52, 119 (1967); R. K. Hobbie, Williams Laboratory, U. S. Atomic Energy Commission Report No. COO-1265-44 (unpublished).
[9]C. Bergman and R. K. Hobbie, Rev. Sci. Instr. 40, 1079 (1969).
[10]C. Bergman, Ph.D. thesis, University of Minnesota, 1968 (unpublished).
[11]C. Jacobs, M.S. thesis, University of Minnesota, 1968 (unpublished). C. Jacobs, J. H. Williams Laboratory of Nuclear Physics, University of Minnesota, Annual Report, 1967 (unpublished).
[12]T. Ericson, Ann. Phys. (N.Y.) 23, 390 (1963); D. M. Brink and R. O. Stephen, Phys. Letters 5, 77 (1963).
[13]B. W. Allardyce *et al.*, Nucl. Phys. 85, 193 (1966).
[14]J. P. Aldridge, C. E. Crawford, and R. H. Davis, Phys. Rev. 167, 1053 (1968).
[15]C. P. Robinson, J. P. Aldridge, J. John, and R. H. Davis, Phys. Rev. 171, 1241 (1968).
[16]R. Stryk, Ph.D. thesis, University of Minnesota, 1966 (unpublished).
[17]J. A. McIntyre, K. H. Wang, and L. C. Becker, Phys. Rev. 117, 1337 (1960).
[18]N. P. Klepikov, Zh. Eksperim. i Teor. Fiz. 41, 1187 (1961) [transl.: Soviet Phys.-JETP 14, 846 (1962)].
[19]T. Teichmann and E. P. Wigner, Phys. Rev. 87, 123 (1952).

PHYSICAL REVIEW C VOLUME 3, NUMBER 5 MAY 1971

Neutron Capture Cross Sections of ^{13}C and ^{16}O†

B. J. Allen
Australian Atomic Energy Commission, Lucas Heights, Australia, and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

R. L. Macklin
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 2 December 1970)

Measurements have been made of the radiative widths of the lowest energy resonances in ^{13}C and ^{16}O. Maxwellian-averaged capture cross sections calculated for $kT = 30$ keV indicate that ^{13}C and ^{16}O could not have been significant neutron poisons in s-process nucleosynthesis.

The neutron capture cross sections of ^{13}C and ^{16}O are of astrophysical interest in the keV energy range. Because of their high abundances, these isotopes could act as significant neutron poisons if their capture cross sections were sufficiently high. Nucleosynthesis by slow-neutron capture (i.e., the s process[1]) starts near ^{56}Fe, which would therefore compete with these lighter isotopes for the available neutrons. If this were indeed the case, it might also be possible to set an upper limit to the neutron temperature compatible with the observed s-process buildup.

Measurements of the capture cross sections of ^{13}C and ^{16}O have been made at the Oak Ridge linear accelerator.[2] The accelerator was pulsed at 800 pulses/sec, with a beam-pulse width of 50 nsec. Operating power was 24 kW. Targets used were a 1-g 58% enriched sample of ^{13}C and a 99.992% enriched $^{7}Li_2CO_3$ sample which yielded data on both ^{16}O and ^{7}Li. Measurements were made at 40 m,[3] with a pair of total-energy detectors (TED) which have been described previously.[4] Two 4.1-in. fluorocarbon liquid scintillator cells (NE 226) flanked the sample when it was in the 2×1-in. collimated neutron beam. The pulse-height weighting technique[4] was not used in these measurements and consequently the detector efficiency was sensitive to the shape of the resonance-capture spectrum. However, the detector response function is relatively independent of the spectrum shape, and an over-all systematic error of 30% is estimated to include this effect.

Capture yields were normalized relative to the iodine capture cross section. A PbI_2 sample was used for this purpose; corrections were made for the time-dependent background as determined by a graphite scatterer and the black-resonance-transmission technique. In the latter case the yield after transmission through a 5-cm pressed sulphur filter at the 105-keV resonance gave an estimate of the time-dependent background as observed with the PbI_2 sample. The time-of-flight spectrum was also calibrated in this measurement using the energies of sulphur resonances as listed by Garg *et al.*[5]

The discriminator levels for the TED's were set at ~0.12 MeV for the ^{13}C/PbI_2 comparison. Thus, inelastic scattering to the 57.6-keV level in iodine did not contribute to the iodine yield, and the 153-keV ^{13}C resonance lay below the second inelastic

level at 203 keV. However, this was not the case for the 442-keV ^{16}O resonance. It was therefore necessary to raise the discriminator level to ~0.5 MeV in order to eliminate all inelastic scattering in iodine and ^{7}Li in the region of interest.

A photomultiplier placed at the end of the beam tube detected the γ-ray flash and started the time-to-pulse-height converter, which was stopped by an event in either TED. The flash signal was also monitored and used to estimate the time-independent background. Runs were monitored by a fission chamber at 3 m from the neutron source in another small beam tube.

The experimental time-of-flight spectra for ^{13}C and Li_2CO_3 are shown in Figs. 1 and 2. No structure was observed in either case below the energy range shown. The ^{13}C was first enclosed in a thin Al wrapper but considerable structure was observed in the time-of-flight spectrum due to capture in the aluminum. In this measurement the ^{13}C was contained in a thin polyethylene bag.

Capture yields were estimated by subtracting a smooth interpolation of the background under the peaks. The iodine yield was obtained over the same energy range for each resonance and corrected for resonance scattering and γ-ray attenuation.[4] Resonance capture areas (A_γ b eV) were calculated for each sample S from the relation

$$A_{\gamma S} = \frac{Y_S N_I M_I}{Y_I N_S M_S}(\sigma \Delta E) ,$$

where subscript I refers to iodine, Y is the observed yield after background subtraction in the interval ΔE keV, N is in atm/b for equal-area targets, M is the fission monitor count, and $(\sigma \Delta E)$ the integrated capture cross section in b eV. The iodine cross sections were taken from *Neutron Cross Sections*.[6]

The radiative width Γ_γ eV is obtained from the capture area by

$$A_\gamma = 2\pi^2 \lambda\!\!\!^{-2} g \Gamma_n \Gamma_\gamma / \Gamma$$

$$= \frac{A+1}{A} \frac{2.60}{E(\text{MeV})} g \Gamma_\gamma \quad \text{for } \Gamma_n \gg \Gamma_\gamma ,$$

$$\Gamma = \Gamma_n + \Gamma_\gamma, \quad \text{and } g = \frac{2J+1}{2(2I+1)} ,$$

where I and J are the target and resonance spins, respectively.

The capture areas and radiative widths are tabulated in Table I, together with the observed resonance energies and neutron widths. Also given are resonance parameters taken from the literature.

An important consideration is the sensitivity of the detector to resonance-scattered neutrons. This was determined using the method of Hockenbury *et al.*[7] Here the resonance area at 85 keV in a $\frac{1}{2}$-in.-thick Mg sample (almost black on resonance) is compared with that measured when a 1-in.-thick graphite sample is placed an inch behind in the beam line. The change in resonance area indicates the resonance-scattering contribution to the observed yield. Two such measurements were made to determine the neutron sensitivities with low and high bias settings. The ratio $\Gamma_\gamma/\Gamma_n \sim 1.3 \times 10^{-4}$, used by Hockenbury *et al.*,[7] has since been revised as a result of new measurements at Rensselaer Polytechnic Institute.[8] The new parameters are $\Gamma_\gamma/\Gamma_n = 6.3/7800 = 8 \times 10^{-4}$. The relative decrease in resonance area results in neutron sensitivities of 3.8×10^{-4} and 2.4×10^{-4} for the low and high bias settings, respectively. Thus the observed radiative width ($\Gamma_{\gamma\,\text{obs}}$) is given by

$$\Gamma_{\gamma\,\text{obs}} = \Gamma_\gamma + k\Gamma_n ,$$

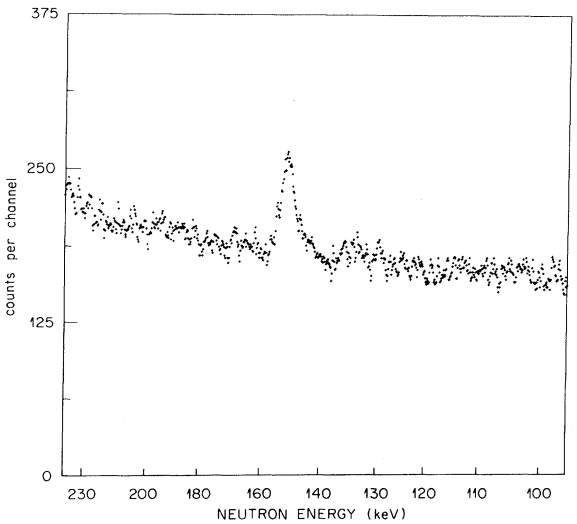

FIG. 1. Neutron capture yield at the 152-keV resonance ^{13}C.

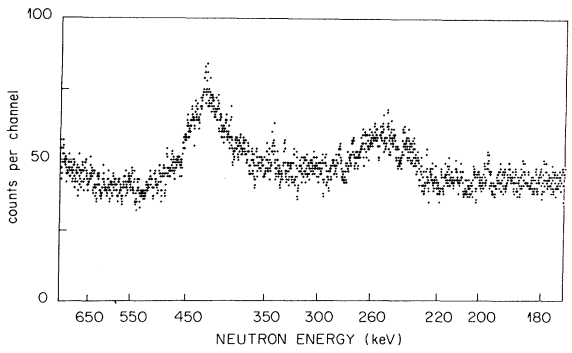

FIG. 2. Neutron capture and scattering in $^{7}Li_2CO_3$. The resonance structure results mainly from the sensitivity of the detectors to resonance-scattered neutrons.

TABLE I. Resonance parameters.

Isotope	atm/b	E_r (keV)	Γ_n (keV)	J^π	$A_{\gamma\,\mathrm{obs}}$ (b eV)	$\Gamma_\gamma + k\Gamma_n$ (eV)	Γ_γ (eV)	$\langle\sigma\rangle_{30}$ (mb)
^{7}Li	0.0139	254 ± 3	31 ± 7		89 ± 27	4.3 ± 1.3		
Refs. 9; a–c		258	40	3^+			0.07	0.035 ± 0.011
^{13}C	0.0020	152 ± 1	5 ± 1		112 ± 34	5.2 ± 1.6	4.0 ± 1.6	0.12 ± 0.04
Ref. d		153 ± 5	13	1^+				
^{16}O	0.0209	426 ± 10	60 ± 15		106 ± 32	5.4 ± 1.6	<4.0	0.0002 ± 0.0001
Refs. 9; d–g		442	46	$\frac{3}{2}^-$				

[a] E. G. Bilpuch, J. A. Farrell, G. C. Kyker, P. B. Marks, and H. W. Newson, private communication to *Neutron Cross Sections*, Brookhaven National Laboratory Report No. BNL-325 (U. S. Government Printing Office, Washington, D.C., 1964), Suppl. 2, Vol. 1.

[b] P. H. Stelson and W. M. Preston, Phys. Rev. 84, 162 (1951).

[c] W. L. Imhof, R. G. Johnson, F. J. Vaugh, and M. Walt, Phys. Rev. 114, 4 1037 (1959).

[d] H. O. Cohn, J. K. Bair, and H. B. Willard, Phys. Rev. 122, 534 (1961).

[e] A. Okazaki, Phys. Rev. 99, 55 (1955).

[f] R. K. Adair and H. H. Barschall, Phys. Rev. 84, 69 (1951).

[g] C. K. Bockelman, D. W. Miller, R. K. Adair, and H. H. Barschall, Phys. Rev. 84, 69 (1951).

where k is the neutron sensitivity and Γ_γ, Γ_n the radiative and neutron widths of the observed resonance.

These values of k, however, are found to be too large as $k\Gamma_n > \Gamma_{\gamma\,\mathrm{obs}}$ for both ^{7}Li and ^{16}O. We therefore conclude that this determination of neutron sensitivity at 85 keV cannot hold at higher neutron energies. Other measurements have shown that this is indeed the case, since the detector sensitivity tends to follow the recoil broadened capture cross section of ^{19}F, a major constituent of the liquid scintillator.

An independent estimate of the neutron sensitivity is available, as the radiative width of ^{7}Li is known to be very small.[9] In this case $\Gamma_\gamma/\Gamma_n = 1.9 \times 10^{-6}$ and $\Gamma_{\gamma\,\mathrm{obs}} = 4.3 \sim k\Gamma_n$ and $k = 1.1 \times 10^{-4}$. If we allow a factor of 4 uncertainty in this determination of neutron sensitivity, the radiative widths of ^{16}O and ^{13}C are:

$$^{16}O\text{: } 0 < \Gamma_\gamma < 4 \text{ eV},$$

$$^{13}C\text{: } 3 < \Gamma_\gamma < 5 \text{ eV}.$$

The ^{16}O result is in agreement with an estimate of 1.0 ± 0.5 eV by McGrory,[10] derived from a shell-model calculation.

The uncertainty in neutron sensitivity determines the error in the ^{16}O result. However, this is not the case for ^{13}C where the experimental uncertainty in the detector response to capture γ rays (~30%) dominates the error in the radiative width for ^{13}C (i.e., $\Gamma_\gamma = 4.0 \pm 1.6$ eV).

In stellar interiors the neutron flux is described by a Maxwell-Boltzman distribution with temperature kT.[11] It is therefore of interest to calculate the Maxwellian-averaged capture cross section ($\langle\sigma\rangle_{kT} = \langle\sigma v\rangle / v_T$) of these isotopes at a temperature appropriate to stellar interiors; i.e., $kT = 30$ keV. The averaged capture cross section is the sum of both thermal and resonance contributions, and is obtained from[12]:

$$\langle\sigma\rangle_{kT} = \sigma^{\mathrm{th}}\left(\frac{25.3\times10^{-6}}{kT}\right)^{1/2} + \frac{2}{\sqrt{\pi}} A_\gamma \frac{E_r}{(kT)^2} e^{-E_r/kT} \text{ mb}$$

for σ^{th} in mb,[13] kT and E_r (the energy of a single resonance) in keV, and A_γ in b eV.

The 30-keV averaged capture cross sections are given for each isotope in Table I and are considered accurate to ~±30%.

The relative reaction rates in s-process nucleosynthesis are determined by the product of the isotopic abundance[14] and the Maxwellian-averaged capture cross section at temperature kT. Relative to ^{56}Fe, the seed of the s process, the ratios of rates are:

$$R\left(\frac{^{7}Li}{^{56}Fe}\right) = 1.4\times10^{-7}, \quad R\left(\frac{^{13}C}{^{56}Fe}\right) = 1.7\times10^{-3},$$

and

$$R\left(\frac{^{16}O}{^{56}Fe}\right) = 5\times10^{-5}.$$

Of these, ^{13}C is the most significant but is only 0.2% of the ^{56}Fe value. At $kT = 80$ keV, where the Maxwellian-averaged capture cross section of ^{13}C maximizes, the reaction rate is still only 1% of the ^{56}Fe rate. Thus, the s process could not have been inhibited at all by capture in these light isotopes.

†Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

[1]E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957).

[2]T. A. Lewis and N. C. Pering, Bull. Am. Phys. Soc. 14, 1244 (1969).

[3]R. L. Macklin, to be published.

[4]R. L. Macklin and J. H. Gibbons, Phys. Rev. 159, 1007 (1967).

[5]J. B. Garg, J. Rainwater, S. Wynchank, and W. W. Havens, Jr., in *International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, 1965,* edited by M. Nère de Mevengries, P. Van Assche, and J. Vervier (North-Holland Publishing Company, Amsterdam, The Netherlands, 1966).

[6]*Neutron Cross Sections,* compiled by M. D. Goldberg, S. F. Mughabghab, S. N. Purohit, B. A. Maguro, and V. M. May, Brookhaven National Laboratory Report No. BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1966), 2nd ed. Suppl. 2.

[7]R. W. Hockenbury, Z. N. Bartolome, J. R. Tatarczuk, W. R. Moyer, and R. C. Block, Phys. Rev. 4, 178, 1746 (1969).

[8]R. C. Block, Z. N. Bartolome, J. R. Tatarczuk, W. R. Moyer, R. W. Hockenbury, and R. H. Wolfe, Rensselaer Polytechnic Institute Report No. RPI-328-142, 1968 (unpublished).

[9]R. O. Lane, A. S. Langsdorf, J. E. Monahan, and A. J. Elwyn, Ann. Phys. (N.Y.) 12, 135 (1961).

[10]J. B. McGrory, private communication.

[11]D. D. Clayton, W. A. Fowler, T. E. Hull, and B. A. Zimmerman, Ann. Phys. (N.Y.) 12, 331 (1961).

[12]R. L. Macklin and J. H. Gibbons, Rev. Mod. Phys. 37, 166 (1965).

[13]G. A. Bartholomew *et al.,* Nucl. Data A3, 367 (1967).

[14]A. G. W. Cameron, in *Origin and Distribution of the Elements,* edited by L. H. Ahrens (Pergamon Press, New York, 1968).

PHYSICAL REVIEW C VOLUME 3, NUMBER 5 MAY 1971

Three-Fluid Hydrodynamical Model of Nuclei*

Radhe Mohan

Physics Department, Duke University, Durham, North Carolina 27706, and Physics Department, Rutgers, The State University, New Brunswick, New Jersey 08903†

and

M. Danos

National Bureau of Standards, Washington, D. C. 20234

and

L. C. Biedenharn

Physics Department, Duke University, Durham, North Carolina 27706

(Received 30 November 1970)

A three-fluid model of nuclei is introduced, the three fluids being the protons, the neutrons of the same orbitals as protons, and the excess neutrons, to account for the fact that the excess neutrons interact less strongly with the protons than do the neutrons which occupy the same space-spin states as the protons. Calculations of proton and neutron density distributions, of isotope shifts, and of isospin impurities have been carried out. The giant-dipole phenomenon is also studied in the present model. It is found that considerable improvement is achieved in the results for the proton density distribution and for the isospin impurities as compared with the two-fluid model. The other results are found to be consistent with previous calculations.

1. INTRODUCTION

There have been several attempts, based on hydrodynamical models, to explain some of the collective properties of nuclei, e.g., giant-dipole-resonance (GDR) phenomena, neutron and proton distributions in nuclei, the isospin mixing in the ground states of nuclei, and fission, etc. In all cases, the nucleus was considered to be composed of a proton fluid and a neutron fluid (except for fission where only one fluid is considered). Goldhaber and Teller[1] proposed three different models in an attempt to account for the cross sections and the A dependence of the GDR energies. In the first model it was assumed that a displacement of the average position of the protons from the equilibrium position requires a force which is proportional to the displacement but is independent of A. This would be a good assumption if the nucleus consisted of α-particle clusters. In this model the GDR energy will be the same for all nuclei. In the second model the protons and neutrons on the