Carbon-13 Neutron Total Cross Section

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The total neutron cross section of carbon-13 was measured for neutron energies from 110 kev to 9 Mev and from 16 Mev to 23 Mev. Four narrow resonances were observed as well as broad resonance structure above 3 Mev. The most probable spin assignments based on the resonance heights and widths are as follows: $E_R=153\pm5$ kev, $\Gamma=13$ kev, $J=1^+$; $E_R=1751\pm8$ kev, $\Gamma=20$ kev, $J=1$; $E_R=2432\pm10$ kev, $\Gamma=17$ kev, $J=2$; $E_R=2454\pm10$ kev, $\Gamma=10$ kev, $J\geqslant1$.

INTRODUCTION

THE level structure of C^{14} in the energy region above 8.176 Mev, the binding energy of carbon-13 plus a neutron, has previously been investigated by means of the $C^{13}(d,p)C^{14}$ and $Be^9(Li^6,p)C^{14}$ reactions.[1–3] However, no sufficiently massive enriched carbon-13 samples had been available previously to measure the total neutron cross section. The present work reports a measurement of the neutron total cross section by a transmission type experiment done with a carbon-13 enriched sample.

THE SAMPLE

Elemental carbon 58.3% atom enriched with C^{13} was prepared from isotopically enriched $BaCO_3$ by chemical reduction.[4] The carbon was packed under pressure into a thin walled nickel cylinder $\frac{3}{4}$ in. in diameter and 2.2 in. long, yielding a density slightly above 0.6 g/cm^3, which is as high an apparent density as one can maintain after compressing soot.[5] Since carbon is an excellent absorber of gases, the sample was kept in a moderate temperature oven under vacuum, until the total weight of the sample did not decrease with time. Even after this treatment the neutron cross-section measurements showed the presence of a large fraction of oxygen through the well known 440-kev and 1-Mev resonances.[1] At the end of the run the sample was analyzed with a mass spectrometer and was found to contain 0.5% water by chemical moisture test, and gases consisting of 55% CO, and 40% CO_2, with the remainder water vapor and hydrocarbons.[6]

From the height of the oxygen resonances in the neutron total cross section the amount of oxygen was determined to be 8%. This figure and the chemical analysis data were used to evaluate the amount of contaminants in the sample, and the measured cross section was adjusted accordingly.

EXPERIMENTAL PROCEDURE

Standard-type transmission experiments were performed with a propane recoil counter detector and various neutron-producing targets at the exit port of the ORNL 5.5-Mv Van de Graaff accelerator.[7] The counter was located slightly more than one foot from the neutron source, with the sample placed about half way between target and counter. Low-resolution runs ($\sim$30 kev) with neutrons produced by a tritium gas target with the $T(p,n)$ reaction and higher resolution runs ($\leq$10 kev) with $Li^7(p,n)Be^7$ neutrons were made for neutron energies of 110 kev up to 4 Mev. The region from 3.7 to 9 Mev was explored with $d-D$ neutrons. In the region of 16 to 23 Mev the total neutron cross section was measured with the help of d-T neutrons. In the low kev region two points were measured by time-of-flight techniques. The effect of the container and the C^{12} was subtracted experimentally by using a similar nickel shell containing an appropriate amount of C^{12}. Sample inscattering was negligible compared to other errors for the geometry used in the experiment. The cross section measured with the $Li(p,n)$ reaction was corrected for the presence of the second neutron group.[8]

RESULTS AND DISCUSSION

Figure 1 shows the C^{13} total neutron cross section for neutron energies from 110 kev to 23 Mev, with typical standard deviation errors due to counting indicated in the cross section. The actual error in the measured cross section is somewhat larger due to the uncertainty in the amount of contaminants in the sample as discussed above. Since the uncertainty is primarily in the amount of hydrogen present, the error in the cross section is largest for the low-energy region, and would tend to lower the cross section; however, this lowering is at most 0.35 barn at 200 kev and 0.1 barn at 1.0 Mev, assuming the largest amount possible of water in the contaminant.

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[3] C. S. Littlejohn and G. C. Morrison, Bull. Am. Phys. Soc. **3**, 227 (1958).
[4] W. F. Libby, *Radiocarbon Dating* (The University of Chicago Press, Chicago, Illinois, 1952), pp. 48.
[5] C. L. Mantell, *Industrial Carbon* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1946), 2nd. ed., p. 83.
[6] The carbon in the gases was of the same isotopic enrichment as the sample.
[7] J. D. Kington, J. K. Bair, H. O. Cohn, and H. B. Willard, Phys. Rev. **99**, 1393 (1955).
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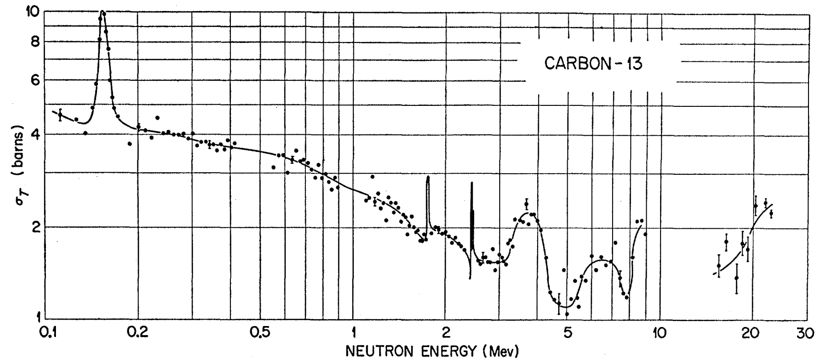

FIG. 1. Total neutron cross section of carbon-13.

Four narrow resonances are observed at 153±5 kev, 1751±8 kev, 2432±10 kev, and 2454±10 kev, which correspond to levels in C^{14} at excitation energies of 8.318±0.008, 9.801±0.010, 10.433±0.012, and 10.453 ±0.012 Mev, respectively. Three of these resonances are shown in detail in Fig. 2. In addition a broad resonant structure is observed at neutron energies above 3 Mev. At the peak of the first broad resonant structure (~3.8 Mev) the measurements were done with *p*-T and *d*-D neutrons, overlapping about 300 kev. No points are shown in the regions of 440 kev and 1 Mev, which correspond to resonances in the oxygen contamination. Since these two resonances measured about 1.0 and 0.4 barns above the C^{13} cross section, they could have obscured possible weak resonances in C^{13}, especially at the lower energy.

The cross section at 14 kev and 23 kev was measured by the time-of-flight technique[9] to be 6.1 and 6.9 barns, respectively. Counting-statistics standard deviations are less than 0.2 b; however, at these low neutron energies the uncertainty in the hydrogen contamination necessitates an increase in the cross-section error to about ±0.8 b.

The observed peak cross section of the 153-kev resonance was about 6 barns above the nonresonant (potential) scattering with a width of 13 kev. Corrections for finite energy resolution (~5 kev), sample contamination, and inscattering raise this value to 7 barns, significantly above the 4.9 barns expected for $J_0=0$, however much lower than expected for a $J_0=1$ spin assignment. Thus this level could be formed by *s*-, *p*-, or *d*-wave neutrons. However, the reduced width for *d* waves is 2.3 times the Wigner limit ($3\hbar^2/2MR^2$, with R the channel radius taken equal to 4.86 fermis), but only 0.006 and 0.045 for *s* and *p* waves, respectively. Moreover, an *s*-wave resonance should be preceded by an observable dip of about 3 barns due to interference with the predominant (at this low energy) *s*-wave background scattering. Therefore we conclude that the level in C^{14} at 8.32-Mev excitation is $J_0=1^+$.

The natural width of the resonance at 1.75 Mev [Fig. 2(a)] was measured to be 20 kev. Corrections made to the observed peak cross-section place it in excellent agreement with a $J_0=1$ value for this level. Again *s*, *p*, and *d* waves could form this resonance with reduced widths of 0.003, 0.004, and 0.016 the Wigner limit, respectively. This time only *s* waves can be eliminated (on the basis of no observed dip). Thus the parity of the 9.80-Mev level in C^{14} is not fixed by this data.

Resonances were also observed at 2.432 and 2.454 Mev [Fig. 2(b)] with apparent widths of 17 and 10 kev, respectively. On the basis of the adjusted heights of these resonances, the spin assignments are $J_0=2$ for the 10.43 Mev level in C^{14}, and $J_0 \geqslant 1$ for the 10.45-Mev level. Again, the parity cannot be uniquely determined.

The four narrow levels observed in this experiment agree well in excitation energy with those found in the $C^{13}(d,p)C^{14}$ reaction[2] with the excitation of that at 10.453 Mev, which is about 50 kev lower.

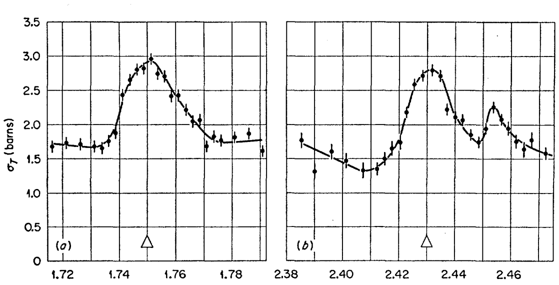

FIG. 2. Total neutron cross section of carbon-13, (a) in the region of the resonance at 1.75 Mev, (b) in the region of the resonances at 2.43 and 2.45 Mev.

[9] W. M. Good, J. H. Neiler, and J. H. Gibbons, Phys. Rev. **109**, 926 (1958).

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