Systematics of Photoneutron Reactions*

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USING the method of direct neutron detection previously reported,[1] we have measured the photoneutron yields from 13 singly isotopic elements when irradiated with betatron *bremsstrahlung* at energies from threshold to 24 Mev. Four enriched BF_3 proportional counters were symmetrically placed 13.5 cm

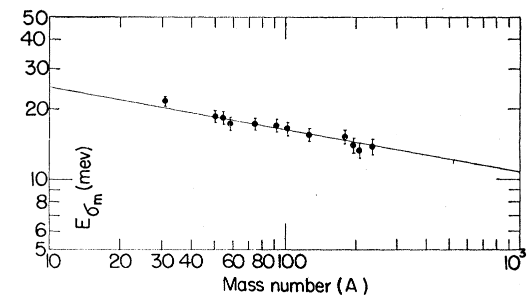

FIG. 1. Log-log plot of E_{σ_m} *versus* mass number.

from the target in the paraffin house of reference 1 to increase the sensitivity of the apparatus. Neutron yields were taken at 0.5-Mev intervals to a statistical accuracy of better than 1 percent, except for the first two points near threshold, where the statistical inaccuracy never exceeded 3 percent. The energy of the betatron was stable to better than 0.1 Mev, as evidenced by repeated daily checks of the bismuth (γ,n) threshold during the course of the experiment.

Excitation functions constructed from the total neutron yield data by the usual method of successive subtractions[2] show the characteristic large dipole resonance behavior for all the elements investigated. The data are summarized in Table I, where the

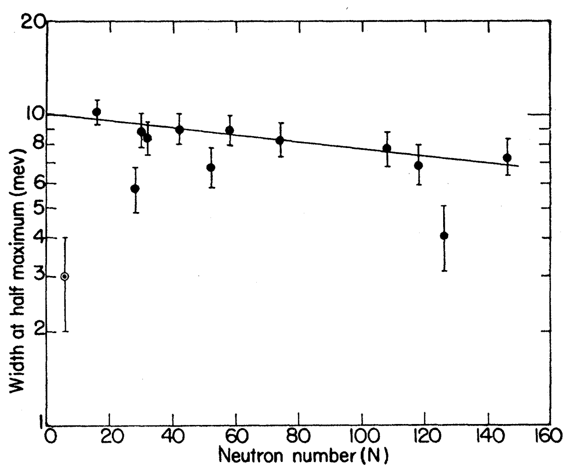

FIG. 2. Width at half-maximum of neutron emission resonance *versus* neutron number.

significant parameters for the resonances are given. Here σ_m represents the maximum value of the cross section, E_{σ_m} the energy at which this maximum occurs, Γ the width of the resonance at half maximum, and $\int\sigma dE$ the integrated cross section to 25 Mev. Also tabulated is the neutron yield at 22-Mev betatron energy for comparison with the measurements of Price and Kerst.[3]

The log-log plot of E_{σ_m} against mass number is shown in Fig. 1. The least-squares straight line through the experimental points yields $E_{\sigma_m}=38.5A^{-0.19}$, in close agreement with the results of Cameron[4] from other data and in striking agreement with the predictions of Goldhaber and Teller.[5]

A plot of the dipole resonance half-widths against neutron number (Fig. 2) shows a slow decrease in half-width as N in-

TABLE I. Summary of data.

Isotope	Target thickness (g/cm²)	Thresholds (Mev) (γ,n)	$(\gamma,2n)$	E_{σ_m} (Mev)	Γ Half-width (Mev)	σ_m $(10^{-26}$ cm²)	$\int\sigma dE$ (Mev-barns)	22-Mev yield/mole-r $\times10^{-6}$ (this paper)	22-Mev yield/mole-r $\times10^{-6}$ (Price & Kerst)
$_{6}C^{12}$	12.8	18.7	32.6	22.0	3.0	0.93	0.030	0.026	
$_{15}P^{31}$	4.31	12.05	24.50	21.5	10.2	1.77	0.178	0.35	0.33
$_{23}V^{51}$	2.68	11.15	19.88	18.7	5.8	9.8	0.625	2.05	1.6
$_{25}Mn^{55}$	1.57	10.00	19.40	18.4	8.8	10.7	0.974	2.86	1.9
$_{27}Co^{59}$	2.59	10.25	19.67	17.3	8.4	8.1	0.697	2.28	2.3
$_{33}As^{75}$	1.34	10.10	17.42[a]	17.3	9.0	10.1	0.888	3.39	3.9
$_{41}Cb^{93}$	1.36	8.70	17.88[a]	17.0	6.8	21.3	1.62	6.05	5.8
$_{45}Rh^{103}$	1.81	9.35	17.47[a]	16.5	8.9	22.8	2.16	8.18	
$_{53}I^{127}$	1.23	9.10	16.72	15.5	8.3	26.7	2.27	10.2	11.0
$_{73}Ta^{181}$	0.468	7.55	13.84[a]	15.1	7.9	36.8	3.17	19.4	19.0
$_{79}Au^{197}$	0.455	7.90	13.71[a]	13.9	6.9	49.2	3.54	20.4	19.0
$_{83}Bi^{209}$	0.434	7.40	13.30[a]	13.2	4.1	45.0	2.92	17.9	25.0
$_{92}U^{238}$	0.548	5.97	12.18[a]	13.8	6.6	109.0	7.94	52.3	51.0

[a] Computed from mass formula.

creases, with the exception of four elements having unusually narrow resonances. The correlation of these elements, C^{12} $(N=6)$, V^{51} $(N=28)$, Cb^{93} $(N=52)$, and Bi^{209} $(N=126)$, with the shell model is unusual for phenomena concerned with such high excitation energies.

Further details of this study will appear later.

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Low-Lying Many-Particle Levels in Odd Mass Nuclides with 21, 23, 25, or 27 Protons or Neutrons

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LOW-LYING excited levels in odd-mass nuclei with 21, 23, 25, or 27 protons or neutrons are to be expected because of the coupling of nucleons in the $f_{7/2}$ state.[1,2]

We were able to confirm their occurrence in some hitherto uninvestigated cases with 23 and 25 identical nucleons. Our results, which will be discussed below, are given in Table I, together with other data.[3–9]

V^{49}:—The positron decay of Cr^{49} was investigated both with a Geiger counter $\beta\gamma$-coincidence apparatus and with a NaI-scintillation spectrometer. The maximum energy of the beta spectrum is 1.47 ± 0.04 Mev by Al absorption, while roughly half of the positrons go to the ground-state of V^{49}. Gamma lines of 0.060 (5 percent), 0.091 (18 percent), 0.151 (12 percent), and 1.57 (5 percent) Mev were found (intensities relative to the total number of positrons). The 0.151-Mev line is presumably the crossover. The 1.57-Mev line is also found by O'Connor *et al.*[10] There is no indication of their 0.19-Mev line. Experiments are in progress to determine the multipolarity of the low-energy lines.

V^{51}:—The 0.325-Mev gamma line has been reported by several workers,[4] both in the electron-capture decay of Cr^{51} and in the β^- decay of Ti^{51}. From $V(p,p')$ reactions Hausman *et al.*[5] reported a second low-lying level at 0.48 Mev. We could not find a corresponding gamma line in the scintillation spectrum, either from the decay of Ti^{51} or from that of Cr^{51}. If present, this line has an intensity of less than 3 percent compared with the 0.325-Mev line. In addition, Kern *et al.*[3] reported a gamma ray of energy 0.237 Mev in the decay of Cr^{51}, which so far has not been confirmed.[2,5,11]

Ca^{43}:—By means of the scintillation spectrometer we have confirmed the existence of a gamma line at 0.375 Mev. Its intensity is 25 percent compared to the total positron intensity in the beta decay of Sc^{43} This line had already been reported by Haskins *et al.*[7] The line could be clearly separated from the Compton distribution of the annihilation line by a method proposed by A. H. W. Aten, Jr. The spectrum was first measured with a thin source and was then remeasured with the source covered by a perspex absorber opposite to the crystal. The intensity of the annihilation peak was then found nearly doubled. Subtraction of the two curves, after normalization to the same annihilation peak height, yielded the 0.375-Mev gamma line.

Mn^{53}:—No gamma line was found by Nelson *et al.*[12] in the positron decay of Fe^{53}. From (p,n) reactions, however, a level at 0.370 Mev is reported.[8] We have investigated the scintillation spectrum of Fe^{53} by the method described above, and we found a gamma line at 0.370 Mev with an intensity of 30 percent compared to the total positron spectrum, which classifies the transition to this level as allowed.

Application of Edmonds and Flowers' results[1] indicates that low-lying excited levels should occur both from the coupling of $f_{7/2}$ identical particles and from mixed proton-neutron configurations. In the case of 23 and 25 odd nucleons, no exclusive assignment to one or the other coupling mechanism can be given so far for the experimentally known low-lying levels. However, with 21 or 27 odd nucleons, the occurrence of such levels could be accounted for by mixed configurations.

From the available data on nuclear energy levels in this region, the following preliminary conclusions can be derived:

1. In nuclei with 23 and 25 protons or neutrons the first excited levels are found below 0.5 Mev in all cases investigated.

2. In nuclei with 21 and 27 protons or neutrons no states below 1.0 Mev have been found. It seems therefore that mixed configurations of $f_{7/2}$ protons with $f_{7/2}$ neutrons do not give rise to low-lying levels.

3. The first single-particle level in all investigated odd-mass nuclides with 21, 23, 25, or 27 identical nucleons is found between 1.0 and 1.5 Mev.

4. In V^{49} two low-lying levels have been found exceptionally close to the ground state (possibly forming the triad $J=7/2$, 5/2, and 3/2), in complete agreement with the theoretical predictions;[1] this seems to be the first clear cut case in which all three competing levels appear.

The following cases have been reported as possible exceptions to the conclusions 2 and 3:

Sc^{45}:—An indication was reported[13] for the existence of a ≤ 4 percent 0.45-Mev gamma ray in the positron decay of Ti^{45}. Studying this decay, both by means of the scintillation spectrometer and with a $\beta\gamma$-coincidence apparatus, revealed no evidence for this line. The number of coincidences per positron was compared with that of Cu^{64} and F^{18}. Taking three times the standard error as limit, the intensity of the 0.45-Mev line is less than $1\frac{1}{2}$ percent.

TABLE I. Excited states below 1.0 Mev in odd-mass nuclei with 23 and 25 protons or neutrons.

Z	N	Nuclide	Levels (Mev)	Method	References
23	26	V^{49}	0.060 or 0.091	$Cr^{49}(\beta^+)$	this work
			0.151		this work
23	28	V^{51}	(0.237)	Cr^{51}(E.C.)	3
			0.325	Cr^{51}(E.C.); $Ti^{51}(\beta^-)$; $V(p,p')$	3, 4, 5
			0.48	$V(p,p')$	5
18	23	A^{41}	0.50	$A(d,p)$	6
20	23	Ca^{43}	0.375	$Sc^{43}(\beta^+)$	this work; 7
25	28	Mn^{53}	0.38	$Fe^{53}(\beta^+)$; $Cr^{53}(p,n)$	this work; 8
25	30	Mn^{55}	0.13	$Mn^{55}(p,p')$	5
22	25	Ti^{47}	0.16	$Sc^{47}(\beta^-)$	9

Cr^{51}:—From (p,n) reactions Stelson *et al.*[14] report the possible existence of levels at 0.78, 1.17, 1.42, and 1.53 Mev. Muckerjeeh *et al.*[2] reported a gamma ray of 1.5 Mev, following an allowed (not l-forbidden) partial positron spectrum in Mn^{51}.

A^{39}:—From the β^- decay of Cl^{39} a 0.35-Mev first excited state was proposed.[15] Reinterpretation of the experimental results places the first excited state at 1.35 Mev.[16]

A detailed discussion of these results will be published in *Physica*, together with a survey of the positions of nuclear energy levels in odd-mass nuclei with 13 to 27 odd particles, showing some regularities.

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Temperature Dependence of the Nuclear Susceptibility of He^3 between 1.2°K and 4.2°K†

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THE extent to which liquid He^3 behaves as an ideal Fermi-Dirac gas has recently been the object of considerable study.[1–6] Experiments to date have failed to give a unique answer to this problem. The measurement of the temperature dependence of the nuclear magnetic susceptibility of liquid He^3 would allow a quantitative check on this question. At sufficiently low temperatures the spins of the particles of an ideal Fermi-Dirac gas would be expected to line up antiparallel and this would cause the spin magnetic susceptibility to deviate from the classical $1/T$ law and finally to become temperature-independent. Goldstein[2] has discussed the magnetic properties of He^3. It appears unlikely that conventional methods of susceptibility measurements can be extended to indicate more than the already demonstrated[7] absence of nuclear ferromagnetism in this liquid.

We have succeeded in measuring directly the temperature dependence of the nuclear susceptibility of He^3 by observing the strength of the nuclear magnetic resonance absorption signal in He^3 gas at 4.2°K and 900-mm pressure and in the liquid from 2.8°K to 1.2°K. The results of the experiment are given in Fig. 1. It is seen that the nuclear susceptibility of liquid He^3 follows a $1/T$ law down to the lowest temperature reached. There is no evidence in this temperature range of the degeneracy expected of an ideal Fermi-Dirac gas[2,8] of the same density. At 4.2°K and 900-mm pressure the curve for an ideal Fermi-Dirac gas is