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INDUCED RADIOACTIVITIES AND CROSS SECTION MEASUREMENTS OF THE 14 MeV IRRADIATED MOLYBDENUM FOILS

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Abstract: The radioactivities of 14 MeV neutron irradiated Molybdenum foils have been measured for comparison exercise conducted by the IAEA Nuclear Data Section. The spectra of the characteristic gamma-rays emitted as a result of the induced radioactivity were taken with a Ge(Li) detector and an Intrinsic Germanium detector. The cross sections for the reaction $^{92}Mo(n,np)^{91m}Nb$, $^{95}Mo(n,p)^{95}Nb$ and $^{98}Mo(n,\alpha)^{95}Zr$ have been determined using the information provided by the IAEA on the irradiation time, total fluence and masses of the irradiated foils. The activation cross sections determined from the present measurements have been compared with previous work.

Introduction: In the Second Research Coordination Meeting (RCM) of the IAEA Coordinated Research Programme on the Measurement and Analysis of 14 MeV Neutron Cross Sections [1] held at Chiang Mai, Thailand, from 4-8 February 1985 and after the successful comparison exercise of the 14 MeV neutron irradiated Nickel foils [2] it was decided to carry out a similar, rather complex, exercise for 14 MeV neutron irradiated natural Molybdenum foils. In the present report we present the measurements of the radioactivities of the two 14 MeV neutron irradiated Molybdenum foils received from the Nuclear Data Section of the IAEA.

Experimental Details:

The natural Molybdenum foils were irradiated at the RTNS-II Neutron Generator facility of the Lawrence Livermore National Laboratory. A package of 24 foils was positioned at 10.0 ± 0.2 cm from the centre of the target at 30^o angle with respect to normal direction. Foil number 1 was the closest and the foil number 24 the farthest away from the target and the neutron fluence received by the two foils had values of 5.259×10^{15} and 4.86×10^{15} n/cm^2 respectively. The total irradiation time was 23,196.9 minutes. The irradiation started on 27th January 1986, 10h 57m, Pacific time and ended on 22nd February 1986, 07h 45m Pacific time. The time difference between the start and stop of the run, 37248 minutes, was much longer than the actual irradiation time. The reasons for this difference were discussed at the third RCM held at Dubrovnik, Yugoslavia 26-30 May, 1986.

The induced gamma-ray activities of the Molybdenum Foil # 8 and 17 having masses of 0.11672 and 0.11718 gram respectively, have been measured with the help of a Ge(Li) detector and an Intrinsic Germanium detector. The nominal active volume of the Ge(Li) detector is 105 cm^3 and has a resolution of 5 keV at 1332 keV ^{60}Co gamma-ray energy. The nominal active volume of the Intrinsic Germanium detector is about 61 cm^3 and has energy resolution of 2 keV at 1332 keV gamma-ray energy. The data were processed by a Canberra Series 85 multichannel analyser which has a built in facility of energy calibration, back ground subtraction, automatic searching of peaks and determination of the areas of the peaks togather with error estimates. The absolute peak-efficiencies of the Ge(Li) and the Intrinsic Germanium detectors were measured by using the standard radioactive sources kit supplied by the IAEA under the Coordinated Research Programme. The Spectra of emitted gamma-ray from the Molybdenum foils are shown in Figures 1-4. The measured efficiencies of the two detectors are given in Figures 5-6.

Results and Discussions:

The reactions leading to the radioactivities, measured by us, in different isotopes of Molybdenum together with the information on the half life of the radioactive products, energies of the characteristic gamma-rays and their transition strengths are listed in Table 1. The two gamma-rays of energies 766 keV due to ^{95}Nb and 757 keV due to ^{95}Zr could not be completely resolved by the Ge(Li) detector. These were stripped mannually. However these two lines were resolved by the Intrinsic Germanium detector as is evident from the spectra. In order to avoid errors in the relative strengths of the 724, 757 keV lines due to ^{95}Zr, the areas of the two lines were summed and their summed transition strength was taken as 98 percent. The time interval between the end of irradiation of the foils and our measurements was about 11.2 x 10^6 sec. The measured activities extrapolated back to the end time of the irradiation of the foils are shown in

Table 2. The measured activity of $^{95}Mo(n,p)^{95}Nb$ has been corrected for the ^{95}Zr, produced in the reaction $^{98}Mo(n,\alpha)^{95}Zr$ decaying into ^{95}Nb. The activity of $^{92}Mo(n,np)^{91m}Nb$ has been corrected for the activity arising from the reaction $^{92}Mo(n,2n)^{91m}Mo$ only for the following reasons. The spin-parity value of ^{91g}Mo is $9/2^+$ and that of ^{91m}Mo is $1/2^-$. Similarly the spin-parity values of ^{91g}Nb and ^{91m}Nb are $9/2^+$and $1/2^-$ respectively. Therefore, on account of large angular momenta values involved in the transition of ^{91g}Mo to ^{91m}Nb or states having spin values equal to or close to 1/2 whose transitions end on ^{91m}Nb are highly retarded. However the transition of ^{91m}Mo to ^{91m}Nb and states having spin-values equal to or close to 1/2 decaying to ^{91m}Nb are allowed. A similar argument applies to the high transition strength of ^{91g}Mo to ^{91g}Nb and excited states of ^{91}Nb which have spin-values equal to or close to 9/2 and decay to ^{91g}Nb. The deduced cross section values are given in Table 3 and compared with reported values. The present cross sections for the reactions $^{95}Mo(n,p)^{95}Nb$ and $^{98}Mo(n,\alpha)^{95}Zr$ are in good agreement with reported values. The present value of cross section for the reaction $^{92}Mo(n,np)^{91m}Nb$ does not agree with the only measurement of Qaim reported in reference [3]. Measurements by Haight et al [4] give a higher value for the proton production from ^{92}Mo.

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Table 1 Information on half life, gamma-ray energy and transition strength of radioactive products*.

Reaction	half life (days)	gamma-ray energy (keV)	Strength (percent)
$^{92}Mo(n,np)^{91m}Nb$	62	1205	3.4
$^{95}Mo(n,p)^{95}Nb$	35.15	766	99.0
$^{98}Mo(n,\alpha)^{95}Zr$	65.5	724 757	43.0 54.6

*Gerbard Erdtmann, Kernchemie in Einzeldarstellungen Volume 6, 1976.

Table 2 Activities of Molybdenum Foils on 22nd February, 1986 07h 45m Pacific time

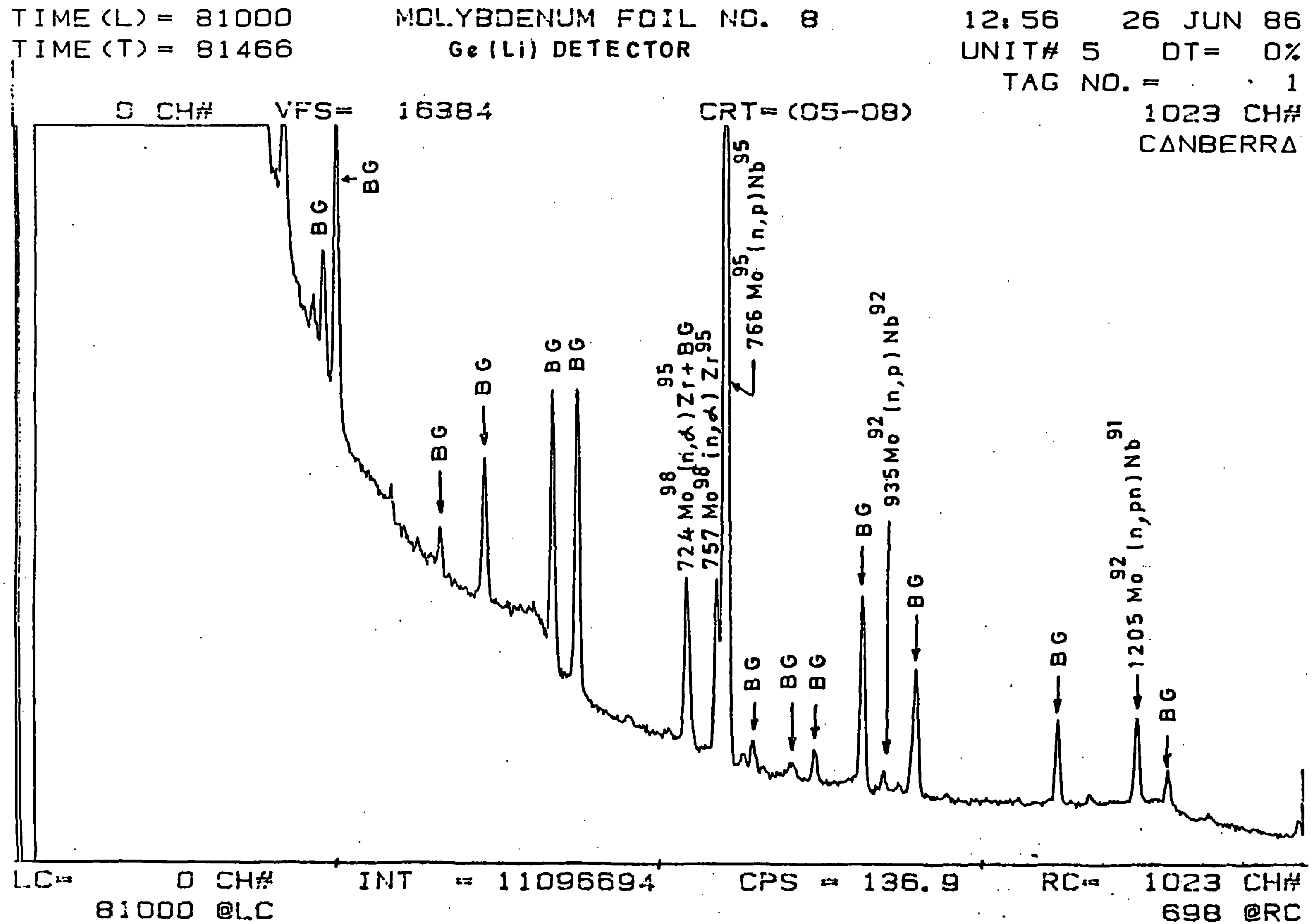
Foil Number	$^{92}Mo(n,np)^{91m}Nb$ (10^3 dis/sec-gm)	$^{95}Mo(n,p)^{95}Nb$ (10^3 dis/sec-gm)	$^{98}Mo(n,\alpha)^{95}Zr$ (10^3 dis/sec-gm)
8	71.0 ± 6.4	43.6 ± 2.3	6.0 ± 0.66
17	69.8 ± 7.7	43.4 ± 2.9	6.0 ± 0.8

Table 3 Neutron activation cross section of Mo isotopes at 14.7 MeV[a]

Reaction	Present Work (mb)	Previous work (mb)
$^{92}Mo(n,np)^{91m}Nb$	124 ± 19	44 ± 15 [3] , 967 ± 116[b] [4]
$^{95}Mo(n,p)^{95}Nb$	44 ± 3.5	41.1 ± 3.6 [5] , 31 ± 3 [6] 44.8 ± 3.5 [8]
$^{98}Mo(n,\alpha)^{95}Zr$	6.8 ± 0.8	5.5 ± 1.5 [5] , 5.5 ± 0.7 [6] 8.1 ± 1 [7] , 8.1 ± 0.8 [8]

a) The incident energy may be out by ± 200 keV.

b) This value includes the sum of (n,p) and (n,np) cross sections.



TIME (L) = 81000
TIME (T) = 81466
MOLYBDENUM FOIL NO. 8
Ge (Li) DETECTOR
12:56 26 JUN 86
UNIT# 5 DT= 0%
TAG NO. = 1
0 CH# VFS= 16384
CRT= (05-08)
1023 CH#
CANBERRA
BG
$766\ ^{95}Mo\ (n,p)\ ^{95}Nb$
$724\ ^{98}Mo\ (n,\alpha)\ ^{95}Zr + BG$
$757\ ^{98}Mo\ (n,\alpha)\ ^{95}Zr$
$935\ ^{92}Mo\ (n,p)\ ^{92}Nb$
$1205\ ^{92}Mo\ (n,pn)\ ^{91}Nb$
LC= 0 CH#
INT = 11096694
CPS = 136.9
RC= 1023 CH#
81000 @LC
698 @RC

7

Fig.

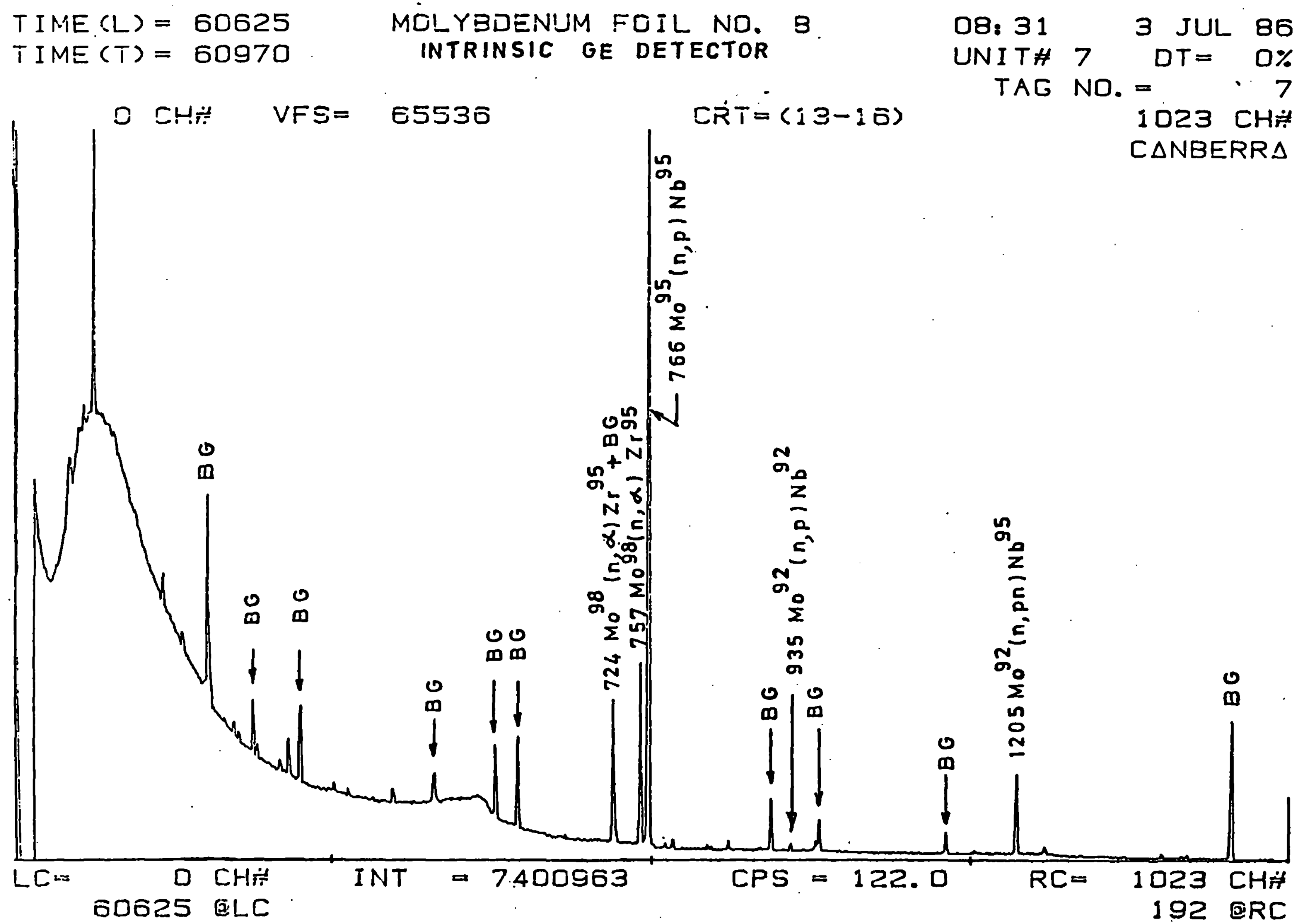

TIME(L) = 60625
TIME(T) = 60970
MOLYBDENUM FOIL NO. 8
INTRINSIC GE DETECTOR
08:31 3 JUL 86
UNIT# 7 DT= 0%
TAG NO. = 7
0 CH# VFS= 65536
CRT=(13-16)
1023 CH#
CANBERRA
766 Mo95(n,p)Nb95
724 Mo98(n,α)Zr95+BG
757 Mo98(n,α) Zr95
935 Mo92(n,p)Nb92
1205 Mo92(n,pn)Nb95
BG
LC= 0 CH#
INT = 7400963
CPS = 122.0
RC= 1023 CH#
60625 @LC
192 @RC

Fig.

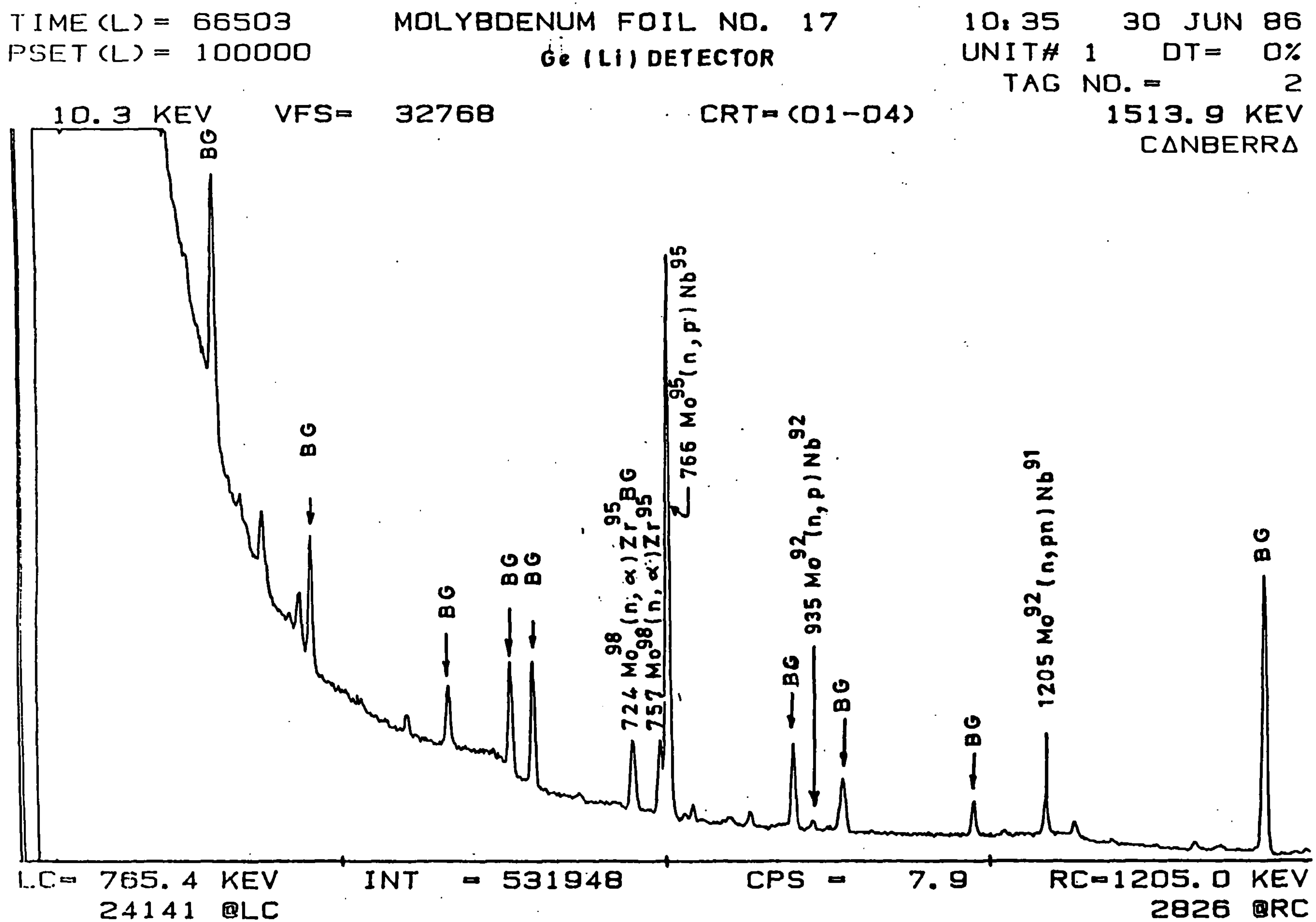
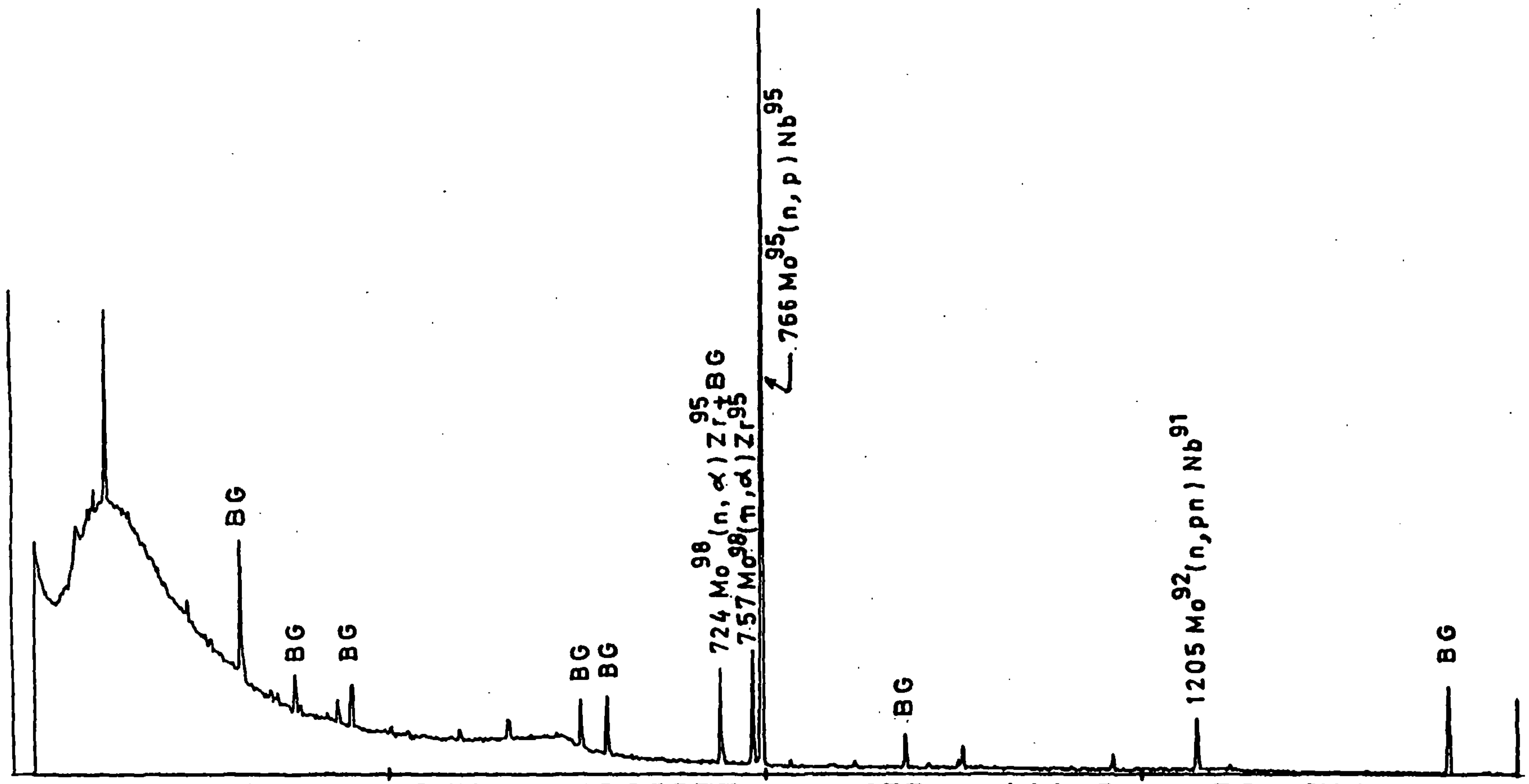

TIME (L) = 66503
PSET (L) = 100000
MOLYBDENUM FOIL NO. 17
Ge (Li) DETECTOR
10:35 30 JUN 86
UNIT# 1 DT= 0%
TAG NO. = 2
10.3 KEV VFS= 32768
CRT=(01-04)
1513.9 KEV
CANBERRA
BG
BG
BG
BG
BG
724 Mo98(n,α)Zr95
757 Mo98(n,α)Zr95
BG
766 Mo95(n,p)Nb95
BG
935 Mo92(n,p)Nb92
BG
BG
1205 Mo92(n,pn)Nb91
BG
LC= 765.4 KEV
24141 @LC
INT = 531948
CPS = 7.9
RC=1205.0 KEV
2826 @RC

Fig. 6

TIME (L) = 15800 MOLYBDENUM FOIL NO 17 15:50 3 JUL 86
PSET (L) = 100000 INTRINSIC GE DETECTOR UNIT# 1 DT = 0%
TAG NO. = 8
9. 6 KEV VFS= 32768 CRT= (01-04) 1528. 9 KEV
CANBERRA



LC= 9. 6 KEV INT = 1766675 CPS = 111. 8 RC=1528. 9 KEV
15800 @LC 56 @RC

Fig.

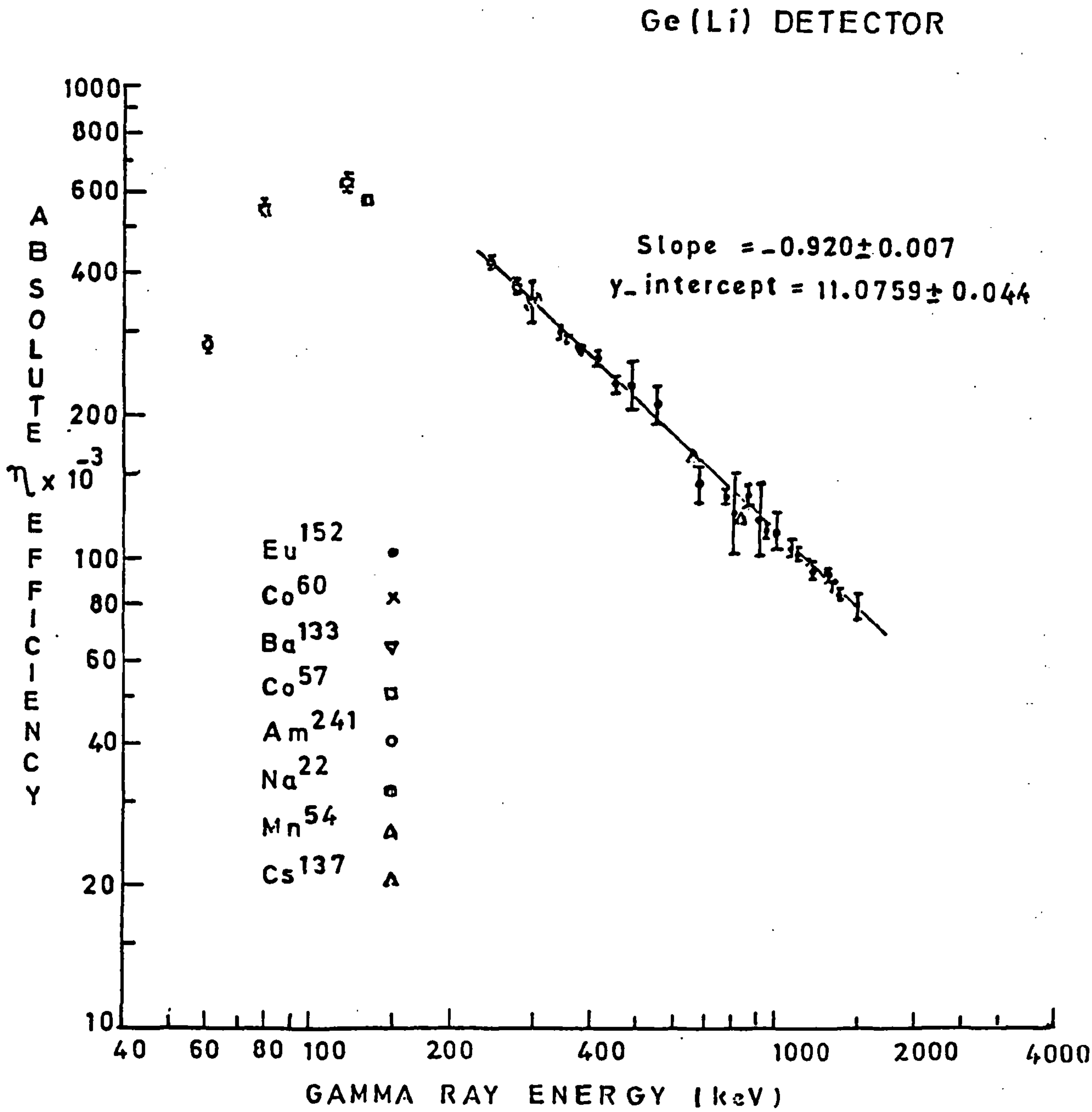

Ge(Li) DETECTOR
Slope = -0.920±0.007
y-intercept = 11.0759±0.044
ABSOLUTE η x 10^-3 EFFICIENCY
1000
800
600
400
200
100
80
60
40
20
10
40
60
80
100
200
400
1000
2000
4000
GAMMA RAY ENERGY (keV)
Eu^152
Co^60
Ba^133
Co^57
Am^241
Na^22
Mn^54
Cs^137

Fig-

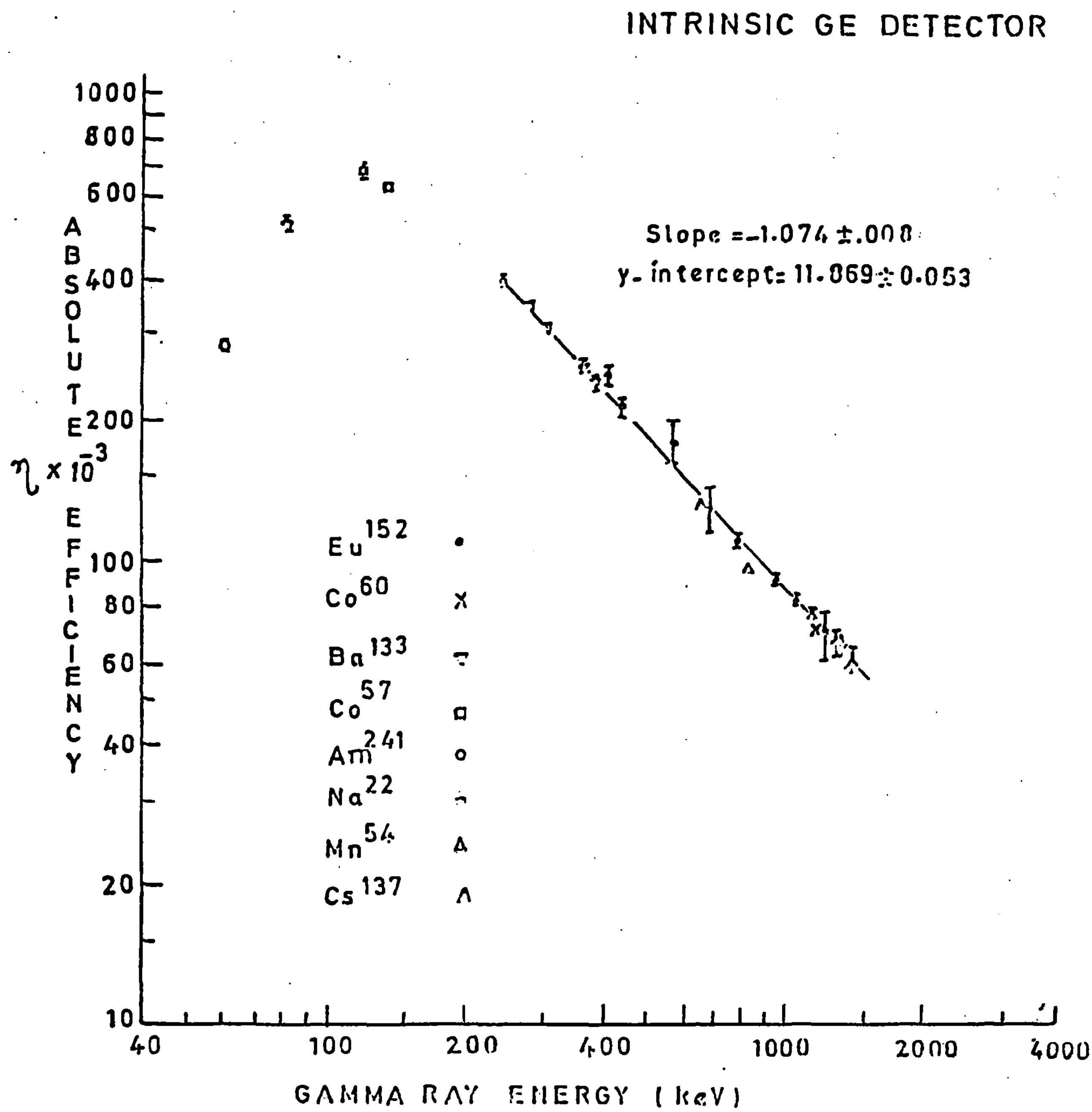

INTRINSIC GE DETECTOR
Slope =-1.074 ±.008
y- intercept= 11.869 ± 0.053
ABSOLUTE EFFICIENCY
η x 10⁻³
1000
800
600
400
200
100
80
60
40
20
10
40
100
200
400
1000
2000
4000
GAMMA RAY ENERGY (keV)
Eu152
Co60
Ba133
Co57
Am241
Na22
Mn54
Cs137

Fig.