STUDIECENTRUM VOOR KERNENERGIE

CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

STANDARDIZATION OF RADIONUCLIDES AT THE SCK/CEN

C. BALLAUX

February 1985

E. Plaskylaan 144, 1040 BRUSSEL
(BELGIE)

BLG 575

144, avenue E. Plasky, 1040 BRUXELLES
(BELGIQUE)

STANDARDIZATION OF RADIONUCLIDES AT THE SCK/CEN

C. BALLAUX

February 1985

BLG 575

C. BALLAUX
BLG 575 (Feb. 1985)

STANDARDIZATION OF RADIONUCLIDES AT THE SCK/CEN

Summary. - This status report summarizes the techniques applied and the results achieved, between 1973 and 1983, in the laboratory for radionuclide metrology of SCK/CEN. The techniques for the quantitative and qualitative preparation of radioactive sources are briefly described and a few details are given concerning $4\pi\beta$ and $2\pi\alpha$ proportional counting, 4π (PC)-γ coincidence counting with efficiency extrapolation and measurements with well-type NaI(Tl) detectors. From several intercomparisons it appears that accuracies were achieved, comparable to those from important national and international standardizing laboratories. During this periode the annual production was about 100 standards of about 20 different radionuclides.

C. BALLAUX
BLG 575 (Feb. 1985)

STANDARDIZATION OF RADIONUCLIDES AT THE SCK/CEN

Samenvatting. - Een overzicht wordt gegeven van de toegepaste technieken en van de resultaten, die bekomen werden in het laboratorium voor metrologie van radionucliden van het SCK/CEN, gedurende de periode 1973-1983. De technieken voor de kwalitatieve en kwantitatieve bereiding van radioactieve bronnen worden bondig beschreven; daarna volgen enige details over metingen met $4\pi\beta$ en $2\pi\alpha$ proportionele tellers, 4π (PT)-γ coincidentiemetingen met efficientie-extrapolatie en metingen met NaI(Tl) putdetectoren. Uit verschillende intervergelijkingen blijkt dat de bereikte nauwkeurigheden vergelijkbaar waren met deze van belangrijke, nationale en internationale standaardlaboratoria. De jaarlijkse produktie bedroeg tijdens deze periode, ongeveer 100 standaarden van een twintigtal verschillende radionucliden.

C. BALLAUX
BLG 575 (Feb. 1985)

STANDARDIZATION OF RADIONUCLIDES AT THE SCK/CEN

Résumé. - Ce rapport donne un aperçu des techniques utilisées et des résultats, qui ont été obtenus au laboratoire de métrologie des radionucléides du CEN/SCK, au cours de la période 1973-1983. Les techniques de préparation quantitative et qualitative de sources radioactives sont brièvement décrites et des détails sont fournis sur les mesures aux compteurs proportionnels $4\pi\beta$ et $2\pi\alpha$, les mesures par comptages par coïncidences 4π(CP)-γ et en extrapolant l'efficacité et celles effectuées avec des détecteurs NaI(Tl) à puits. Plusieurs intercomparaisons ont montré que les exactitudes étaient comparables à celles des bureaux nationaux et internationaux de métrologie. Pendant cette période la production annuelle était d'environ 100 étalons, se rapportant à une vingtaine de radionucléides.

STANDARDIZATION OF RADIONUCLIDES AT THE SCK/CEN *

C. BALLAUX **
Nuclear Metrology, SCK/CEN, B-2400 Mol (Belgium)

1. Introduction

The radioactivity of a sample is characterized by its mean decay rate at a given time, and by its standard deviation. The Poisson distribution is generally sufficiently accurate to describe the random emissions from a radioactive source. This process is, however, distorted by counting losses (dead time) and by decay, if it occurs appreciably during the measurement.

As distinct from relative measurements, direct methods do not depend on previous calibrations. The direct methods (1) mainly start from a known geometric efficiency or use cascade radiations. There is in fact no universal standardizing method. For each radionuclide the type of the detected radiation, its energy and probability per decay should be considered; the effect of other radiations and of the source and the mount has to be taken into account as well as the fraction of the emitted radiations which interact in the detector, and its response. For high-accuracy work (~ 0.1 %, equivalent standard deviation), two or more independent direct methods are usually applied in standardizing laboratories, after testing the radiochemical purity. These standard solutions can often serve as the basis for accurate decay data, for the benefit of all users.

One of the principal tasks of the laboratory at SCK/CEN is to issue, mostly on special order, standardized radioactive sources (1) with the desired characteristics (activity, accuracy, geometry, chemical

---

* On October 25, 1984 a seminar was given at the NBS, entitled : " An Overview of Reactor and Waste-Disposal Programs at the Belgian Centre for Nuclear Energy, with Some Details of the Radionuclide Metrology Involved". Various subjects of this paper were discussed during this lecture.

** Controle-Stralingsbescherming/Contrôle-Radioprotection.

composition...), for use inside and outside of SCK/CEN. The annual production for the last several years was around 100 standards of about 20 different radionuclides. Traceability links with the BIPM and with national and international laboratories were maintained by participation in international and bilateral comparisons of activity measurements and computer codes and by coordinating ICRM-actions within the SCK/CEN.

This status report summarizes the techniques applied, and the results achieved between 1973 and 1983. Due to the limited staff (0.7 Dr. Sc. and 1.1 technician), only a few techniques have been applied.

2. Source Preparation and Dilution

Standards of radionuclides are usually maintained as chemically stable and radiochemically pure solutions with a few μg of carrier per gram solution.(1)

2.1. Quantitative methods (9)

For the quantitative preparation of sources and for the dilution of the master solutions, the polyethylene-pycnometer technique is applied in a small (10 m^3), isolated and air-conditionned balance room, constructed according to current recommendations.(2) With an electronic micro-balance and a classical analytical balance, the estimated standard deviation amounts to 3 μg for sources and < 0.05 % for dilutions.(a)

For proportional and coincidence counting the sandwich technique is applied.(4) The VYNS foils of ~20 μg/cm2 are coated with one (top) or two (bottom) layers of ~20 μg/cm2 gold. The electric resistance of these foils appears to increase from about 4 Ohm to about 8 Ohm after a storage in a plastic box, placed in a dessicator, during 6 weeks. Generally 20 μl of Ludox, freshly diluted with 10^4 parts water, is added to the weighed drops (5 to 20 mg) in order to reduce the inhomogeneity and the self-absorption.(5) In the case of measurements in

---

(a) All uncertainties are expressed according to the recommendations of the BIPM. (3)

the $4\pi\gamma$ system, either a lucite cell or two thin plastic films are used as holders. Usually the sources are dried in the balance room, at 21.5°C; precipitation in situ is applied in the case of volatile compounds.(5) Impurity testing is normally performed on 1-cm^3 samples, by the Nuclear-Spectrometry Group.

2.2. Non-quantitative methods (6)

Alpha-particle standards are mostly issued as thin and homogeneous sources of rather large area and of low activity ($\lesssim$ 1 kBq). They are prepared by electrodeposition from aqueous solutions, multiple painting (e.g. for ^{237}Np sources, used for fission-track dosimetry), or by adsorption of precipitates on thick and flat metal backings (1 to 5 cm ∅). The last method is very suitable for the preparation of sources for α-ray spectrometry : very thin sources can be made, invisible to the unaided eye.

In a few cases the homogeneity was tested by means of autoradiography.

3. Applied Direct or "Near-Direct" methods (1)

3.1. Weighing of a Radioactive Element of Known Isotopic Composition

This method is applied, for example, if standards of ^{40}K and ^{232}Th have to be issued for whole-body counting.

3.2. $4\pi\beta$ Proportional Counting

A modified "pill-box" counter is used for $4\pi\beta$ proportional counting and for coincidence counting (see 3.4.). With a filtered mains, the background is lower than 1 s^{-1}. Both halves are nearly equal, as appears from x-ray spectrometry and from the onset of the α-plateau, measured with sources, mounted on metallic backings.

If the required accuracy is not high, pure β-emitters, such as ^{32}P, ^{36}Cl, ^{90}Sr and ^{204}Tl, are directly measured in our proportional counter, through which methane flows at atmospheric pressure. The β-ray efficiencies are calculated from the foil- and self-absorption

factors, measured in other laboratories (7,8) and in Mol.(9) A few values are listed in Table I. Uncertainties are also given which take into account the variations in the thicknesses of the films and of the inhomogeneous sources (local agglomerates).
Efficiency tracing is applied for high-accuracy work and for low-energy β-emitters, such as ^{63}Ni.(9,10)

Table I - β-ray efficiencies for our conditions. (Ludox added). The mean surface density amounts to 2 µg/cm2 of the chlorides. The corresponding "cut-off" values (see 3.4.) amount to about 8 keV, i.e. much larger than the lower-level discriminator setting (about 0.3 keV). (1,25)

Nuclide	E_β(Max) (keV)	$\bar{E}_\beta$ (keV)	ε_β (7,8)	ε_β (9)	unc. (%)
^{35}S	165.47	48.8	0.891	0.901	4.1
^{99}Tc	293.5	84.7	0.940	0.937	1.8
^{90}Sr	546	196	0.976	0.975	0.9
^{210}Bi	1161.4	389.0	0.989	0.987	0.4
^{90}Y	2283.9	939	0.995	0.997	0.2

3.3. 2πα Proportional Counting

Owing to the characteristics of the sources, the moderately accurate 2πα method is applied in a large, cylindrical proportional flow counter ($Ar-CH_4$ 9/1, at atmospheric pressure). The corrections for scattering from the source, the flat metal backing and from the counting gas, and for self-absorption, are calculated according to the Gaussian model worked out at the NBS.(11)

For near-massless sources of ^{241}Am (reduced thickness $d \cong 10^{-4}$), prepared by adsorption of the hydroxide on polished-aluminium and stainless-steel backings, we obtained results, which differ by about 0.1 % from those achieved with the more accurate $2\pi\alpha$-γ method. (see 3.4.). The correction factors for the backscattering from the backings appear to be in reasonable agreement with the classical, multiple-scattering theory of Williams, as can be seen from Table II. A more detailed analysis is given elsewhere.(6)

Table II - Comparison of the experimental and theoretical correction factors $N_{2\pi}/N_0$ for $d = 0$.

BACKING	5.31 MeV		4.64 MeV		4.19 MeV	
(Z)	exp.	theor.	(11)	theor.	(11)	theor.
Al(13)	0.5028	0.5048	0.5030	0.5050	0.5034	0.5050
Ti(22)	0.5052	0.5062	0.5056	0.5064	0.5062	0.5066
Cu(29)	0.5070	0.5084	0.5076	0.5086	0.5082	0.5090
Ag(47)	0.5116	0.5106	0.5126	0.5110	0.5136	0.5112
Ta(73)	0.5182	0.5148	0.5197	0.5154	0.5211	0.5158
Pt(78)	0.5195	0.5158	0.5213	0.5164	0.5227	0.5170

3.4. 4π(PC)-γ Coincidence Counting with Efficiency-Extrapolation(9,10)

A new 102- x 102-mm NaI(Tl) detector has been recently installed; the FWHM amounts to 6.5 %, at 662 keV and the peak-to-valley ratio is 15 at 1332 keV. DDL amplification and constant-fraction timing discrimination is applied in both channels. The data can be stored in a Personal Computer and sent to the main frame for computation.

Measuring $N_{PC}N_{\gamma}/N_C$ in function of the efficiency parameter N_C/N_{γ} and fitting the efficiency function with a low-order polynomial leads to an extrapolated value equal to the disintegration rate.

Thus the activity is determined from observables only.(b) Experimental conditions should be choosen so that a linear fit can be obtained, where possible.

The precision of this powerful method is high (~0.02 %) and the accuracy is in fact only limited by the uncertainties of the dead times and the resolving time, and by the delay mismatch. The dead times of the PC- and the γ-channel, as measured with a calibrated oscilloscope and by the source-pulser and the two-oscillator methods, are normally equal to (2.48 ± 0.01) and (2.46 ± 0.01) µs, respectively. The resolving time is usually set to (1.0143 ± 0.0003) µs, as measured from the accidental-coincidence rate with two independent oscillators. The uncertainty of the time synchronisation of the two channels is about 6 ns. The FWHM of the time-distribution, measured with the time-to-amplitude convertor, amounts to 95 ns for ^{60}Co in CH_4 and to 17 ns for ^{54}Mn in Ar-CH_4. The system works satisfactorly up to about 50 kBq ^{60}Co.(see 5.)

Data fitting is applied because the exact analytical form of the efficiency function is unknown. There is at present no comprehensive theory of the complex physical processes responsible for the counting losses of β particles of energy E in a $4\pi\beta$ proportional counter. The β-ray detection efficiency can be written :

$$\varepsilon_\beta = \int_0^\infty P(E)\,\phi(E)\,dE = \int_0^\infty P'(E)\,dE\ .$$

The original emission-probability function and that for degraded particles, P(E) and P'(E), respectively, can be approximated by polynomials in E, just like the efficiency function, and $\phi(E)$ is the detection-probability function ($0 \leqslant \phi(E) \leqslant 1$). $\phi(E)$ has been taken to be a unit step function. In the case of the efficiency tracing of ^{137}Cs

---

(b) For complex EC decay, corrections should be applied, according to FUNCK E. and NYLANDSTED A. (Int. J. Appl. Radiat. Isot. 34 565 (1983)).

by ^{134}Cs, the following expression has been deduced for the β-ray efficiency :

$$\varepsilon_\beta = \sum_i P_j(E_i)\ \Delta E\ \left[1 - (k_1 \bar{d}_s E_i^{-1.1} + n k_2 \bar{d}_f E_i^{-1.5})\right] .$$

The β-ray spectrum $N_j(E_i) = P_j(E_i)\ \Delta E$. The number of supplementary VYNS foils, n, is equal to 0, 1, 2, ...; k_1 and k_2 are proportionality constants, and $\bar{d}_s$ and $\bar{d}_f$ are the mean source thickness and the mean foil thickness , respectively. In a 4πβ proportional counter, mainly low-energy electrons are involved in self- and foil-absorption, energy discrimination, and scattering; hence single and plural scattering predominate and the backscattering from VYNS foils decreases with the energy.

3.5. Measurements with a Large NaI(Tl) Well-Type Detector (9,12,23)

Overload problems can occur in the preamplifier and the amplifier, due to cosmic rays; the suitable characteristics of an amplifying system have been reviewed.(12)

3.5.1. The Sum-Peak Coincidence Method of Brinkman (13)

This method is applicable to radionuclides with two- or three-photon cascades and no β- or EC-transition to the ground state nor excessive internal conversion. The uncertainty varies from a few tenths of a percent to a few percent, according to the complexity of the spectrum. The principal component of uncertainty is associated with the determination of the non-linear background under the full-energy peaks and the limited resolution of the detector (FWHM = 7.5 % in our case, at 662 keV). The following differences have been obtained between this method and 4π(PC)-γ coincidence counting : ^{60}Co, - 0.5 %; ^{88}Y, - 1.2 % and ^{22}Na, + 1.7 %. This method has been frequently used for the standardization of ^{125}I.

3.5.2. $4\pi\gamma$ [NaI(Tl)] Integral Counting

This method is particularly useful for the measurement of radionuclides with complex decay schemes incorporating cascade photon transitions. Although the individual decay-scheme parameters and the detection efficiencies of the various radiations may not be known with high accuracy, the probability of not detecting any radiation from a decay in a large well-type NaI(Tl) detector is often small enough that the uncertainty of this fast and simple method is only two to three times larger than that of coincidence counting. The accuracy for a dual decay, e.g. ^{192}Ir, can be even higher. For the determination of neutron cross-sections, it is furthermore practical to measure a thin (~ 0.2 mm) irradiated fluence monitor directly in the well, without the necessity of dissolving.

Computer codes have been developed to calculate the total efficiency of each decay path from the branching ratio (25) and from the total efficiencies for the x- and γ-rays and also for the β-particles and the conversion electrons. Summations between γ-rays and x-rays from EC and, or, internal conversion are taken into account and also the contribution of annihilation radiation in the case of β^+-emission. Photon-efficiency curves have been calculated and measured, above 22.1 keV (^{109}Cd) and extrapolated to zero energy. For some radionuclides, the effect of using threshold-corrected efficiencies has to be considered.(14) The theoretical total efficiencies have been calculated from the well-known dimensions of the detector and from experimental linear absorption coefficients.(15,16) The Monte-Carlo method gives practically the same results as numerical integration : for 10^3 histories the agreement is within 0.1 % and, for 10^4 histories, within 0.01 %. It follows from Table III that the experimental and theoretical total efficiencies agree closely; our most popular radionuclides are listed there.

Using either the threshold or the extrapolated efficiencies with the corresponding counting rates, practically the same results are achieved.

Table III - A few total efficiencies in our $4\pi\gamma$ system.

Nuclide	LLD = 22.1 keV		extrapolated
	experimental	theoretical	
	SINGLE GAMMA-EMITTING RADIONUCLIDES		
^{51}Cr	0.0916(5)	0.0919	0.0928
^{54}Mn	0.7459(37)	0.7436	0.7496
^{85}Sr	0.8319(42)	0.8308	0.8447
^{22}Na	0.9600(8)	0.9591	0.9608
^{57}Co	0.9613(49)	0.9589	0.9616
^{58}Co	0.7876(32)	0.7865	0.7942
^{60}Co	0.8933(22)	0.8873	0.8973
^{131}I	0.8881(44) *	0.8900	0.9023
^{198}Au	0.8733(52)	0.8731	0.8868
	MULTI-GAMMA-RAY SOURCES		
^{56}Co	0.9399(13)	0.9389	0.9414
^{133}Ba	0.9783(19)	0.9825	0.9823
^{134}Cs	0.9590(15)	0.9594	0.9629
^{152}Eu	0.9523(16)	0.9600	0.9547

* in equilibrium with ^{131m}Xe; ε_t = 0.8909(44) for pure ^{131}I.

3.5.3. Measurement of Low-Energy Photons (17,18)

The gamma-emission rate of low-energy photons can be measured by γ-ray spectrometry. The following corrections have to be applied : the escape from the well; the absorption and scattering from the source holder and the well-liner; the photo-electron escape; and eventually the efficiency for conversion electrons and for interfering peaks.

The live-time clock of our 1024-channel analyzer has been found accurate ($<$ 0.1 % error up to 10^4 c/s), by applying the pulser method. (1) The uncertainty arises mainly from the uncertainties and the non-uniformity of the thicknesses of the liner (0.5 mm Al) and of the reflector (0.28 and 0.32 mm Al_2O_3). Due to the presence of these materials the total efficiency at 10 keV is about 0.01 %. The efficiencies and uncertainties for a few radionuclides with low-energy photons are listed in Table IV; lower uncertainties can e.g. be achieved with a Be liner. This efficiency function method was also applied to ^{137}Cs.(9)

Table IV - Summary of the results (%). E : escape from the well (direct and after Compton and coherent scattering from the liner). P : photoelectric absorption in the liner. A : percentage of the photons, absorbed in the NaI(Tl) crystal. T : threshold (keV), used in the measurement;* experimental

Nuclide	keV	E	P	A	total eff. and unc.*	T
^{109}Cd	22.0-25.5	1.47	55.16	43.37	44.7 ± 1.2	8
^{125}I	27.2-35.5	1.36	35.65	62.99	61.1 ± 1.9	10
^{241}Am	59.54	1.14	4.72	94.14	93.5 ± 0.9	38.5
^{109m}Ag	88.03	1.08	1.39	97.53		39
^{57}Co	122.06 - 136.47	1.03 (1.11)*	0.49	98.49	99.1 ± 0.5	22.1

4. Relative Measurements

In the absence of an ionization chamber, a 44- x 51-mm NaI(Tl) well-type detector has been calibrated for 1-cm3 samples of γ-emitters.(19) Preliminary results, with an uncertainty of a few percent, can be quickly communicated to the users.

High-precision relative measurements are performed at 2-, 5-, 10-, 12- and 15-cm from the 127- x 127-mm well-type detector, as described in the literature.(20)

Table V - International and bilateral intercomparisons.

Nuclide	Reference	Deviation (%)	Remarks
ALPHA-EMISSION RATE IN 2π GEOMETRY (1600-2600 α/s)			
^{239}Pu	LMRI	+ 0.03	12/1976
^{241}Am	LMRI	+ 0.02	09/1979
4π(PC)-γ COUNTING (5 to 45 kBq) AND EFFICIENCY TRACING			
^{54}Mn	BIPM	0.01	10/1980
^{60}Co	CBNM	- 0.05 to - 0.26	09/1978
^{60}Co	BIPM	+ 0.06 to + 0.22	10/1980
^{134}Cs	int. compar.	- 0.22	10/1978; (21)
^{137}Cs	int. compar.	+ 0.12	05/1982; (22)
4πγ [NaI(Tl)] COUNTING (≤ 10 kBq)			
^{56}Co	4π(PC)-γ SCK	- 0.28	12/1982
^{58}Co	4π(PC)-γ SCK	- 0.08	11/1979
^{85}Sr	4π(PC)-γ PTB	- 0.43	11/1981
^{123}I	IRE compar.	- 0.9	06/1983; (23)
^{133}Ba	mini compar.	- 0.19	11/1981; (24)
^{134}Cs	int. compar.	- 0.11	10/1978; (21)
^{137}Cs	int. compar.	+ 0.09	05/1982; (22)
COMPUTER CODE FOR 4πγ [NaI(Tl)] COUNTING			
^{134}Cs	IRK, PTB	≤ 0.03	04/1981; (12)

5. Intercomparisons and Conclusions

In Table V the results of a number of intercomparisons are listed. They compare favourably with those from important national and international standardizing laboratories. Compared with 1972, the accuracies were improved in Mol by a factor larger than 10 for many radionuclides. However a continuous effort is necessary, not only to maintain this level, but also to improve it, according to the aims of the BIPM and the ICRM.

REFERENCES

1. NCRP Report No 58. A Handbook of Radioactivity Measurements Procedures (1978).
2. Monographie BIPM-1. Procedures for Accurately Diluting and Dispensing Radioactive Solutions (1975).
3. GIACOMO P., Metrologia 17 73 (1981).
4. COLAS C., RYTZ A. and VEYRADIER C., Rapport BIPM/72-1.
5. MERRITT J.S., Nucl. Instr. Meth. 112 325 (1973).
6. BALLAUX C., Int. J. Appl. Radiat. Isot., in press.
7. PATE B.D. and YAFFE L., Can. J. Chem. 33 929 (1955).
8. CAMPION P.J., TAYLOR J.G.V. and MERRITT J.S., Int. J. Appl. Radiat. Isot. 8 8 (1960).
9. BALLAUX C., Int. J. Appl. Radiat. Isot., 34 1159 (1983).
10. BAERG A.P., Nucl. Instr. Meth. 112 143 (1973).
11. LUCAS L.L. and HUTCHINSON J.M.R., Int. J. Appl. Radiat. Isot. 27 35 (1976).
12. BALLAUX C., Int. J. Appl. Radiat. Isot. 34 493 (1983).
13. BRINKMAN G.A., ATEN A.H.W. Jr. and VEENBOER J. Th., Int. J. Appl. Radiat. Isot. 14 153, 433 and 503 (1963).
14. PAVLIK A. and WINKLER G., Int. J. Appl. Radiat. Isot. 34 1167 (1983).
15. HOLMBERG p., RIEPPO P. and PASSI P., Int. J. Appl. Radiat. Isot. 23 115 (1972).
16. MANNHART W. and VONACH H., Nucl. Instr. Meth. 136 109 (1976).
17. HUTCHINSON J.M.R. and GARFINKEL S.B., Int. J. Appl. Radiat. Isot. 22 405 (1971).

18. HUTCHINSON J.M.R. and MULLEN P.A., Int. J. Appl. Radiat. Isot. 34 543 (1983).

19. NABLO S.V. and MARTIN T.C., Int. J. Appl. Radiat. 10 55 (1966).

20. VANINBROUKX R. and GROSSE G., Int. J. Appl. Radiat. Isot. 17 41 (1966).

21. RYTZ A., Nucl. Instr. Meth. 192 427 (1982).

22. RYTZ A., Nucl. Instr. Meth., in press

23. REHER D., VANINBROUKX R., CHAUVENET B., MOREL J., VATIN R., WOODS M., LUCAS S., BALLAUX C. and JACQUEMIN R., Int. J. Appl. Radiat. Isot., 35 923 (1984).

24. RYTZ A., Rapport BIPM-82/6.

25. LAGOUTINE F., COURSOL N. and LEGRAND J., Table des Radionucléides, Vol. I, II and III (1983-1984).

APPENDIX : Most Important Fortran IV Programs.

1. BALANS : calculation of the buoyancy corrections when weighing aqueous solutions (9)
2. COINC : calculation of the disintegration rate in coincidence counting and efficiency tracing.(9)
3. POLFIT : least-square fiting of data with polynomials of the first, second and the third order.(9)
4. GEWO : unweighted and weighted mean values.
5. BETASP : calculation of the β-ray spectra according to the Fermi theory.(9)
6. BACKUP : calculation of the scattering corrections in 2πα counting. (6)
7. BSA : calculation of these scattering corrections, according to the theory of Williams.(6)
8. MOLIERE : multiple-scattering theory of Molière.(6)
9. EFNAI : calculation of the total efficiency of a radionuclide from decay-scheme data and from efficiency curves.(12)
10. QMATSYS and MCPUT : numerical and Monte-Carlo calculation of total efficiencies of photons, from the dimensions and the absorption coefficients of a NaI(Tl) well-type crystal.(9)
11. AG109 : calculation of the escape from the detector, of the photo-electric absorption by and the Compton scattering from the liner, and the photo-electron escape when measuring low-energy photons in a NaI(Tl) well-type detector.(17)