On the Radioactivity of Certain Stable Isotope-Enriched Substances[1]

We wish to draw attention to an effect which has not yet been mentioned in the scientific literature, so far as we know. This effect consists in the considerable increase in specific radioactivity which chemical compounds show under treatment for stable isotope enrichment, if these compounds contain a naturally occurring radioactive nuclide which undergoes a concentration process in the same time.

The simultaneous changes in concentrations of different isotopes in substances being submitted to an isotopic enrichment process are of course well known. Nevertheless we believe that consideration of this effect was restricted to stable isotopes, on one side, or to nuclear fuels on the other side, and that the existence of a link between the enrichment of stable isotopes and radioactivity in substances containing elements of low mass numbers has not yet been generally realized. In the case of heavy water, however, the situation described is well known by the specialists in nuclear energy. The link mentioned does not merely consist in the conjugated action of natural physical facts, but is rather a consequence of the technical circumstances under which deuterium and tritium are produced and used in nuclear plants and centers[2].

A conspicuous example is given by deuterium enriched substances. It is easy to verify experimentally that the specific tritium activity of water, deuterium enriched to a concentration of 99.5 atom-%, is of the order of 0.1–1 µCi/ml. This specific activity range is in accord with the values which are computed on the basis of the following data: natural specific tritium activity of water before enrichment: 10–100 TU (tritium units, 1 TU corresponding to 10^{-16} atom-% tritum in the tritium/protium mixture of hydrogen, or to about 7.2 dpm/l water); deuterium concentration of same water: 0.015 atom-%. Electrolytic isotope enrichment, with the simple process separation factors $\alpha = 7$ for deuterium and $\beta = 10$ for tritium. In the case of ^{13}C-enriched compounds, the calculated specific activity amounts to about 80 µCi/mol carbon for a ^{13}C-enrichment from 0.1 to 90 atom-% in the case of a probe of recent origin with about 15 dpm per gram carbon due to ^{14}C before enrichment.

The specific activities attained as a result of isotopic separation depend on the specific activities of the substances before enrichment, on the simple process separation factors α and β for the stable and the radioactive isotope considered, which in turn depend on the type of enrichment process, and finally on the degreee of enrichment performed, which may be mesured by the isotopic concentrations of the stable isotope before and after enrichment, or by the number n of stages (theoretical plates) of the separation process. It is thus not possible to give precise indications without considering in detail the data pertaining to a given system. But some clues of general interest may already be drawn from a simple theoretical examination of the situation, as will be done now very briefly.

Let us start from the fundamental expression $x \equiv c_A/c_{oA} \times (1-c_{oA})/(1-c_A) = \alpha^n$, where c_{oA} and c_A are the mole fractions of the stable isotope before and after enrichment and x a short form for the left member of the equation. Considering that the mole fractions c_{oB} and c_B of the radioactive species are always much less than unity, the corresponding expression applies: $f \equiv c_B/c_{oB} = \beta^n$, where f represents the factor of multiplication of the specific activity consecutive to the isotope enrichment process. Defining $k \equiv \beta/\alpha$, we get after some simple algebraic operations $f = x^{(1+\log k/\log \alpha)}$. For tritium/deuterium, $k \simeq 1.4$, $\alpha = 7$, $f = x^{(1+0,18)} \approx x$. For ^{14}C/^{13}C, $k = 1.01$, $\alpha = 1.01$ (chemical exchange method), $f \approx x^2$. For α and $k \simeq 1$, the general relation $f = x^{[1+(k-1)/(\alpha-1)]}$ applies with a good approximation. Thus, the ^{3}H- and ^{14}C-specific activities of organic compounds are enhanced by the same approximate factor of about 10^6 when the deuterium concentration passes from 0.015 to 99.5 atom-%, or when the ^{13}C-concentration passes from 1 to 90 atom-%. The increase of specific radioactivity of a given element consecutive to the isotopic enrichment of another element in a same compound depends on the chemical processes, in particular isotopic exchanges, which the considered elements may undergo. Thus it is not possible to foresee the specific ^{3}H-activity of water enriched in ^{17}O or ^{18}O. Table I reproduces the values measured in our laboratory by liquid scintillation counting.

The facts described have far reaching consequences. Thus the presence of tritium in pure, higly deuterated compounds may heavily impair the establishment of correct isotopic balance in dual tracer (deuterium/tritium) studies. It seems inevitable that suppliers of chemical substances enriched in stable isotopes will have to provide in future radioactivity specifications for stable isotope enriched substances which are to be used jointly with radioactive tracers. Furthermore, there is the question whether substances enriched in stable isotopes which are free of radioactivity, will be requested and to what extent it will be possible to meet such requirements. In another connection, it is worthwhile mentioning that the specific activity of strongly ^{2}H-, ^{17}O-, ^{18}O-enriched water and of certain ^{2}H- and possibly ^{13}C-enriched organic compounds is of such a level that these substances fall definitely into

	Substance	Enrichment atom-%	Activity 10^4 dpm/ml	Activity µCi/mol H
1	D_2O	99.76	1.90	0.08
2	D_2O	99.75	0.88	0.04
3	D_2O	99.75	15.7	0.64
4	D_2O	99.8	24.0	0.99
5	D_2O	99.7	267	10.9
6	H_2O	[a]	2.57	0.11
7	Acetone-d_6	99	15.0	0.82
8	Acetone-d_6	99.5	14.6	0.79
9	Benzene-d_6	99.5	0.25	0.02
10	Methanol-d_4	99	1.10	0.05
11	Methanol-d_4	99	0.46	0.02
12	DMSO-d_6	99.5	12.4	0.66
13	Pyridine-d_5	99	3.66	0.26
14	$CDCl_3$	99.5	5.86	2.12
15	Acetonitrile-d_3	99	9.34	0.74
16	Methyliodide	50–60[b]	Ø	Ø

1, Norsk Hydro Elektrisk, Oslo; 2, Norsk Hydro Elektrisk (more than 16 years old); 3, Merck Darmstadt, BRD; 4 and 5, Eidgen. Institut für Reaktorforschung; 8, 9, 10, 12, 13, 14 and 15, Ciba Basel, Swiss; 7 and 11, Elektrochemie Turgi, Swiss. [a] ^{17}O: 11,1%; ^{18}O: 44,8%; D: 64,8%. [b] Enriched in ^{13}C; Ø means no activity above background detected.

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[2] D. LÉGER, G. DIRIAN and E. ROTH, Énergie nucl. *12*, 135 (1970).

the category of radioactive substances as to the safety regulations of most countries concerning the transport, handling and use of open radioactive sources. This very problem is left to the attention and responsibility of the competent national as well as international authorities.

Résumé. Des mesures de radioactivité de nombreux échantillons d'eau lourde et de substances deutérées de provenances les plus diverses ont montré que les substances de teneur élevée en deutérium (>99%) présentent une radioactivité spécifique de l'ordre de 5 μCi par gramme de deutérium, due au tritium d'origine naturelle concentré en meme temps que le deutérium. Le phénomène ne se limite pas aux isotopes de l'hydrogène. Il est de caractère général et comporte d'importances conséquences théoriques et pratiques.

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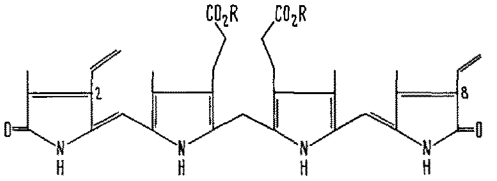
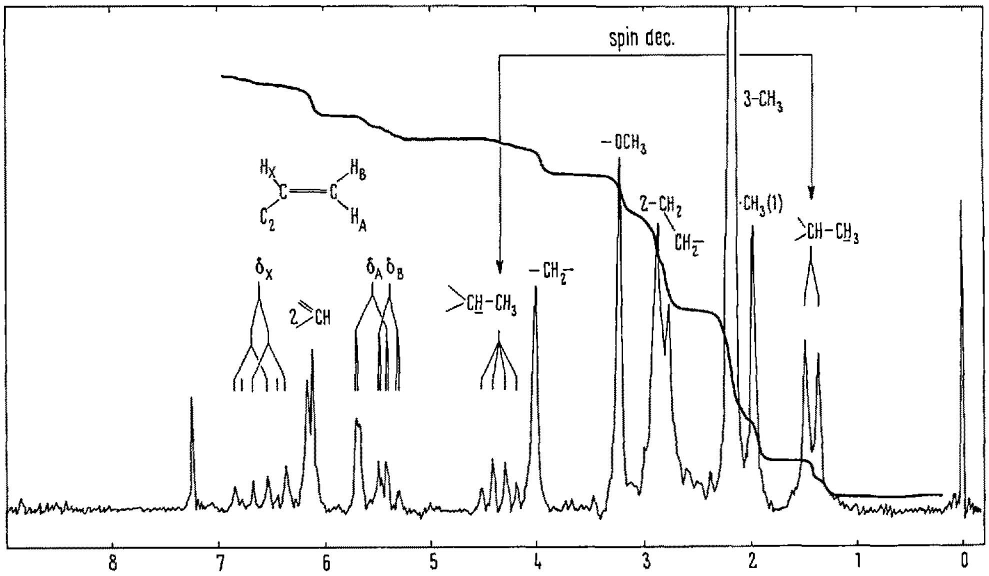
Photochemistry of Bilirubin

Although the phenomenon of a decrease in serum bilirubin levels in animals and humans irradiated with UV-light is well known (and exposure of infants to fluorescent light is commonly utilized to treat neonatal jaundice[1]), the mechanisms involved and the products of bilirubin decay have not been identified. In vitro photodecomposition of bilirubin was also studied at length[2], but no photoderivative has been isolated as yet. In this paper we wish to report the structure determination of the products we succeeded in isolating after irradiation of bilirubin in vitro in the presence of alcohols.

When bilirubin (I)[3] dissolved in chloroform containing 10% (v/v) methanol was exposed in a pyrex flask to a mercury lamp ($\lambda > 300$ nm)[4], formation of a photoproduct was observed and followed by TLC on polyamide[5] [methanol – 10% ammonia 9:1 (v/v)]. After 60–70% of bilirubin was converted (ca. 30 h), chromatography of the reaction mixture on a polyamide column developed with acetone gave the yellow photoderivative [20% yield on the starting material after crystallization from $CHCl_3$–CH_3OH; it blackens without melting over 250°; $\lambda_{max}^{CHCl_3}$ = 446 nm (ε 58,800); ν_{max} = 3420, 3260, 1695, 1645, 1615 cm^{-1} (in $CHCl_3$)] to which the formula $C_{34}H_{40}N_4O_7$ could be attributed on the basis of its mass-spectrum [*m/e* 616 (2.5%, M^+), 584 (37%), 286 (100%)] and its elemental analysis[6]. In addition, this photopigment gave a positive diazoreaction[7] and afforded bilirubin when its chloroform solution was stirred with aqueous HCl 10*N* for 2 h at r.t. In the NMR-spectrum, as shown in the Figure, it exhibited the characteristic ABC pattern of 1 vinyl group[8], which could be analyzed as an ABX system[9] (6 lines in the X part and 8 lines in the AB part: δ_A, δ_B, δ_X = 5.53, 5.38, 6.59 ppm; J_{AX}, J_{BX}, J_{AB} = 17.2, 10.3, 1.7 Hz), and further a set of peaks associated to the grouping $-CH(OCH_3)-CH_3$ [a singlet at δ 3.21 (3H, $-OCH_3$), a doublet centered at δ 1.40 (3H, J = 7 Hz, $-CH_3$) and a quartet centered at δ 4.32 (1H, J = 7 Hz;



I R=H
II R=CH3



NMR-spectrum at 60 MHz of 8a-methoxy-8a,8b-dihydrobilirubin (III) in $CDCl_3$. Chemical shifts are in ppm (δ) from internal tetramethylsilane.