University of California

Ernest O. Lawrence Radiation Laboratory

PARTIAL CAPTURE RATES OF MUONS BY ^{16}O LEADING TO EXCITED NUCLEAR STATES OF ^{15}N

S. N. Kaplan, R. V. Pyle, L. E. Temple, and G. F. Valby

September 5, 1968

Berkeley, California

Submitted to Physics Letters

UCRL-18427
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

PARTIAL CAPTURE RATES OF MUONS BY ^{16}O LEADING TO EXCITED NUCLEAR STATES OF ^{15}N

S. N. Kaplan, R. V. Pyle, L. E. Temple, and G. F. Valby

September 5, 1968

PARTIAL CAPTURE RATES OF MUONS BY ^{16}O LEADING TO EXCITED NUCLEAR STATES OF ^{15}N †

S. N. Kaplan, R. V. Pyle, L. E. Temple and G. F. Valby

Lawrence Radiation Laboratory
University of California
Berkeley, California

September 5, 1968

Abstract

Partial interaction rates have been measured for the muon capture reaction $\mu^- + {}^{16}O \rightarrow {}^{15*}N + n + \nu$ leading to the excited levels at 6.323 MeV ($3/2^-$), 5.270 MeV ($5/2^+$), and 5.299 MeV ($1/2^+$). The observed partial capture rates were $2.50 \pm 0.23 \times 10^4$ sec^{-1}, $0.89 \pm 0.14 \times 10^4$ sec^{-1}, and $0.70 \pm 0.30 \times 10^4$ sec^{-1} respectively. With somewhat more precision but with poorer energy resolution a combined transition rate to the latter two levels of $1.28 \pm 0.23 \times 10^4$ sec^{-1} was found. The total observed transition rate to excited levels of ^{15}N is in good agreement with predictions attending recent calculations of total capture rate. The distribution of the excitation among the three excited levels for which measurements were made is very similar to that observed from the photoexcitation reaction $\gamma + {}^{16}O \begin{cases} \rightarrow {}^{15*}N + p \\ \rightarrow {}^{15*}O + n \end{cases}$.

†Work done under auspices of the U. S. Atomic Energy Commission.

Calculations [1-4] of μ^- capture in ^{16}O give good agreement with the experimentally measured value [5, 6] only if it is assumed that there is a high likelihood of nuclear excitation in excess of 20 MeV. There are strong similarities between this reaction and the absorption of high energy giant-resonance photons, with respect to both the energy involved and the attendent changes in nuclear spin, I-spin, and parity of the closed-shell ^{16}O nucleus. Nuclear transition-matrix elements, when first obtained from photoexcitation cross-section data, [1] produced good agreement between calculated and measured muon capture rates in ^{16}O.

Measurements [7, 8] of the rate of capture to the bound levels of ^{16}N show that approximately 10% of the μ^- captures are particle-stable. Presumably all, or nearly all, of the remainder of the captures are accompanied by neutron emission, thereby producing ^{15}N. Two of the cited capture-rate calculations [2, 3] include explicit predictions for partial transition rates to bound levels of this ^{15}N. The experiment described here had a twofold motivation; first, to compare the measured partial transition rates with calculated values, and second, to compare the excitation distribution with that observed in the photoexcitation of ^{16}O leading to $^{15*}N + p$ or its isobaric analog (mirror) state $^{15*}O + n$.

The experiment was performed in the meson cave at the Berkeley 184-inch cyclotron. A muon beam defined by a 4-in.-square counter telescope was stopped in a 2-in.-thick water target. The target was viewed at 90 deg by a Ge(Li) detector. Beginning 200 nsec after each muon stopping, a 2-μsec gate was generated. Gamma rays detected by the Ge(Li) detector during this gate were analyzed in a 1024-channel pulse-height analyzer. To reduce background from decay electrons a plastic scintillator in anticoincidence was placed between the water target and the Ge(Li) detector.

The spectrum obtained from 4.3×10^9 μ^- stoppings is shown in fig. 1a. The energy calibration of the solid-state detector was made with γ rays from the ^{16}O line at 6.130 MeV. [9] Energy calibrations were made at frequent intervals by irradiating water on the cyclotron platform and then circulating it through plastic tubing to the gamma detector outside the primary cyclotron shielding. ^{16}N, with a β^- half-life of 7.2 sec, was produced by the reaction $^{16}O\,(n,p)^{16}N$ in sufficient quantity to provide an ample source of γ rays for detector calibration. The energy spectrum from a typical calibration run is shown in fig. 1b.

The efficiency of our detector was determined by using the μ-mesic K_α x rays from Pb. Targets of three different thicknesses of Pb were used to permit correction for γ-ray absorption. The targets, each made of lead foil uniformly dispersed between thin sheets of Lucite, were so constituted and spaced as to have the same total stopping power and dimensions as the water target. The mesic x rays were detected in prompt coincidence with the muon stopping. A typical Pb x-ray spectrum is shown in fig. 1c.

Background was measured by analyzing the γ-ray spectrum from the detector, uncorrelated with stopping muons, but during the beam pulse.

In the course of the experiment two Ge(Li) detectors were used. For the first half of the experiment we used a coaxial detector of nominal intrinsic volume of 35 cm^3 that gave an energy resolution of about 30 keV at 6 MeV. For the second half we used a planar detector with a volume of about 12 cm^3 and a resolution of approximately 12 keV at 6 MeV. The data shown in fig. 1 were taken with the planar detector.

All experimental results are based on the observed intensities of the double escape (de) peaks (E_γ - 1.022 MeV). With the planar detector, 29 ± 1 K_α x rays from lead were detected per 10^6 stoppings in lead. Assuming a yield of 0.913 K_α x rays per μ^- stopping in lead, [10] we had an efficiency for detecting lead K_α x rays of $(2.65 \pm 0.09) \times 10^{-5}$. The efficiency of the coaxial detector was greater, $(4.32 \pm 0.24) \times 10^{-5}$. On the basis of the analysis by Cline [11] we assumed the efficiency to be independent of energy over the range of interest. This analysis indicated that for the size of detectors we were using the double-escape-peak detection efficiency goes through a broad maximum in the neighborhood of 6 MeV. An extrapolation error for our range of energies of as much as 10% seems unlikely.

The area under the broad 6.322-MeV (de) γ peak (5.300 MeV) was determined by subtracting from the total area under this peak an average "base-line" area. The area of the 5.269-MeV peak was determined in the same way. The 5.298-MeV peak area was determined by first subtracting the previously determined 5.269-MeV area and then finding the net area of the remaining broad peak. The variations in widths of the peaks are completely consistent with the known level-lifetime limits and slowing-down time. [12] That is, the 6.322- and 5.298-MeV levels decay while the ^{15}N nucleus is still recoiling. However, the 5.269-MeV level is sufficiently long-lived that the ^{15}N nucleus has already slowed down before decay. The observed Doppler broadening of the short-lived levels is somewhat larger than would be expected if one assumed only recoil from an 80-MeV neutrino. The additional contribution to the broadening can be attributed to the recoiling neutron. (A 3-MeV neutron has the same momentum as an 80-MeV neutrino. Each independently can produce here a Doppler broadening of about 60 keV full width.) Analysis of the shape of such Doppler-broadened peaks has been proposed by Grenacs et al. [13] as a means of determining angular correlation between nuclear orientation and the direction of neutrino emission. We have not yet attempted such an analysis.

The observed γ-ray yields are shown in table 1.

Column three gives the absolute yield of γ's per μ^- stop on ^{16}O. In addition to the counting statistics, the error quoted includes also uncertainties due to corrections for gate widths and delays, μ^- stoppings in scintillators and target-container walls, and detection efficiency. Each of these corrections contributed an uncertainty of about 3%; these uncertainties have been combined quadratically with the counting uncertainty. The partial capture rates, λ_c, are determined by multiplying the absolute γ yields by the total μ^- disappearance rate, $\lambda = \lambda_a + \lambda_D$, where $\lambda_a = (0.97 \pm 0.03) \times 10^5\ \text{sec}^{-1}$,[5] and $\lambda_D = (0.4549 \pm 0.0002) \times 10^6\ \text{sec}^{-1}$;[14] λ_a is the total absorption rate and λ_D is the decay rate.

The coaxial detector resolution was inadequate to allow separation of the 1/2+ and 5/2+ levels. The results show, therefore, only the sum of these. In addition, an insufficient amount of background data was taken with the coaxial detector, so all background corrections were based on the planar detector results and the assumption that the relative background was the same for both detectors.

The measured transition rate to the 3/2– level of ^{15}N can be compared with theoretical values of 0.052×10^6 sec^{-1} and 0.030×10^6 sec^{-1} obtained respectively from the calculations by Balashov et al. [2] and by Raphael et al. [3] We are not aware of theoretical predictions of the transition rates to the 5/2+ and 1/2+ levels. Their presence suggests a more complicated initial interaction than a single-particle–single-hole (first-forbidden electric dipole). These levels are also observed with the 3/2– level following giant-dipole-resonance photoexcitation. [15-17] The level broadening observed in photoexcitation is sufficient also to allow one to distinguish between the 5/2+ and 1/2+ levels. [17] The The photoabsorption experiments all have results similar to ours in the sense that the predominant excitation observed is the odd-parity level of 3/2-. They also observe the two even-parity levels, 1/2+ and 5/2+. The relative branching ratios to the odd-parity states in the $^{15*}N + p$ system is greater than in our experiment. However, the observed relative branching ratios in the mirror levels for the $^{15*}O + n$ system appear to be consistent with ours.

References

1. L. L. Foldy and J. D. Walecka, Nuovo Cimento 34 (1964) 1026.
2. V. V. Balashov, V. B. Beliaev, R. A. Eramjian, and N. M. Kabachnik, Physics Letters 9 (1964) 168; see also W. Balashov and R. A. Eramjian, Atomic Energy Review 5, 3 IAEA, Vienna (1967).
3. R. Raphael, H. Uberall, and C. Werntz, Phys. Letters 24B, (1967) 15.
4. Mannque Rho, Phys. Rev. Letters 19, (1967) 248.
5. M. Eckhouse (Thesis), Carnegie Inst. of Tech. Report NYO-9286, Feb. 1962 (unpublished).
6. J. Barlow, J. C. Sens, P. J. Duke, and M. A. R. Kemp, Phys. Letters 9, (1964) 168.
7. R. C. Cohen, S. Devons, and A. D. Kanaris, Nucl. Phys. 57, (1964) 255.
8. J. P. Deutsch, L. Grenacs, P. Igo-Kemenes, P. Lipnik, and P. C. Macq, Nuovo Cimento 52B, (1967) 557.
9. Energy levels and γ-ray energies (rounded to the nearest keV) are taken from the compilation by C. M. Lederer, J. M. Hollander, and I. Perlman in Table of Isotopes (John Wiley and Sons, New York, 1967). Recent precise measurements for ^{16}O and ^{15}N respectively may be found in C. Chasman, K. W. Jones, R. A. Ristinan, and D. E. Alburger, Phys. Rev. 159, (1967) 830, and R. C. Greenwood, Physics Letters 27B, (1968) 274.
10. M. K. Sundareson (Carlton University, Ottowa, Canada), private communication, 1968. This number is based on the calculation of

a cascade in the field of a finite nucleus. We are grateful to Prof. Sundareson for supplying us with this as yet unpublished result.

11. J. E. Cline, I.E.E.E. Trans. in Nucl. Sci. NS15 [3] (1968) 198.
12. E. K. Warburton, K. W. Jones, D. E. Alburger, C. Chasman, and R. A. Ristinen, Phys. Rev. Letters 14, (1965) 146.
13. L. Grenacs, J. P. Deutch, P. Lipnik, and P. C. Macq, Nucl. Instr. Methods 58, (1968) 164.
14. A. H. Rosenfeld, N. Barash-Schmidt, A. Barbaro-Galtierri, L. R. Price, M. Roos, P. Söding, W. J. Willis, and C. G. Wohl, Rev. Mod. Phys. 40, (1968) 77.
15. R. O. Owens and J. E. E. Baglin, International Nuclear Physics Conference, held at Gatlinburg, Tennessee, Sept. 12-17, 1966 (Academic Press, New York, 1967), p. 337.
16. John T. Caldwell, S. C. Fultz, and R. L. Bramblett, Phys. Rev. Letters 19, (1967) 447.
17. K. Murray and J. Ritter, in Proceedings of the International Conference on Nuclear Structure, Supp. to J. Phys. Soc. Japan 24, (1968) 724; K. Murray (Naval Research Laboratory, Washington, D. C.), private communication, 1968.

Table 1. Observed γ-ray yields.

J^{π}	$E\gamma$(MeV)	γ's per μ^- stop in ^{16}O	$\lambda_c \times 10^{-6}$ (sec^{-1})	Branching ratio λ_c/λ_a
		Planar detector (4.306×10^9 μ^- stoppings)		
$5/2^+$	5.269	0.0161 ± 0.0025	0.0089 ± 0.0014	0.092 ± 0.014
$1/2^+$	5.298	0.0127 ± 0.0054	0.0070 ± 0.0030	0.072 ± 0.031
$3/2^-$	6.322	0.0445 ± 0.0055	0.0246 ± 0.0030	0.254 ± 0.031
		Coaxial detector (2.917×10^9 μ^- stoppings)		
$5/2^+ + 1/2^+$		0.0178 ± 0.0039	0.0098 ± 0.0022	0.101 ± 0.023
$3/2^-$		0.0460 ± 0.0052	0.0254 ± 0.0029	0.262 ± 0.030
		Average of coaxial plus planar detectors		
$5/2^+ + 1/2^+$		0.0232 ± 0.0042	0.0128 ± 0.0023	0.132 ± 0.024
$3/2^-$		0.0452 ± 0.0042	0.0250 ± 0.0023	0.258 ± 0.024

Figure Caption

Fig. 1. PHA spectra of (a) γ rays following μ^- stoppings in an H_2O target, (b) a typical energy calibration run, and (c) a typical Pb-x-ray efficiency calibration run. The peaks labeled "bkgd" in (a) disappear after background subtraction. The "?" denotes tentative identification. In (c) only the peaks used in the efficiency calibration are labeled. The designations se (single escape) and de (double escape) indicate ($E\gamma$ - 0.511) MeV and ($E\gamma$ - 1.022) MeV respectively.

UCRL-18427

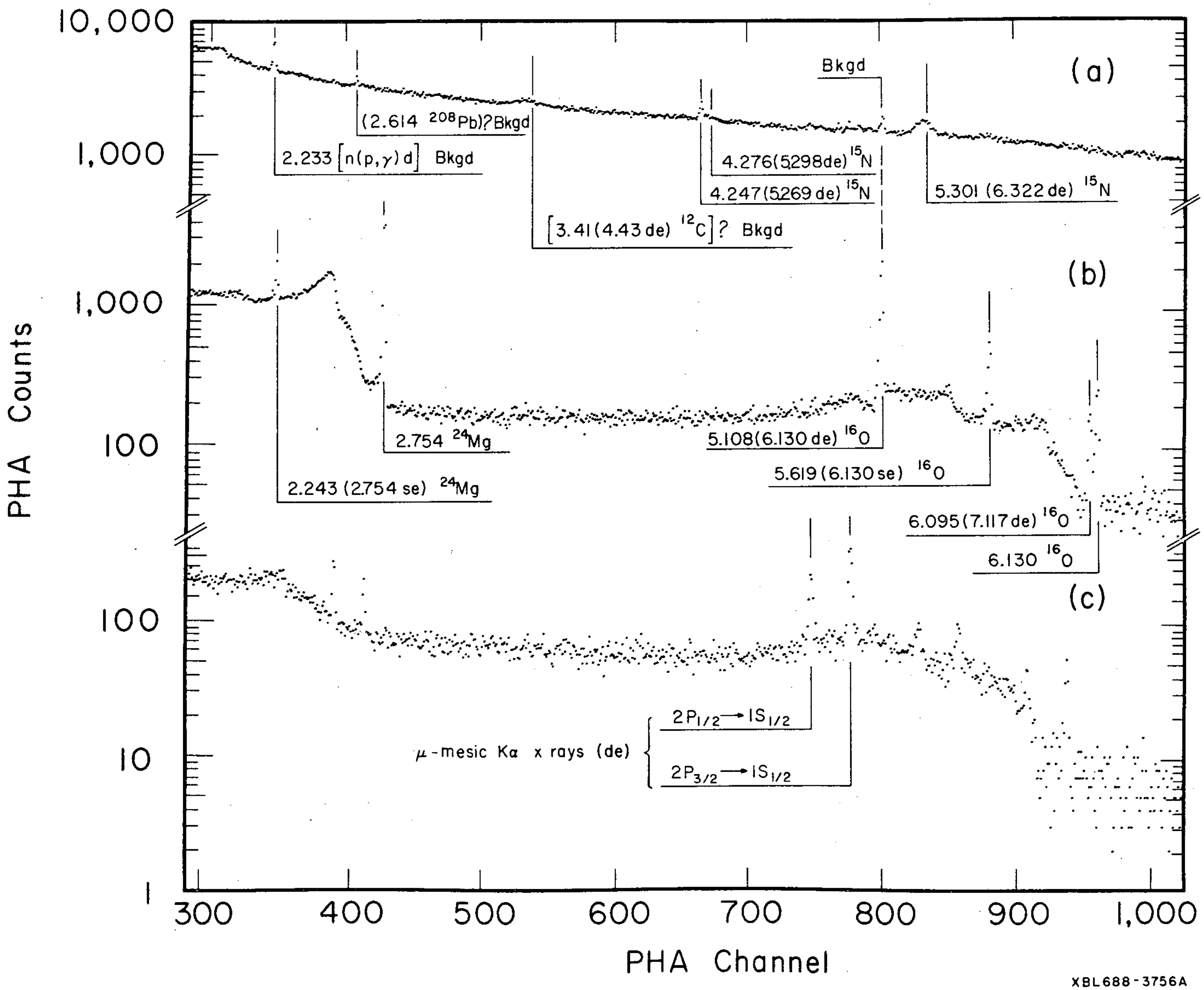

Fig. 1