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PUBLICAÇÃO IPEN 12 IPEN - Pub - 12	MAIO/1980

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CENTRO DE OPERAÇÃO E UTILIZAÇÃO DO REATOR DE PESQUISAS
COURP - AFN 073

INSTITUTO DE PESQUISAS ENERGÉTICAS E NUCLEARES
SÃO PAULO -- BRASIL

Série PUBLICAÇÃO IPEN

INIS Categories and Descriptors

E41
A34

GAMMA SPECTROMETERS: Calibration
RADIATION DETECTORS: Li-drifted ge detectors
THERMAL NEUTRONS: Prompt gamma radiation

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ABSTRACT

"A simple method to obtain precise energy and intensities of thermal neutron capture γ-rays is described. Results are presented for the gamma lines of the reaction $^{20}Ne(n,\gamma)^{21}Ne$.

A single detector is utilized, but the method can be used for a three-crystal pair spectrometer".

1 – INTRODUCTION

A precise knowledge of the gamma ray energy and intensity is very important in nuclear structure studies. These data are fundamental in the construction of the level scheme; for if we measure precisely the primary gamma-rays, the secondary transitions can be placed in order to determine the energy levels. As the precision is improved many doubts about the level structure are eliminated. The intensity balance of the transitions (i.e., the ratio between the feeding and decaying transitions of a certain level) is also a valuable information data which confirms the placing of the levels. Other results which are obtained from these measurements are the reaction Q value and the thermal neutron capture cross section.

The standard utilized in our measurements is the spectrum of gamma rays from the $^{14}N(n,\gamma)^{15}N$ reaction. Nitrogen is a very convenient calibration standard because of several spaced lines in a broad energy range with very well known energy and intensity values[1].

In order to avoid possible errors caused by reactor power (neutron flux) fluctuations and different target-detector geometries, the calibrating sample and the target under study must be measured at the same time. In this sense, it would be desirable to have a homogeneous mixture.

Our target of interest was natural neon, so we used nitrogen gas and obtained a mixture with well known partial pressures to calibrate the system. The data analysis was done by the computer program GAUSS V[2] which also includes an automatic peak location routine.

2 – EXPERIMENTAL SYSTEM

The experimental apparatus (Figure 1) is installed in the through tube which is tangential to the core of the 2 MW research reactor (IEAR 1) of the Instituto de Pesquisas Energéticas e Nucleares. A detailed description can be found in a previous work[5]. The Ge(Li) detector is placed behind a 4 mm diameter lead collimator. This detector is an ORTEC 8101-0723 model (open-ended coaxial detector) with an active volume of 42.5 cm^3. The energy resolution is 2 keV at 2 MeV and 7.6 keV at 7 MeV. Data acquisition is performed by a HEWLETT-PACKARD 8192-channel analyser. A HEWLETT-PACKARD 5586A digital stabilizer with precicion pulsers was used to prevent baseline and gain drifts. The electronics is showed in the Figure 2. In front of the detector we use $^6Li_2CO_3$ as an absorber for thermal neutrons.

Aproved for publication in May 1979.

Writing, orthography, concepts and final revision are of exclusive responsibility of the Authors.

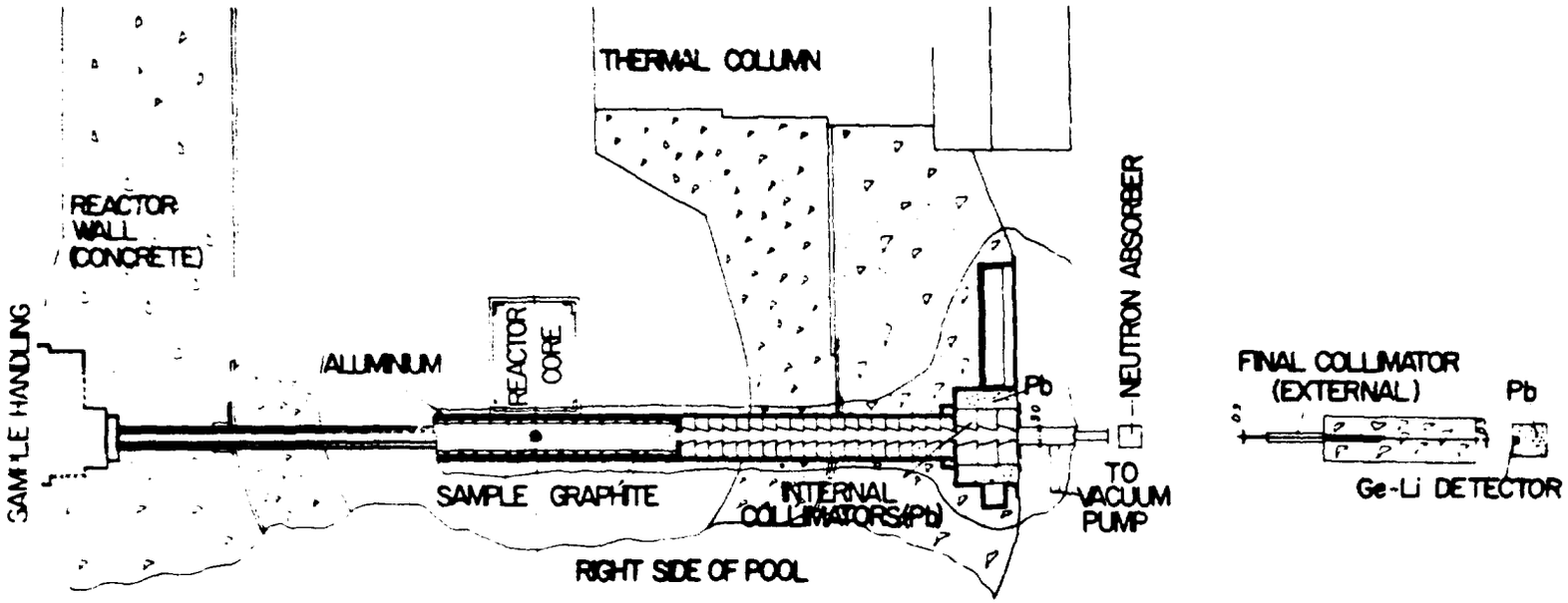

Figure 1 — Experimental Facility

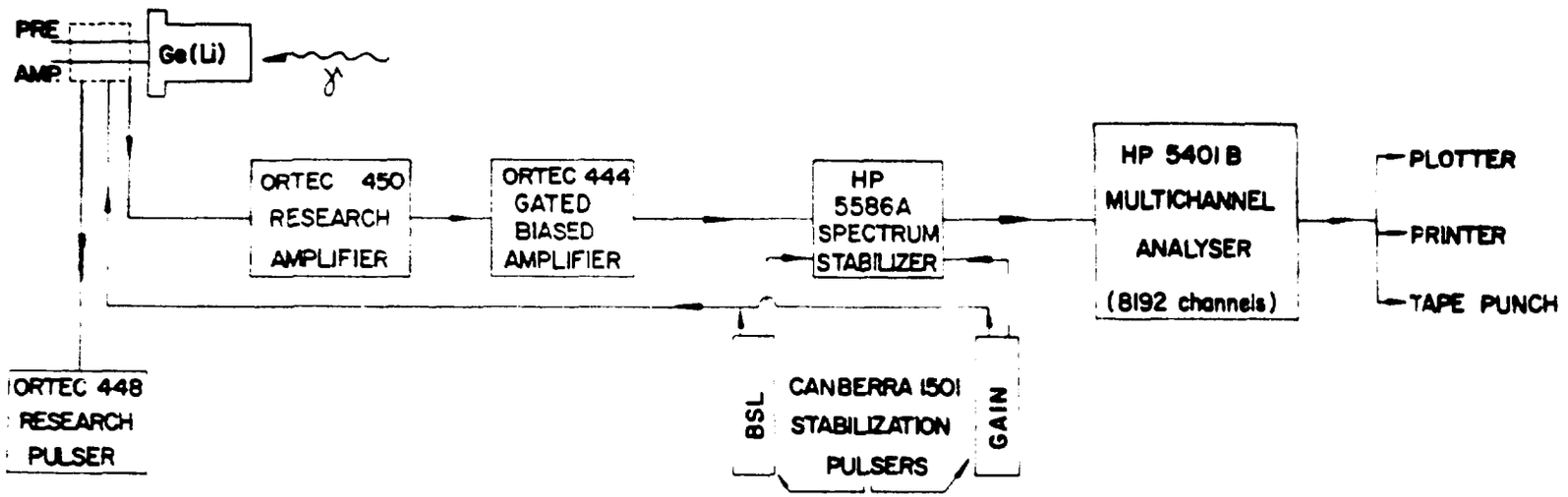

Figure 2 – Electronics

3 – RESULTS AND DISCUSSION

We filled the reactor tube with a mixture of nitrogen (1.25 atm) and neon (2.75 atm) and the pressure was constant up to the end of the measurements. Part of the 36 hours spectrum is showed in the Figures 3 and 4.

3.1 – Energy Measurements

In the selected range of interest (300 to 7000 keV) the γ-ray lines of nitrogen were used to establish a relation between the energy $\underline{E}$ and the channel position $\underline{X}$. The peak centroids were calculated using the GAUSS V program by simple gaussian curve fitting.

Due to non-linearities of the sistem, the relationship between energy and channel is not linear. In order to take this into account, we measure the deviation from linearity and correct the peak positions. We select two nitrogen lines at the extremes of the energy range, whose positions are assumed to have zero deviation. A linear function $E = a\,X + b$ is obtained with these two points. The deviation ΔX of the observed peak positions of the nitrogen lines from that straight line is the non-linearity of the system. The plot of this deviation is showed in the Figure 5.

In order to calculate energies the program needs the energy and position values of the calibration lines and non-linearity information. With these input data the parameters of a polynomial are calculated by least square fit. This calculation can be summarized as follows. The function to be minimized is:

$$\phi = \Sigma\, w_k \left[E_k - \bar{E}(X'_k) \right]^2$$

where:

w_k is the weight of the fit

E_k are the energies of the calibration lines

X'_k are the peak positions corrected for the non-linearity

$\bar{E}(X'_k) = a + b\,X'_k + c\,X'^2_k$ is the equation whose parameters are being calculated. In this equation, the second order term arises from small errors in the linearity correction. The weight w_k can be 1 (unweighted fit) or a function of the uncertainties $\sigma(E_k)$ of the calibration lines and the errors $\sigma(X'_k)$ in the peak positions.

The errors $\sigma(E)$ in the energies are calculated in the Gauss V program by:

$$\sigma(E) = \left[\sigma_1^2 + \sigma_2^2 \right]$$

where:

σ_1 are the errors in the peak location and

σ_2 are the uncertainties in a, b and c. For detailed discussion see Reference 2.

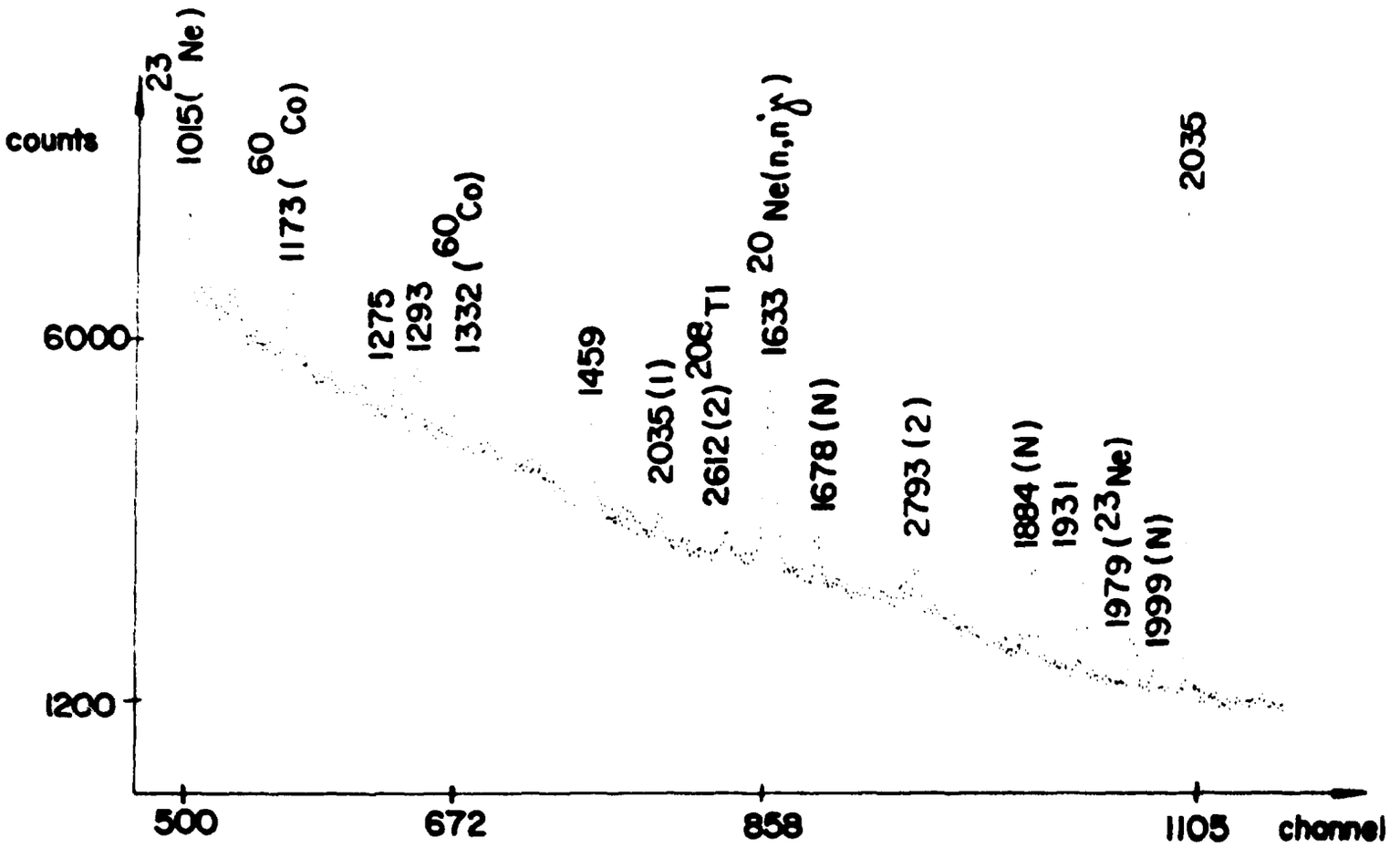

Figure 3 — Ne + N 36 hs spectrum. (N) indicates the nitrogen lines. (1) and (2) indicates the first and second escape peaks. Here is shown part of the low energy region. (Energies in KeV)

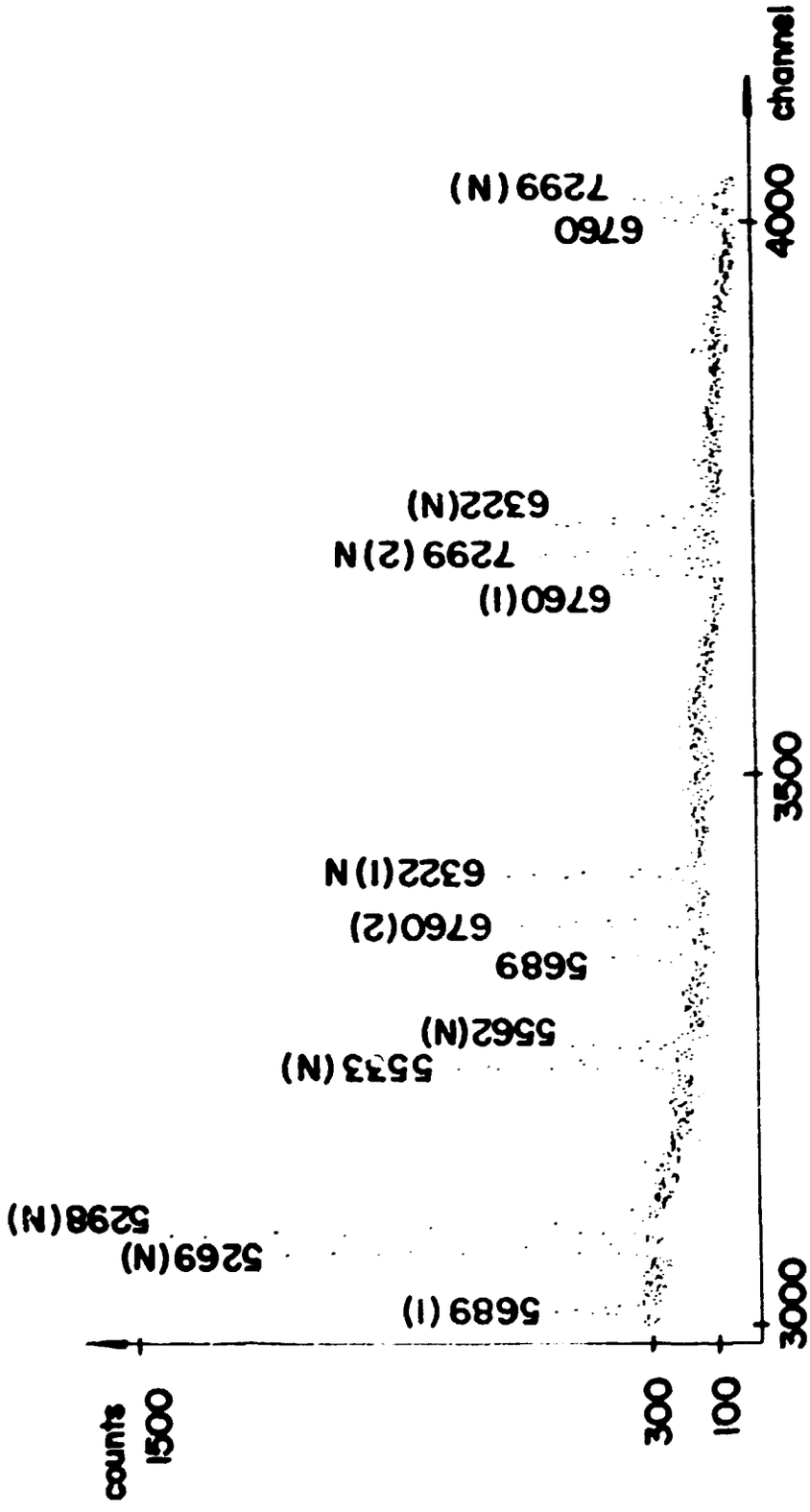

Figure 4 — High energy region

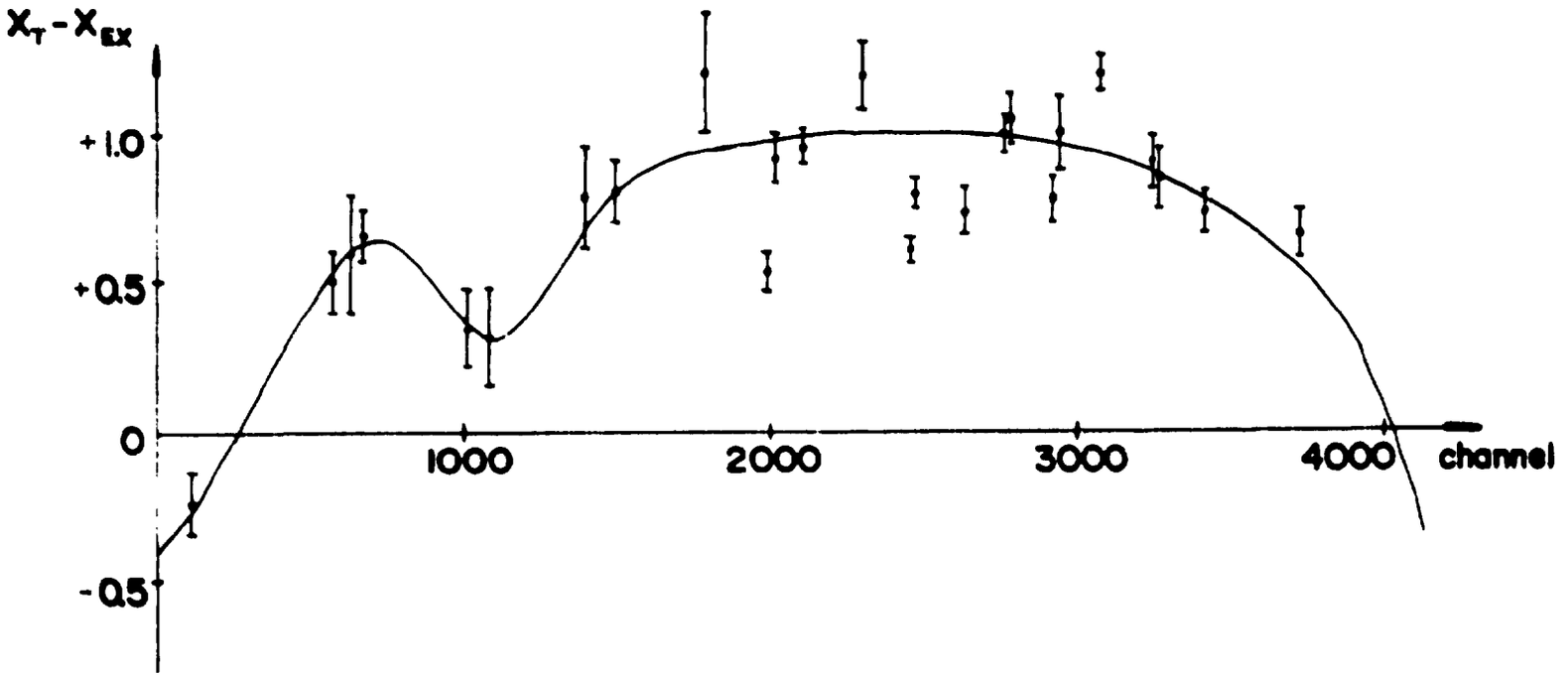

Figure 5 – Non-linearity Curve

Since the equation $E(X'_k)$ is obtained, the energy of each peak found by the locating routine is calculated taking into account the "zero" of the scale and the linearity correction. Table I is a typical output of the program.

3.2 – Efficiency Calibration and Intensity Calculations

The relative intensity I of the lines of a neutron capture γ-ray spectrum can be calculated as[7]

$$I = A/\epsilon T$$

where A, ϵ and T are respectively the peak area, the relative efficiency of the spectrometer and the γ-ray transmission of the possible attenuators in the gamma beam. The peak area is calculated in the GAUSS V program by gaussian curve fit with a linear sloping background. The only attenuator we use in the beam is the $^6Li_2CO_3$ thermal neutron absorber, but we also take into account the transmission through the air outside of the reactor and the gas target itself. The relative efficiency of the spectrometer is obtained by calibrating the system in terms of the nitrogen γ-ray capture lines whose intensities are well known[1]. As we use a single crystal spectrometer, our spectrum is complicated by the escape peaks. Thus, we have three efficiency curves corresponding to the full energy(FE), single(SE) and double(DE) escape peaks. The curves presented in Figure 6 are calculated by the expression:

$$\epsilon = A/IT$$

where A and I are respectively the area and the intensity of the nitrogen lines.

The relative intensity of a certain neon is found calculating the relative efficiency of the corresponding γ-ray energy by interpolation in the experimental curve. We use the single or double escape curve for the higher energies and the full energy curve in the low energy region.

The relative intensities of the neon lines are converted to absolute intensities by requiring that the sum of the relative intensities of all the primary transitions be equal to 100%. So, we have:

$$I_\gamma = (A/\epsilon T)\eta$$

where η is the normalizing factor of the spectrum given by:

$$(\Sigma I_p)\eta = 100$$

I_p are the relative intensities of the primary transitions. The error ΔI_γ in the intensities can be estimated by the expression.

$$(\Delta I_\gamma/I_\gamma)^2 = (\Delta A/A)^2 + (\Delta\epsilon/\epsilon)^2$$

As the error in the efficiency is found to be never greater than 6%, we took for $\Delta\epsilon/\epsilon$ the value 5% for all the lines. The errors ΔA in the areas are of statistical nature and were calculated by the GAUSS V program.

Table I

Typical Output of the GAUSS V Program

GAUSS4 AUGUST 1969 VERSION IBM 360/75 DATE COMPUTED 00/00/00
NEON E NITROGENIO 1-9-77 FNNE.FN221.H34SC MINI INPUT
WEIGHTED ENERGY CALCULATIONS
LINEARITY CORRECTION AT CHANNEL NUMBER PLUS 1.4508D 02
***LINEARITY TABLE (1) TABELA DE LINEARIDADE
***EFFICIENCE TABLE (0) NO INTENSITIES

ENERGY AND INTENSIVITY CALCULATIONS

ENERGY = 7.7227184D-01 + 1.6266502D-00 (x) + 2.1873195D-07 (x**2)
ERRORS 7.6325245D-01 6.0322271D-04 1.1498768D-07

CALIBRATION LINES

CHANNEL	CORRECTED CHANNEL	ENERGY	CALCULATED ENERGY	DELTA E	ERROR IN INPUT ENERGY	TOTAL CALIB ERROR
1012.537	1157.964	1884.880	1884.668	- 0.212	0.120	0.145
1083.107	1228.617	1999.720	1999.632	- 0.088	0.090	0.303
1402.682	1548.614	2520.620	2520.351	- 0.269	0.110	0.310
1486.409	1632.374	2655.793	2656.656	0 863	0.090	0.190
1799.431	1945.472	3166.797	3166.202	- 0.595	0.090	0.341
1996.805	2142.855	3487.053	3487.452	0.399	0.110	0.169
2023.950	2170.001	3532.100	3531.634	- 0.466	0.150	0.213
2113.591	2259.646	3677.800	3677.544	- 0.256	0.090	0.135
2310.167	2456.234	3998.053	3997.526	- 0.527	0.110	0.218
2463.881	2609.947	4247.353	4247.733	0.380	0.100	0.119
2481.412	2627.474	4276.153	4276.264	0.111	0.120	0.146
2643.737	2789.793	4540.173	4540.492	0.319	0.100	0.164
2777.457	2923 499	4758.357	4758.152	- 0.205	0.100	0.142
2795.140	2941.178	4787.157	4786.932	- 0.225	0.120	0.182
2939.907	3085.902	5022.277	5022.538	0.261	0.120	0.176
2957.334	3103.328	5051.177	5050.908	- 0.269	0.100	0.224
3091.231	3237.165	5269.360	5268.800	- 0.560	0.100	0.136
3253.773	3399.632	5533.380	5533.312	- 0.068	0.120	0.199
3271.573	3417.422	5562.180	5562.277	0.097	0.100	0.204
3424.844	3570.581	5811.417	5811.648	0.231	0.120	0.167
3711.381	3856.764	6277.173	6277.633	0.460	0.170	0.210
3738.868	3884.188	6322.420	6322.288	- 0.132	0.120	0.181
4025.732	4170.303	6788.177	6788.201	0.024	0.170	0.254

ALL LINES

CHANNEL	CORRECTED CHANNEL	ENERGY	SIGMA (E)
36.729	181.676	296.303	2.1335
53.371	198.305	323.354	0.9233
60.537	205.508	335.070	4.4623
70.249	215.286	350.978	0.6476
77.557	222.656	362.966	1.5752

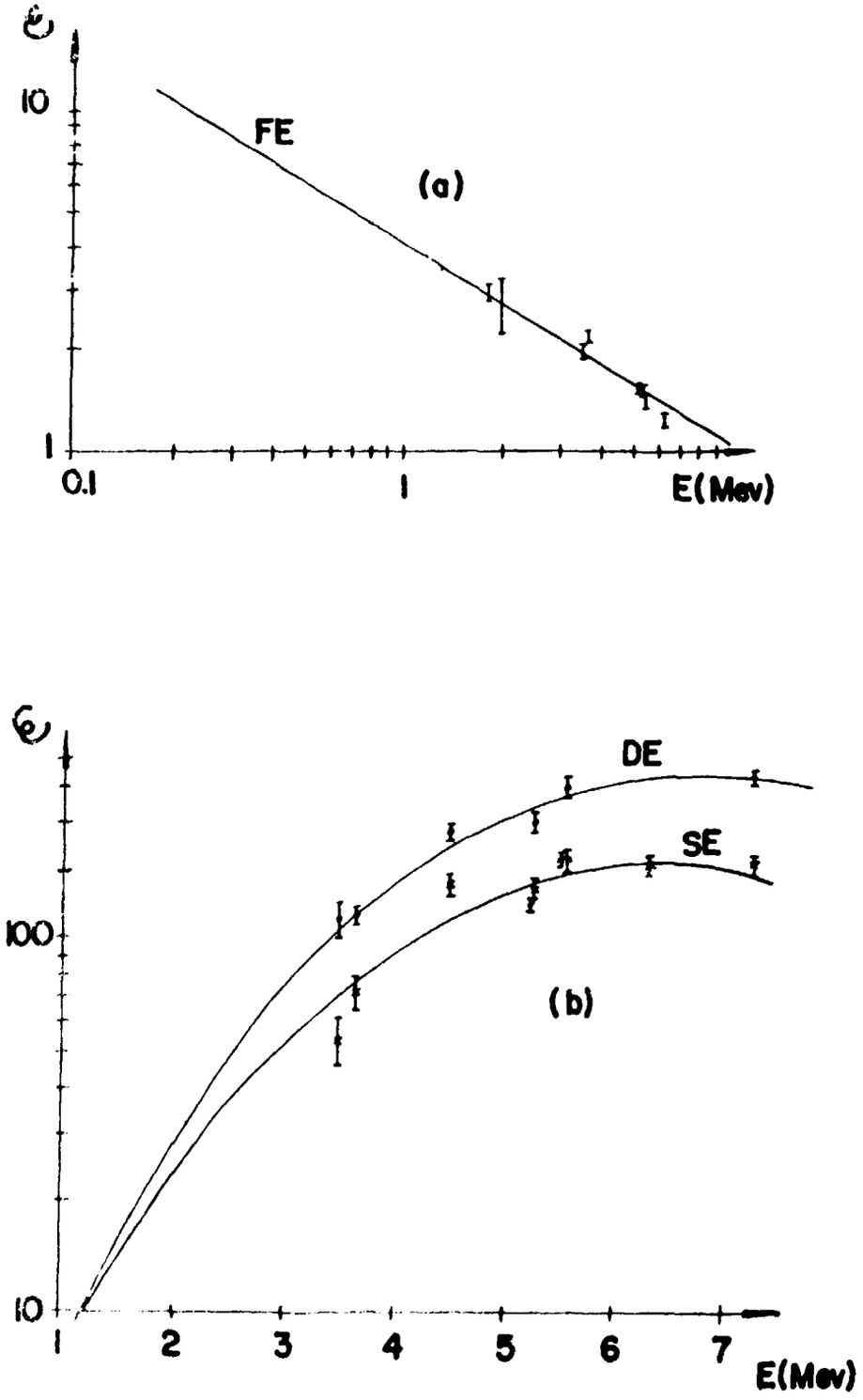

Figure 6 - Efficiency Curves corresponding to full energy peaks(FE), single escape peaks(SE) and double escape peaks(DE).

3.3 – Experimental Results

Our results of energies and intensities for ^{21}Ne are presented in the Table II. As can be seen, our values are in good agreement with previous measurements[1,4,6]. This is verfied for the several strongest lines, since the comparison for the weaker lines is dificult because they have larger errors. However, there is no systematic behaviour of the existing differences between our energy and intensities values and those of the others authors. The intensity of the 350 keV transition seems to be very small. We think that this can be due to the way we obtained the efficiency for that energy. It is usually observed[3] that the full energy curve log ϵ x log E is linear down to the energy of 200 keV and we used this approximation to calculate the efficiency corresponding to 350 keV since we had no experimental points in that neighborhood (the lowest energy of nitrogen in the 1679 keV line). Four our detector, this approximation in not good and this explains the smaller value we obtained. For higher energies (see the 767 and the 1070 keV lines) the approximation works.

3.4 – Cross Section and Reaction Q Value

The reliability of our data may still be confirmed to some extent by the following results for the thermal neutron capture cross section σ_γ of ^{20}Ne and the Q value for $^{20}Ne(n,\gamma)^{21}Ne$ reaction. The cross section was calculated in relation to the nitrogen value (75 mb)[1] since the pressure relation of the mixture was fixed during the measurement. Using several strong transitions of neon and nitrogen the mean value obtained is 41.8 ± 7.6 mb.

The reaction Q value was calculated summing all the transition energies of each cascade which connects the capture level to the ground state. The mean value resulting from several cascades is 6760.2 ± 1.7 keV. The comparison with previous σ_γ and Q values is shown in the Table III.

Table III

	σ_γ (mb)	Q (keV)
This work	41.8 ± 7.6	6760.2 ± 1.7
Bellmann[1]	36.8 ± 4.5	6759.5 ± 0.3
Jonsson et al[4]	45 ± 10	6760 ± 3

These results tend to confirm the reliability of the calibration method used. However, the calibration is valid only for a certain energy range, because the non-linearity correction is not the same for different amplifier gain.

4 – CONCLUSIONS

The energies and intensities of the γ-rays from the reaction $^{20}Ne(n,\gamma)^{21}Ne$ have been determined relative to nitrogen lines with good precision. A good agreement with previous experiments was obtained; however, some improvement could be done in the low energy region if we choose a calibration standard which has strong lines in that region, to be used together with nitrogen.

We would like to recall that an essential part of this work is the peak analysis program. In this sense, the GAUSS V program is very practical to use and saved us a lot of efforts. Even with simple gaussian curve fitting the resulting area values are good enough when compared with hand calculations.

Table II. Results for ^{21}Ne

This Work			Bellmann[1]		Jonsson et al.[4]		Selin[6]
E(keV)	E + Er(keV)*	I(γ/100 capt)	E(keV)	I(γ/100 capt)	E(keV)	I(γ/100 capt)	E(keV)
350,9 ± 0,6	350,9 ± 0,6	32,1 ± 1,4	350,0 ± 0,4	64,2 ± 3,4	350,0 ± 1	51	350,3 ± 1,0
583,4 ± 0,7	583,4 ± 0,7	4,0 ± 0,4	–	–	–	–	586,5 ± 2,0
767,2 ± 1,8	767,2 ± 1,8	3,1 ± 1,6	767,6 ± 1,3	3,2 ± 1,0	762,0 ± 2	0,8	768,5 ± 1,5
935,4	935,4 ± 1,2	1,7 ± 0,5	—	–	–	–	–
1140,1	1140,4 ± 2,7	1,1 ± 0,5	1141,0 ± 1,4	2,1 ± 0,7	–	–	–
1072,4 ± 0,4	1072,4 ± 0,4	10,9 ± 0,8	1070,2 ± 0,5	10,6 ± 1,1	1069,9 ± 1	12	1071,4 ± 1,5
1397,7 ± 2,4	1397,7 ± 2,4	0,6 ± 0,2	1398,2 ± 1,0	4,1 ± 0,8	–	–	1396,6 ± 3,0
1740,1 ± 3,2	1740,1 ± 3,2	1,4 ± 0,3	–	–	–	–	1747,3 ± 3,0
1930,9 ± 0,2	1930,9 ± 0,2	17,3 ± 0,9	1929,5 ± 0,2	16,1 ± 0,5	1930,5 ± 1	19	1930,6 ± 1,5
2035,5 ± 0,2	2035,7 ± 0,2	77,5 ± 3,6	2034,8 ± 0,4	61,6 ± 1,7	2035,9 ± 1	71	2035,5 ± 1,5
2256,9 ± 1,0	2256,0 ± 0,6	0,9 ± 0,3	2254,8 ± 1,1	2,2 ± 0,3	–	–	2255,9 ± 4,0
2437,7 ± 1,1	2437,8 ± 1,1	0,9 ± 0,2	2437,6 ± 0,6	2,7 ± 0,4	2439 ± 2	1,3	2438,4 ± 3,0
2794,1 ± 0,1	2794,3 ± 0,1	26,0 ± 1,2	2793,6 ± 0,4	23,5 ± 0,3	2793,7 ± 1	25	2794,4 ± 1,2
2895,6 ± 0,2	2895,8 ± 0,2	6,8 ± 0,4	2893,9 ± 0,5	5,3 ± 0,4	2896 ± 2	6,3	2896,3 ± 1,5
3095,5 ± 0,6	3095,7 ± 0,6	0,5 ± 0,1	3102,9 ± 1.3	4,4 ± 1,4	–	–	3099,3 ± 3,0
3313,0 ± 0,8	3313,3 ± 0,8	0,5 ± 0,1	3320,2 ± 2,4	2,2 ± 1,0	–	–	3313,6 ± 4,0
3388,4 ± 1,0	3388,7 ± 1,0	1,0 ± 0,4	–	–	–	–	–
3883,6 ± 1,6	3883,9 ± 1,6	2,4 ± 0,8	–	–	–	–	–
3972,7 ± 0,9	3973,1 ± 0,9	1,3 ± 0,4	3973,7 ± 0,6	3,0 ± 0,3	3970 ± 2	1,5	3974,8 ± 2,0
4373,9 ± 0,1	4374,4 ± 0,1	45,8 ± 2,0	4374,0 ± 0,2	47,3 ± 0,8	4374 ± 2	49	4374,9 ± 1,5
4721,5 ± 1,0	4722,1 ± 1,0	0,7 ± 0,3	–	–	–	–	4723,9 ± 4,0
4985,4 ± 0,9	4986,1 ± 0,4	1,1 ± 0,2	–	–	–	–	–
5643,1 ± 0,8	5643,9 ± 0,8	1,5 ± 0,3	5642,3 ± 1,9	0,8 ± 0,3	5643 ± 2	0,3	5642,4 ± 3,0
5688,9 ± 0,2	5689,7 ± 0,2	5,4 ± 0,4	5688,7 ± 0,6	4,8 ± 0,4	5689 ± 2	5,9	5689,9 ± 1,5
5994,0 ± 1,5	5994,9 ± 1,5	1,0 ± 0,4	5993,6 ± 4,7	1,2 ± 0,2	5993 ± 2	0,5	5992,4 ± 2,5
6410,3 ± 0,5	6411,4 ± 0,5	0,8 ± 0,2	6415,4 ± 5,5	0,8 ± 0,4	6409 ± 2	0,6	6409,4 ± 3,0
6759,5 ± 0,4	6760,7 ± 0,4	5,4 ± 0,4	6759,9 ± 0,8	5,0 ± 0,3	6759 ± 2	4,7	6760,9 ± 2,0

* Energies corrected for recoil Energy E_γ

The method here described can be used with any calibration standard which has lines in the energy range of the target. Besides, it should be measured together with the target.

RESUMO

Neste trabalho apresentamos um método simples para obter valores precisos de energias e intensidades de raios gama de captura de nêutrons térmicos. Como resultados, mostramos os valores obtidos para as linhas gama da reação $^{20}Ne(n,\gamma)^{21}Ne$.

Foi utilizado um espectrômetro simples, mas o método pode ser usado também para um espectrômetro de pares de três cristais.

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