab. 2. Not all exposure pathes are relevant for each nuclide. Submersion and surface radiation is irrelevant for ^3H because of its low β energy. For the inert gas ^{41}Ar only submersion is to be considered and for ^{11}C only submersion and inhalation since ^{11}C does not accumulate (half-life 20 min).

The doses due to ^7Be are presented in tab. 6 for an adult at a distance of 100 m as an example to demonstrate the importance of the different exposure pathes. Tab. 7 shows all results for distances 30 m to 1000 m from the exhaust shaft. One sees that the exposure to an adult and to a child is equal within 20 %. The mean of both is entered into the last row of tab. 7 as the sum over all exposure pathes for ^7Be which gives the largest contribution, as a quick synopsis.

4. Summary

We assume a full power operation of 8 MW for each 250-GeV accelerator during 5000 h per year. 20 % of the beam power is absorbed in distributed collimators near the interaction point. They are simulated by unshielded aluminium targets positioned in the tunnel axis. The nuclides ^3H, ^7Be, and ^{11}C produced by secondary photons in air and ^{41}Ar produced by capture of thermal neutrons are transported along the 15-km tunnel to its north end by forced ventilation and are exhausted. The resulting radiation exposure at distances 30-1000 m from the ventilation shaft is calculated taking into account all known exposure pathes (submersion, inhalation, surface radiation, and ingestion). The sum is about 10 µSv/a for an adult and for a child of age 1 year at a distace of 100 m from the ventilation shaft. This is 3 % of the maximum permissible dose for the general public according to the German Radiation Protection Regulation and 1 % of the natural radiation exposure.

5. Literature

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$\Delta\Theta$ (°)	l (cm)	Γ				N + P				
		k = 28-40 MeV	40-50	50-60	60-200	k = 20-40 MeV	40-100	100-400	400-1000	1000-10000
0-0.5	$3\cdot10^3$	6.7	3.8	2.9	15					
0.5-2	$1.5\cdot10^4$	22	12	9.1	41					
2-5	$5\cdot10^3$	32	16	11	38					
5-20	$1.5\cdot10^3$	105	44	27	56	0.001	0.003	0.011	0.005	0.008
20-90	$5\cdot10^2$	27	7.5	3.3	4.1	0.019	0.061	0.10	0.028	0.028
90-160	$5\cdot10^2$	0.40	0.16	0.11	0.76	0.71	1.12	0.64	0.055	0.18
160-175	$1.5\cdot10^3$	0.01	0.01	0.01	0.03	0.13	0.19	0.070	0	0.010

Tab. 1. Number of photons (Γ) and neutrons + protons (N + P) produced from an Al target as a function of angle Θ and energy of secondaries k.
l = path length in air.

Nuclide	A (Bq/a)
^{3}H	$3.7\cdot10^{10}$
^{7}Be	$7.8\cdot10^{11}$
^{11}C	$7.7\cdot10^{9}$
^{41}Ar	$2.4\cdot10^{12}$

Tab. 2. Released activities per year

Distance x (m)	Propagation factors	
	χ_γ (s m^{-2})	χ (s m^{-3})
30	1.5-3	7-5
100	1.0-3	6.5-5
300	4.0-4	3.5-5
1000	9.0-5	7.0-6

Tab. 3. Propagation factors

Nuclide	λ (s^{-1})	c ($a\ mm^{-1} s^{-1}$)	g_a^γ ($Sv\ m^2\ Bq^{-1}\ s^{-1}$)		g_a^β ($Sv\ m^3\ Bq^{-1}\ s^{-1}$)		g_h ($Sv\ Bq^{-1}$)		g_r ($Sv\ m^2\ Bq^{-1}\ s^{-1}$)		g_g ($Sv\ Bq^{-1}$)	
			A *)	Ch *)	A	Ch	A	Ch	A	Ch	A	Ch
^{3}H	5.64-2	4.0-9					1.6-11	4.6-11			1.6-17	4.6-11
^{7}Be	1.51-7	6.0-9	1.7-17	2.0-17			8.7-11**)	8.9-10	4.8-17	7.2-17	3.4-11	1.5-10
^{11}C	5.69-4		3.6-16	4.3-16	2.2-14	2.2-14	2.1-12	1.9-11	1.0-15	1.5-15		
^{41}Ar	1.05-4		4.3-16	5.2-16	2.7-14	2.7-14						

*) A = adult, Ch = child (1 a old)

**) Lung retention class Y

Tab. 4. Decay constants, wash-out coefficients, dose rate factors, and dose factors.

Tab. 5. Consumption per year (kg)

Produce	U (kg)	
	Adult	Child (1 a old)
Plants (without green foliage plants)	460	50
Green foliage plants	40	10
Milk	330	200
Meat	150	20

Nuclide	Submersion		γ surface radiation	Inhalation	Ingestion			
	γ	β (skin dose)			Plants	Foliage plants	Milk	Meat
^{3}H	---	---	---	1.7-9	6.7-9	6.0-10	6.4-9	3.0-9
^{7}Be	1.3-8	---	2.6-6	2.0-7	3.9-6	1.1-6	6.3-8	2.3-7
^{11}C	2.8-9	2.2-9	---	4.8-11	---	---	---	---
^{41}Ar	2.0-6	1.7-6	---	---	---	---	---	---

Tab. 6. Effective doses (Sv) per year for an adult at a distance of 100 m.
1.3-8 means $1.3 \cdot 10^{-8}$

Distance (m)	Nuclide	Submersion				γ surface radiation		Inhalation		Ingestion		All exposure pathes
		γ		β (skin dose)								
		A	Ch	A	Ch	A	Ch	A	Ch	A	Ch	
30	^{3}H	---	---	---	---	---	---	1.9-9	1.4-9	2.3-8	2.1-8	
	^{7}Be	2.0-8	2.3-8	---	---	5.0-6	7.5-6	2.2-7	5.8-7	6.2-6	4.0-6	1.2-5
	^{11}C	4.1-9	5.0-9	2.4-9	2.4-9	---	---	5.2-11	1.2-10	---	---	
	^{41}Ar	3.2-6	3.8-6	1.8-6	1.8-6	---	---	---	---	---	---	
100	^{3}H	---	---	---	---	---	---	1.7-9	1.3-9	1.7-8	1.5-8	
	^{7}Be	1.3-8	1.6-8	---	---	2.6-6	3.9-6	2.0-7	5.4-7	5.4-6	3.4-6	8.0-6
	^{11}C	2.8-9	3.3-9	2.2-9	2.2-9	---	---	4.8-11	1.1-10	---	---	
	^{41}Ar	1.0-6	2.4-6	1.7-6	1.7-6	---	---	---	---	---	---	
300	^{3}H	---	---	---	---	---	---	9.5-10	7.1-10	8.6-9	7.6-9	
	^{7}Be	5.3-9	6.3-9	---	---	1.4-6	2.0-6	1.1-7	2.9-7	2.8-6	1.8-6	4.2-6
	^{11}C	1.1-9	1.3-9	1.2-9	1.2-9	---	---	2.6-11	6.1-11	---	---	
	^{41}Ar	8.3-7	1.0-6	9.0-7	9.0-7	---	---	---	---	---		
1000	^{3}H	---	---	---	---	---	---	1.9-10	1.4-10	1.8-9	1.6-9	
	^{7}Be	1.2-9	1.4-9	---	---	2.8-7	4.3-7	2.2-8	5.8-8	5.9-7	3.8-7	8.8-7
	^{11}C	2.5-10	3.0-10	2.4-10	2.4-10	---	---	5.2-12	1.2-11	---	---	
	^{41}Ar	1.8-7	2.2-7	1.8-7	1.8-7	---	---	---	---	---	---	

Tab. 7. Effective doses (Sv) per year.
A = adult, Ch = child (1 year old)
2.0-8 means $2.0 \cdot 10^{-8}$

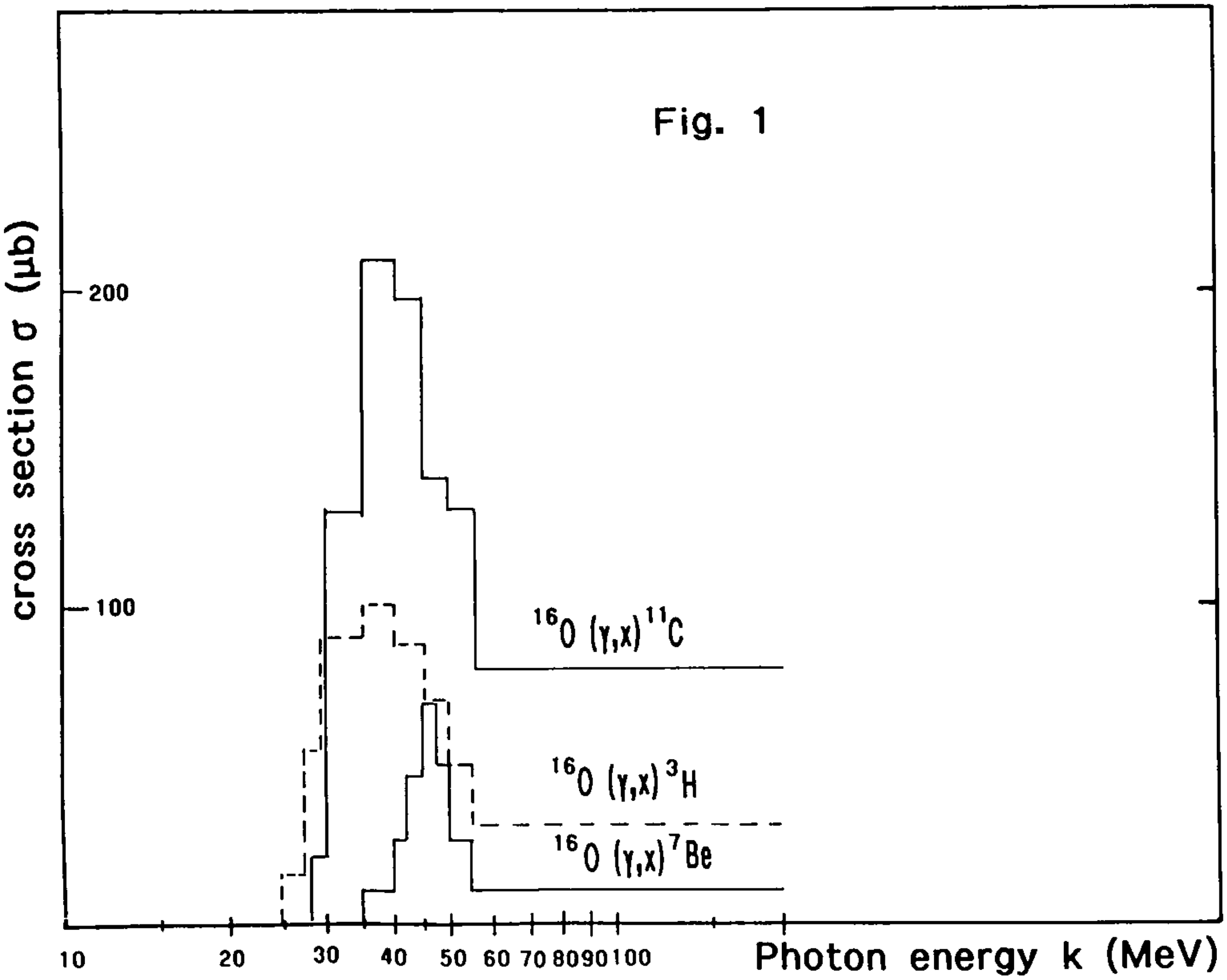

Fig. 1

cross section σ (μb)
200
100
$^{16}O\ (\gamma,x)\ ^{11}C$
$^{16}O\ (\gamma,x)\ ^{3}H$
$^{16}O\ (\gamma,x)\ ^{7}Be$
10
20
30
40
50
60
70
80
90
100
Photon energy k (MeV)