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Resonance Fluorescence of Nuclei

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EXCITED states several million volts above the normal state have been discovered in several of the light nuclei by means of radiations that accompany reactions in which these nuclei are end products. This note discusses an alternative method for locating such states which may extend the amount of data available in nuclear spectroscopy, both through the discovery of additional states and through the determination of the breadths of these states. The process to be employed is that of resonance fluorescence: the nucleus under investigation is exposed to a continuous gamma-ray spectrum, as from a betatron, and the radiation scattered at a large angle ($\sim 90°$) with the primary beam is analyzed. This will consist of sharp lines corresponding to excited states that can make radiative transitions to the ground state, and a continuous background. The intensity of each line depends on the breadth Γ of the state from which it arises, so that this method can in principle yield a value for Γ as well as for the energy E of the state. It is also possible that in favorable cases the scattered energy that is concentrated in the line is enough greater than that in the background so as to provide a useful source of mono-energetic gamma-radiation.

We restrict our attention here to excited states of light nuclei for which $E \gg mc^2$, which however lie low enough so that particle emission cannot occur. Also, we shall not consider explicitly the effect of competition from other radiative transitions; the results can readily be extended to include this, and the orders of magnitude obtained below are not altered. The Breit-Wigner single level dispersion formula gives for the integrated total cross section: $\int \sigma dE = 0.91 \times 10^{-26}\Gamma/E^2$ cm$^2\cdot$Mev, where Γ is measured in volts and E in Mev, and statistical weight factors of order unity are omitted; the angular distribution is characterized by the electromagnetic partial wave that excites the transition. If the radiation is of electric quadrupole character and has a breadth of 10^{-3} volt for $E \approx 1$ Mev,[1] this becomes about $10^{-29}E^3$; if it is of magnetic dipole character, as is probably the case with the 0^{16} 6.2-Mev line,[2] a simple estimate shows that the integrated total cross section is roughly $2 \times 10^{-29}E$.

The continuous background has two principal sources: coherent non-resonant nuclear scattering, and double processes in which high energy Compton recoil electrons produce bremsstrahlung (the similar pair processes are much less probable for light nuclei). The direct Compton scattered radiation is not of great importance, for although it is fairly intense (cross section per unit solid angle $\approx 2 \times 10^{-26}Z/E$ at 90°) all of the quanta have about 0.5 Mev energy and can be filtered out. With reasonable assumptions about the dispersion properties of light nuclei, it appears that the dominant term in the non-resonant scattering is the classical Thomson scattering by the nucleus as a whole, which is about $10^{-31}Z$ cm^2 (this assumes that the atomic weight A equals about twice the atomic number Z).

The effective cross section for double processes is the product of four terms: (1) the Compton scattering cross section, (2) the bremsstrahlung cross section, (3) the number of nuclei per cm^2 encountered by the recoil electron, and (4) a dimensionless factor that takes account of the large angle between incident and outgoing gamma-quanta. This background may be reduced by requiring, for example, that the degradation of the gamma-rays not exceed about 1 Mev, which means that the excited state under investigation is to be within 1 Mev of the maximum gamma-ray energy of the betatron source. The value of (1) for recoil electron kinetic energy within 1 Mev of the primary gamma-ray energy is $1.8 \times 10^{-25}Z/E$ cm^2, where E is in Mev. Similarly, the value of (2) for secondary gamma-ray energy within 1 Mev of the electron kinetic

[1] V. Weisskopf, Phys. Rev. **59**, 318 (1941).
[2] L. I. Schiff, Phys. Rev., to be published.

energy is roughly $6\times10^{-27}Z^2/E$ cm². (3) is the product of the number N of nuclei per cm³ and the effective range R of the recoil electron. This range will be either a typical linear dimension of the scattering sample, or the distance in which the electron loses about 1 Mev of its energy, whichever is smaller. The latter is about $0.23A/\rho Z$, where ρ is the density, and hence is of the order of a few mm. Thus for samples of reasonably large size, NR is a constant equal to about $1.4\times10^{23}/Z$. The angular spreads of both the energetic recoil electrons and the bremsstrahlung are of the order of a few degrees for the conditions of interest here. Thus (4) must be caused either by deflection of the recoil electron by multiple Coulomb scattering before it loses 1 Mev of its energy, or by large angle bremsstrahlung (because of the conservation laws, a recoil electron of definite energy has a definite direction). Both of these are improbable, but the latter much less so than the former at such a large angle as 90°. The fraction of the total number of energetic gamma-quanta radiated per unit solid angle at 90° may be estimated[3] to be $1/16\pi E^2$. Thus the cross section for such double processes is about $3\times10^{-30}Z^2/E^4$.

Comparison between the formulas given above for the resonance and the background cross sections indicates that the resonance should stand out clearly against the background. Thus for the 6.2-Mev oxygen state, the integrated resonance cross section per unit solid angle at 90° is about 1 to 2×10^{-29} cm²-Mev; the background cross section for production of scattered gamma-rays within 1 Mev of the resonance if the betatron is run at a slightly higher energy is about 10^{-30} cm². Since the background cross section does not increase with sample size when it is more than a few mm in linear dimensions, it is desirable to use as large a sample as is otherwise convenient in order to increase the over-all intensity.

[3] A. Sommerfeld, *Atombau und Spektrallinien* (Vieweg, Braunschweig, 1939), Vol. 2, p. 551.

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On the High Pressure Bands of Carbon and the Formation of C_2 Molecules

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IN several previous publications[1-3] it was stated that the so-called high pressure bands of carbon belong to the Swan bands of the C_2 molecule. In view of several recent inquiries concerning this matter it appears desirable to amplify the previous statements.

It has been shown by Johnson and Asundi[4] that the high pressure carbon bands represent a $^3\Pi-{}^3\Pi$ transition just as the Swan bands and that the two band systems have the lower state (presumably the ground state of the C_2 molecule) in common. Using Jevons' formula[5] for the band heads of the Swan system (in which a term in $v'v''$ takes account of the rather large change of the distance between head and origin) one obtains for $v'=6$ and $v''=0, 1, \cdots 11$ the wave numbers given in the second column of Table I

TABLE I. High pressure bands of carbon.

v''	ν_{head}(calculated)	ν_{head}(observed)	Estimated intensity
0	29164	(29241)*	1
1	27560	(27620)*	1
2	25977	—	1
3	24417	24426	2
4	22879	22883	7
5	21362	21361	15
6	19867	—	1
7	18395	18394	5
8	16944	16946	10
9	15515	15518	8
10	14108	14114	6
11	12723	12731	4

* These values are band centers whereas all others are band heads.

[1] J. G. Fox and G. Herzberg, Phys. Rev. **52**, 638 (1937).
[2] G. Herzberg, Astrophys. J. **89**, 290 (1939).
[3] G. Herzberg, *Molecular Spectra and Molecular Structure I. Diatomic Molecules* (New York, 1939), p. 472.
[4] R. C. Johnson and R. K. Asundi, Proc. Roy. Soc. **A124**, 668 (1929).
[5] W. Jevons, *Report on Band Spectra of Diatomic Molecules* (London, 1932), p. 61.