(γ, n) AND $(\gamma, 2n)$ REACTIONS IN Nb^{93}

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I - *Introduction*

The yield of the neutrons emitted by Nb^{93} as a function of the energy of the incident gamma rays was meausured by Montalbetti, Katz and Goldemberg (1) using a BF_3 counter; in the measurements are included the contributions of the (γ, n) and $(\gamma, 2n)$ reactions. For a comparison of the experimental data with theory it is necessary to distinguish between these processes; very few investigations have been made in this direction due to experimental difficulties; in general one uses the method of subtracting the yield of the (γ, n) reaction from the total neutron yield; in order to do that requires that the investigated nucleus have a 100 % abundance and that the residual nucleus for the (γ, n) reaction has a convenient half-life and radioactivity; there are not many of these cases in the Periodic Table: Tantalum was investigated by several authors (2, 3, 4) and an attempt was done in the case of Arsenic by Montalbetti et al (1).

We followed the same general method for the case of Nb^{93}; the excitation function of the reaction $Nb^{93}(\gamma, n)Nb^{92}$ was obtained measuring the radioactivity of Nb^{92} and subtracting it from the total neutron yield curve.

R. A. James (5) reported the existence of an isomeric state in Nb^{92}, with a 13 hour half-life produced by the reaction

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(1) R. MONTALBETTI, L. KATZ and J. GOLDEMBERG – Phys. Rev. 91, 659 (1953).

(2) J. HALPERN, R. NATHANS and A. K. MANN – Phys. Rev. 88, 679 (1952).

(3) E. A. WHALIN and A. O. HANSON – Phys. Rev. 89, 324 (1953).

(4) J. H. CARVER, R. D. EDGE and D. H. WILKINSON – Phil. Mag. XLIV, 404 (1953).

(5) R. A. JAMES – Phys. Rev. 93, 288 (1955).

$Nb^{93}(p, pn)Nb^{92}$. If this state exists one should expect to form it by the (γ, n) reaction in Nb^{93}; special attention was given to this point and an investigation of the spectrum of Nb^{92} was made using a crystal spectrometer.

The cross sections obtained in this paper are compared with the results expected from Levinger and Bethe computations and from the statistical theory of nuclear reactions (7).

II - *Experimental procedure and results*

a) *Exposure and counting of the samples*

Samples of metallic Nb^{93} were exposed to the X-ray beam of the 22 Mev University of São Paulo Betatron; the distance from the samples to the X-ray target was 30 cm and the irradiations time was 10 minutes; in a typical run at 20 Mev about 9,000 roentgens were delivered to each sample; the yield was measured by an ionization chamber calibrated in roentgens according to the usual procedure.

After irradiation the samples were taken to a scintillation spectrometer with a $1'' \times 1''$ $NaI(Tl)$ crystal with discrimination chosen properly. The radioactivity of the samples was followed for several days, a pure 10 days half-life being obtained. Data taken at different energies gave an excitation function (fig. 1); absolute values were obtained by normalization with the curve of Montalbetti et al (1) below the threshold for the reaction $Nb^{93}(\gamma, 2n)Nb^{91}$.

Our results could be modified if the isomeric state reported by James really existed. A preliminary test was made measuring the decay very carefully and the 13 hours activity was not found. Great care was then taken in a search for this isomeric state.

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(7) B. T. Feld, H. Feshbach, M. L. Goldberger, H. Goldstein and V. F. Weisskopf. Final Report on the Fast Neutron Project USAEC NYO-636 (1951).

b) *Isomeric State*

The radioactivity of Nb^{92} was investigated by several authors (8) and the results are reproduced in fig. 1: the ground

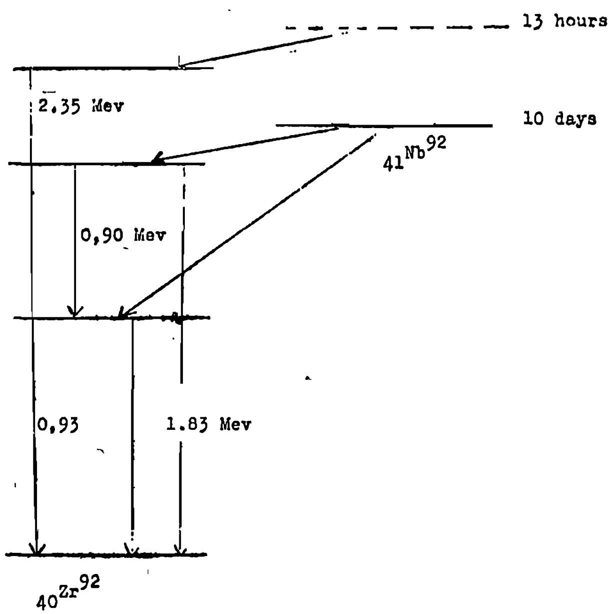

Fig. 1

state disintegrates by K capture with an half-life of 10 days to excited states of Zr^{92} of 1.83 Mev (3,5 %) and 0.93 Mev (96.5 %); the 1.83 Mev state decays directly to the ground state of Zr^{92} (2.2 %) or it goes to a state at 0.93 Mev (1.3 %).

James found a line of 2.35 Mev in the irradiation of Nb^{93} by protons and attributed it to the reaction $Nb^{93}(p, pn)Nb^{92}$ with a half-life of 13 hours; this line was attributed to a state in Nb^{92} which decays by K capture to a state of Zr^{92} of 2.35 Mev of excitation.

It should be possible to reach the same state by a (γ, n) reaction in Nb^{93}; a special irradiation was then made of a sample of metallic Nb to which a dose of 50.000 roentgens at 22 Mev was delivered. The sample was then transferred to a

(8) Nuclear Level Schemes - TID 530, USAEC (june 1955).

γ-ray spectrometer with a $NaI(Tl)$ crystal of the well type; a one channel pulse-height analyser was used in the measurements.

The data concerning the 10 days half-life activity was confirmed but the 2.35 Mev γ line was not found. An upper limit of the abundance of this line was established as smaller than 0.02 % of the abundance of the 0.93 Mev line. No activity with a half-life of approximately 3 days and with an abundance of 3.2 % of the 0.93 Mev line; this is probably due to annihilation radiation of unreported positrons present in the decay scheme of Nb^{92}.

c) *Excitation function and cross section*

In fig. 2 are plotted the excitation fonctions of Montalbetti et al (1) for the total neutron yield (curve a) and the one obtained

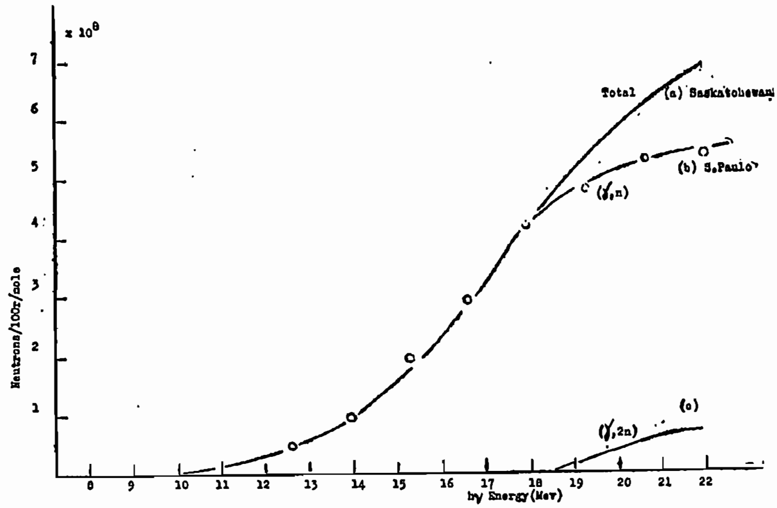

Fig. 2

in this work (curve b). The difference is attributed to the reaction $Nb^{93}(\gamma, 2n)\,Nb^{91}$; one must divide this difference by 2 in order to obtain the excitation function for this process; the results are in curve c of fig. 2.

Using the photon difference method (9) in curves b and c

(9) L. Katz and A. G. W. Cameron – Can. J. Phys. 29, 518 (1951).

of fig. 2 the cross sections of fig. 3, curves II and III are obtained.

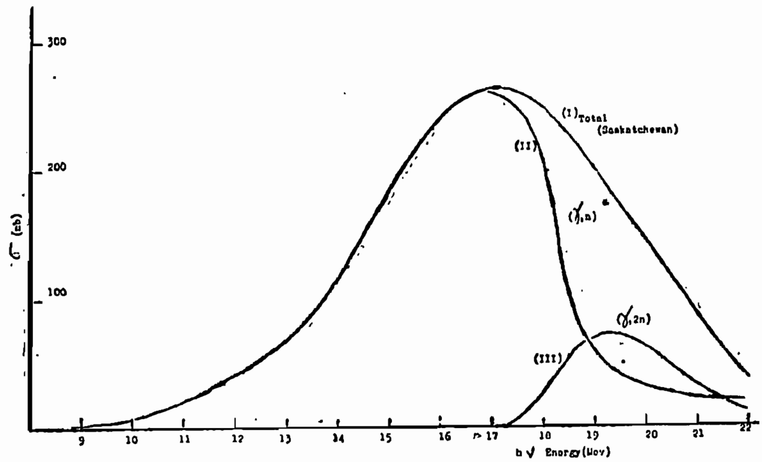

Fig. 3

III - *Conclusions*

An expression for the integrated cross section for dipole absortion of photons was obtained by Levinger and Bethe ([6])

$$\sigma_{int} = \int_0^\infty \sigma_{abs}(E)\, dE = 0{,}015\, A\, (1 + 0{,}8\, x) \tag{1}$$

x is the fraction of nuclear forces of exchange character. This formula has been exaustively compared with experiments ([1, 10, 11, 12]); the small discrepancies found are due to the fact that it is impossible to obtain σ_{abs} at all energies. For the heavy elements the (γ, n) process is predominant; although $(\gamma, 2n)$ processes give an appreciable contribution it is not taken in account generally because it is difficult to obtain information on them.

([10]) J. S. Levinger and H. A. Bethe - Phys. Rev. 85, 577 (1952).
([11]) L. Eyges - Phys. Rev. 86, 325 (1952).2
([12]) R. Nathans and J. Halpern - Phys. Rev. 93, 427 (1955).

In the case of Nb our results for the (γ, n) process give 1.25 Mev-barns for the $(\gamma, 2n)$ process. Halpern and Mann (13) measured the cross section as function of the energy for the reaction $Nb^{93}(\gamma, p)\, Zr^{92}$ and obtained 0.12 Mev-barns for the integrated cross section. Summing all these contributions one gets 1.57 Mev-barns. Expression (1) with $x = 0.55$ gives 1.97 Mev-barns; one can conclude then that the cross sections for the processes not measured (γ, γ), (γ, γ'), $(\gamma, 3n)$, (γ, np) etc. plus the contributions of all the processes above 22 Mev does not amount to more than 0.4 Mev-barns.

Another result of the theory is the energy where the maximum of the cross section occurs (E_m) and a strong correlation between this value and the threshold for the $(\gamma, 2n)$ process was predicted by Eyges (11); as into the case of Tantalum (3) this correlation was found in Nb^{93}: it does not seem however to affect E_m significantly.

The competition between the emission of different kinds of particles can be predicted by the statistical theory of nuclear reactions (7); since the emission of photons is strongly suppressed by the Coulomb barrier the only other process to compete with (γ, n) in the energy range studied is $(\gamma, 2n)$. We can then use as good approximation the expression for the ratio of cross sections of Feld et al (7).

$$\frac{\sigma(\gamma,2n)}{\sigma(\gamma,n)+\sigma(\gamma,2n)} = 1 - \left[1 + \left(\frac{a}{E}\right)^{1/2} (E - E_b)\right] . \exp\left[-\left(\frac{a}{E}\right)^{1/2} (E - E_b)\right]$$

where a is a constant dependent on A, $E_b = 17.1$ Mev is the threshold for the $(\gamma, 2n)$ process and E is the energy of excitation. Comparison of the results of expression 2 (curve a) above and the experiment (curve b) is made in Fig. 4.

An analysis of this figure shows that there is good agreement with statistical theory up to 20 Mev; the small discrepancies

(13) J. Halpern and A. K. Mann - Phys. Rev. 83, 370 (1952).

found up to this energy are not significant since the cross sections are not very precise there.

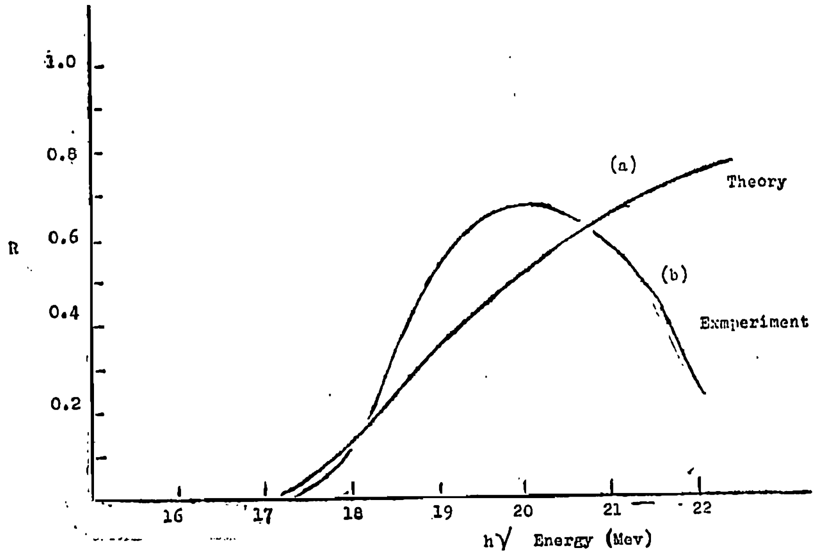

Fig. 4

Above 20 Mev, however, the experimental curve drops considerably below the expected value; this can be interpreted as due to the presence of neutrons emitted by a direct photo-effect ([14]). One can be seen in curve II of Fig. 3 the (γ, *n*) cross section is approximately constant above 20 Mev; one can assume that these neutrons are all emitted by a direct process and compare the value of the cross section with the results predicted by Courant's theory ([14]). Experimentally one finds 20 mb. at 22 Mev and the theoretical value is 4.4 mb; considering the uncertainities involved in this can be interpreted as meaning that a considerable amount of the neutrons above 20 Mev are emitted by a direct photo-effect.

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([14]) E. D. Courant - Phys. Rev. 82, 703 (1951).

Summary

The (γ, n) cross section of Nb^{93} was measured by the residual activity method. Combining this result with the total neutrons yield curve it was possible to separate the contributions of the (γ, n) and $(\gamma, 2n)$ reactions.

The ratio of these cross sections was then compared with special attention to the 2.35 isomeric state ($T_{1/2} = 13$ hs) reported by James; this activity was not found and we determined an upper limit for it as 0.02 % of the 0.93 Mev line. An activity of 3,2 % abundance due probably to γ rays of annihilation of positrons was found.

ON THE PROBLEM OF CANONICAL FIELD QUANTIZATION

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The application of canonical quantization to non-linear relativistic field theory involves difficulties, which are not yet clarified. We wish to discuss some points of this problem.

1. A classical field $\varphi_r(x)$ is described by a relativistic invariant Lagrange density $L(\varphi_r, \varphi_{r/x'})$ (1). From L we derive:

a) The *field equations* as Euler-Lagrange equations of the Hamilton principle $\delta \int L\, dx = 0$:

$$\frac{\partial}{\partial x^\mu} \frac{\partial L}{\partial \varphi_{r/x^\mu}} - \frac{\partial L}{\partial \varphi_r} = 0. \tag{1}$$

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(1) We use the following notation: Space-time point $x = (x^\mu) = (x^0, \vec{x})$; invariant length $x^2 = x^\mu x_\mu = -\vec{x}^2 + x^{0\,2} = x^\mu g_{\mu\nu} x^\nu$ derivative $\frac{\partial}{\partial x^\mu} \varphi_r = \varphi_{r|x^\mu}$; r denotes the spin and iso-spin indices etc.