quency.

We wish to thank Professor R. Lacroix, Professor R. Brout, Professor E. Brun, Dr. R. S. Rubins, and Dr. O. S. Leifson for the many interesting discussions, and Dr. G. M. Zverev for correspondence. We especially acknowledge the comments of Dr. S. Geschwind who was also so kind as to supply the platinum-doped Al_2O_3 crystals.

---

*This work has been supported in part by the Swiss National Science Foundation.

[1]R. Orbach, Proc. Roy. Soc. (London) A264, 458 (1961).

[2]G. M. Zverev and N. G. Petelina, Zh. Eksperim. i Teor. Fiz. 42, 1186 (1962) [translation: Soviet Phys.-JETP 15, 820 (1962)].

[3]S. Geschwind and J. P. Remeika, J. Appl. Phys. Suppl. 33, 370S (1962).

[4]R. S. Rubins and W. Low, Proceedings of the First International Conference on Paramagnetic Resonance, Jerusalem, 1962 (Academic Press, New York, 1963), p. 59.

[5]K. A. Müller and R. S. Rubins, to be published.

[6]Y. Tanabe and S. Sugano, J. Phys. Soc. Japan 9, 753 (1954).

[7]Interpolated from C. K. Jørgensen, Absorption Spectra and Chemical Bonding in Complexes (Pergamon Press, New York, 1962), p. 110.

[8]J. H. van Vleck, J. Chem. Phys. 7, 61 (1939).

[9]U. Höchli, R. Lacroix, and K. A. Müller, to be published.

[10]A. S. Barker, Phys. Rev. 132, 1474 (1963).

[11]J. C. Slonczewski, Phys. Rev. 131, 1596 (1963).

DECAY OF O^{16} GIANT DIPOLE STATES TO EXCITED STATES OF O^{15}†

P. F. Yergin, R. H. Augustson, N. N. Kaushal, H. A. Medicus, W. R. Moyer, and E. J. Winhold
Physics Department, Rensselaer Polytechnic Institute, Troy, New York

(Received 4 May 1964)

Theoretical predictions of the properties of the 1^-, $T=1$ levels of O^{16} which are strongly excited in photon absorption have so far been made almost entirely in terms of single-particle, single-hole configurations.[1-3] While the energies calculated for these states agree fairly well with observations, other features are not so well predicted. For example, it is predicted that nearly all of the integrated cross section given by the dipole sum rule resides in the two states near 22 and 25 MeV, whereas it is found experimentally that at least half the sum rule is elsewhere, mostly spread over a wide range of higher energies.[4] This result agrees with recent calculations of Barker[5] and Abgrall,[6] which take account of two-particle, two-hole configurations in the ground state, but do not include them in the dipole states.

One of the clearest predictions of the strict one-particle, one-hole form of the theory is that decays of the major 1^- states by neutron or proton emission will leave the residual nucleus (O^{15} or N^{15}) in a p-hole state, i.e., a $\frac{1}{2}^-$ or $\frac{3}{2}^-$ state. In each of these nuclides the ground state is $\frac{1}{2}^-$ and the third excited state at about 6.2 MeV is $\frac{3}{2}^-$. There is, however, in each case at about 5.2 MeV a close doublet of positive-parity states ($\frac{1}{2}^+$ and $\frac{5}{2}^+$) which have the character of two p holes plus an s or d particle,[7] so that it is feasible to ascertain whether or not the O^{16} giant dipole states can decay into other than simple p-hole states. Thus one can learn about the strength of the two-particle, two-hole configurations in these giant dipole states. Figure 1 shows the pertinent energy levels of O^{16} and O^{15}. (The energies shown for O^{16} are those we measure, and are in generally good agreement with previously accepted values.[8,9]

The only previous evidence bearing on this point has been contradictory. Johansson and Forkman[10] reported that decays to the positive-parity doublet of N^{15} did not take place, while Milone et al.[11] reported that they did see such decays. A reanalysis of these data by Fuller and Hayward[12] led them to the conclusion that the decays probably take place, but that the data were too sparse to be interpreted unambiguously.

We have measured the 90° photoneutron spectrum of O^{16} irradiated with bremsstrahlung of about 34-MeV end-point energy from the Rensselaer electron linac.[13] The spectrometer consists of a 1024-channel time-to-pulse-height analysis system with 8-nsec channel widths, driven by signals from a 5-in. thick by 20-in. diameter liquid scintillation neutron detector located at the end of a 100-meter evacuated flight path. The one-ampere electron-beam pulse was 10 nsec long, and the over-all time resolution was 16 nsec, giving energy resolutions of 8.5 keV

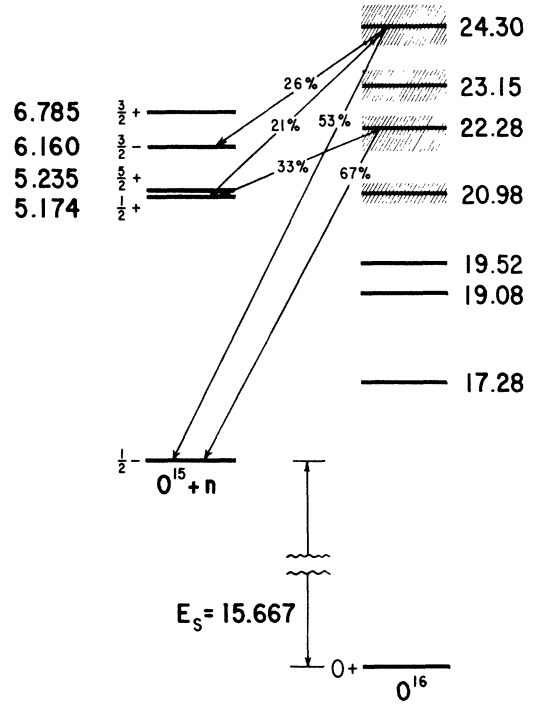

FIG. 1. Some energy levels of O^{16} and O^{15}. Only those levels of O^{16} which appear prominently in the photoneutron spectrum are shown. The energies are those measured in this experiment. All known levels of O^{15} up to the highest shown are included. The branching ratios for the neutron decays at 90° from the 22.2- and 24.3-MeV levels are those deduced from the measurements reported here. Ground-state decays only are observed for the other levels.

for 1.5-MeV neutrons and 100 keV for 8.0-MeV neutrons.

The relevant part of our data and its interpretation are shown in Fig. 2. The largest peaks, at about 6.1- and 8.2-MeV neutron energy, correspond to the excitation of the principal dipole levels in O^{16} at 22.2 MeV and 24.3 MeV and their subsequent decay to the ground state of O^{15}. In the region beyond 9.4-MeV neutron energy (not shown) the neutron yield drops off sharply.

The spectrum of neutrons below about 5 MeV is produced by ground-state decays from O^{16} levels below 21 MeV and by excited-state decays from the giant dipole levels above 21 MeV. The distinctive structure of the giant dipole states, and the fact that the photoneutron cross section below 20 MeV is well known,[14,15] enable us to construct a composite of the contributions to the observed spectrum in the region from 1.0- to 4.0-MeV neutron energy without any major ambiguities. The composite curve, which is the highest dashed curve in Fig. 2, is the sum of the three components shown in the lower part of Fig. 2, which were obtained as follows:

(a) The photoneutron cross section below 18.3 MeV as measured by Geller and Muirhead[14] was normalized in amplitude so that their peak at 17.30-MeV excitation energy fits our sharp peak at 1.52-MeV neutron energy. Their cross section above 18.3 MeV (with the omission of one very narrow peak for which we do not see any evidence) was similarly normalized so that their 19.08-MeV peak fits our sharp 3.20-MeV peak. (A 60-keV upward adjustment of the energy of their 19.47-MeV peak was necessary. This is not excluded by their data, or other data on the location of this level.[9]) The two parts were joined smoothly in the low cross-section region near 18.3 MeV.

(b) The 6- to 9-MeV spectrum of Fig. 2 was translated downward in energy by the amount corresponding to neutrons leaving O^{15} in its $\frac{1}{2}^+$ first excited state at 5.174 MeV, and normalized in amplitude in two parts, at the two main peaks, to give a good fit to the data when combined with the other components. (The choice of the $\frac{1}{2}^+$ level is arbitrary. The result would not be significantly different for the 5.235-MeV $\frac{5}{2}^+$ level, or any mixture of the two.) To get any fit at all it is necessary to assume less than 10% contributions of excited-state transitions from the 23-MeV level. The dashed curve under this peak shows the modified spectrum shape we used. We likewise had to omit the broad shoulder above 8.5-MeV neutron energy, and again the dashed curve there shows what was used.

(c) The same procedure was used as in (b), except that the energy shift corresponds to the residual nucleus being left in the $\frac{3}{2}^-$ state at 6.160 MeV.

There are a few places where the composite fails to match the data exactly. These are readily understandable, and will be discussed in a later paper, as will other features of the spectrum, including much more data than are analyzed here.

While the fitting of the data with the composite curve is strongly suggestive of the correctness of the choice of components and their amplitudes, a really conclusive test would be to take a complete excitation function for the spectrum by varying the bremsstrahlung end-point energy. For a variety of reasons of experimental exigency this has not yet been done, but we did make a

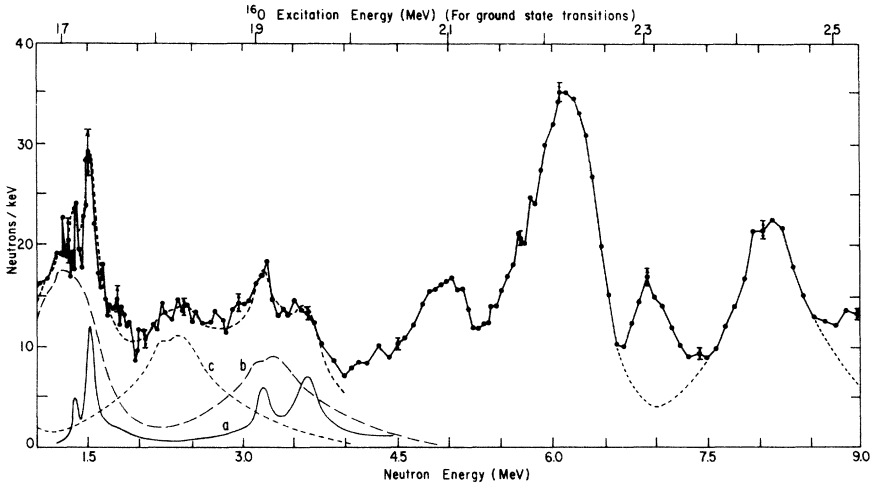

FIG. 2. Neutron spectrum from O^{16} photodisintegration by 35-MeV bremsstrahlung. The points connected by the solid lines, with typical error bars shown, are the experimental results corrected for the detector efficiency. From 1.0 to 1.2 MeV twelve channels of the time analyzer were averaged, from 1.2 to 4.9 MeV four channels, and above 4.9 MeV two channels. The upper dashed curve from 1.0 to 4.0 MeV is the composite fit to the data and is the sum of the lower three curves. (a) is derived from the cross-section curve of reference 14, (b) represents neutrons which leave O^{15} in the $\frac{1}{2}^-$ first excited state, and (c) represents neutrons which leave O^{15} in the $\frac{3}{2}^-$ third excited state. See the text for explanation of the dashed curve sections above 5 MeV. The scale at the top gives the excitation energy in O^{16} for the case of neutrons which leave O^{15} in its ground state. The ordinate is in arbitrary units, and represents the number of neutrons per unit energy interval.

measurement of the 45° photoneutron spectrum of O^{16} with the bremsstrahlung end-point energy low enough so that the major peak at 8.3 MeV was almost completely suppressed. While the data cannot be compared quantitatively with the 90° data presented here, they do have the anticipated feature that the spectrum between 2.0 and 4.0 MeV, which we expect to be largely produced by decays from the 24.3-MeV state, as is the 8.3-MeV peak, is substantially reduced relative to that in the 1.5-MeV region, which we expect to be largely due to decays from the 22.2-MeV state, as is the 6.1-MeV peak.

We conclude that the giant dipole states in O^{16} decay strongly to one or both of the positive-parity states of O^{15} at 5.174 and 5.235 MeV. From the composite fit of Fig. 2 we deduce the branching ratios indicated in Fig. 1. We have ignored the possibility of decays from the 24.3-MeV state to higher excited states of O^{15}, all of which have positive parity in any case, and of decay of the 22.2-MeV state to the 6.160-MeV state, which would give very low neutron energies, which we do not observe reliably. Experimental uncertainties and the possibilities of other ways of fitting the data make the quoted branching ratios uncertain by about 25% of their values.

†Work supported in part by the National Science Foundation.

[1]J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) A242, 57 (1957).

[2]G. E. Brown, L. Castillejo, and J. A. Evans, Nucl. Phys. 22, 1 (1961).

[3]V. Gillet and N. Vinh Mau, Phys. Letters 1, 25 (1962); V. Gillet, Nucl. Phys. 52, 410 (1964). This calculation includes the effect of configurations with odd numbers of particles and holes.

[4]A. N. Gorbunov and V. A. Osipova, Zh. Eksperim. i Teor. Fiz. 43, 40 (1962) [translation: Soviet Phys.-JETP 16, 27 (1963)].

[5]F. C. Barker, Nucl. Phys. 31, 535 (1962).

[6]Y. Abgrall, J. Phys. Radium 24, 1113 (1963).

[7]E. C. Halbert and J. B. French, Phys. Rev. 105, 1563 (1957).

[8]F. W. K. Firk and K. H. Lokan, Phys. Rev. Letters 8, 321 (1962).

[9]N. Tanner, G. Thomas, and E. D. Earle, Nucl. Phys. 52, 45 (1964). Additional references are to be found in this paper.

[10]S. A. E. Johansson and B. Forkman, Arkiv Fysik 12, 359 (1957).

[11]C. Milone, S. Milone-Tamburino, R. Rinzivillo, and A. Rubbino, Nuovo Cimento 7, 729 (1958).

[12]E. G. Fuller and Evans Hayward, Nuclear Reactions, edited by P. M. Endt and P. B. Smith (North-Holland Publishing Company, Amsterdam, 1962), Vol. II, p. 182 ff.

[13]R. H. Augustson, N. N. Kaushal, H. A. Medicus, W. R. Moyer, E. J. Winhold, and P. F. Yergin, Helv.

Phys. Acta 36, 817 (1963).
[14]K. N. Geller and E. G. Muirhead, Phys. Rev. Letters 11, 371 (1963).
[15]J. T. Caldwell, R. R. Harvey, R. L. Bramblett, and S. C. Fultz, Phys. Letters 6, 213 (1964).

LONG-RANGE POLARIZATION IN HIGH SUSCEPTIBILITY METALS

B. Giovannini and M. Peter
Institute of Experimental Physics, University of Geneva, Geneva, Switzerland
and
J. R. Schrieffer
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania
(Received 4 May 1964)

Recent electron paramagnetic resonance (EPR) experiments on metals and alloys of high paramagnetic susceptibility (Pd and Ni_5La)[1-3] have shown an anomalous long range of the spin polarization around magnetic impurities. Wolff[4] has suggested that the exchange interaction between valence electrons in metals will increase the range of the polarization in space. By connecting the enhancement of the polarization in momentum space with the observed uniform susceptibility of the studied metal, we have found that exchange interactions can bring predicted and observed data into agreement.

The susceptibility function of a system is defined by its linear response to an external magnetic field. If the system is homogeneous,

$$\langle\vec{M}(\vec{r},t)\rangle = \int \chi(\vec{r}-\vec{r}',t-t')\vec{H}(\vec{r}',t')d^3r'dt',$$

or

$$\langle\vec{M}(\vec{q},t)\rangle = \int \chi(\vec{q},t-t')\vec{H}(\vec{q},t')dt',$$

where $\langle\vec{M}(\vec{q},t)\rangle, \chi(\vec{q},t)$ are the spatial Fourier transforms of $\langle\vec{M}(\vec{r},t)\rangle, \chi(\vec{r},t)$, respectively.

For an electron gas, χ is given by

$$\chi(\vec{q},t-t') = (2i\mu_B{}^2/V\hbar)\theta(t-t')\langle 0|T\{\sigma(-\vec{q},t)\sigma(\vec{q},t')\}|0\rangle,$$

where

$$\sigma(\vec{q},t) = \rho_{\uparrow}(\vec{q},t)-\rho_{\downarrow}(\vec{q},t),$$

and

$$\rho_{\gamma}(\vec{q},t) = (1/V)\textstyle\sum_{\vec{k}} c_{\gamma}{}^{\dagger}(\vec{k}-\vec{q},t)c_{\gamma}(\vec{k},t);$$

V is the volume of the system, $|0\rangle$ is the ground state of the isolated system, and T is the time ordering operator.

EPR measurements of magnetic impurities in metals allow one to get some insight into the shape of this function.

In a series of recent experiments, the shift and the broadening of the EPR lines of 2% Gd (impurity A) in a matrix formed by 96% of high-susceptibility metals and 2% of additional magnetic impurities (B) have been studied.[1] The magnetic moment of rare earth impurities was found to be practically equal to their ionic moment, contrary to transition elements, which show giant moments in solid solution in Pd alloys.[5] The deformation of the EPR line of Gd in the matrix is very sensitive to the shape of the susceptibility function. This can be best understood by thinking first of only one ion of Gd in the host metal: Each magnetic inpurity B will polarize the valence electrons of the host metal and will therefore shift the g value of the Gd ion. The magnitude of this shift will depend on the value of the susceptibility function of the host metal at the Gd site. Since the magnetic impurities are distributed at random, the statistical average over all Gd ions will give both a displacement and a deformation of the resonance line.

The shift of a resonance line is defined by

$$S = \int (H-H_0)I(H)dH, \tag{1}$$

where H_0 is the center of the nonperturbed line and $I(H)$ the perturbed intensity line; and the mean square deviation by

$$B = \int (H-H_0)^2 I(H)dH - S^2. \tag{2}$$

One can express S and B in terms of $\chi(\vec{r}) \equiv \int_0^{\infty}\chi(\vec{r},t)dt$:

$$S = c_B n_0 a \frac{1}{V}\int \chi(\vec{r})d^3r, \tag{3}$$

$$B = c_B n_0 a^2 \frac{1}{V}\int \chi^2(\vec{r})d^3r, \tag{4}$$

where c_B is the concentration of magnetic impurities in the matrix, n_0 the number of lattice sites per cc, and a is a constant depending on the characteristics of the system. The value of the ratio of the shift squared to the mean square