± 0.01. The error quoted is one standard deviation associated with counting statistics only. The figure of −0.19 was obtained from the neutron asymmetry with the magnets on and the quench field set at 6.7 V/cm. It includes the effect of negative ions made by ionization of ground-state atoms. If one takes instead the asymmetry after subtraction of the counting rate which obtains with the quench field set at 200 V, the resulting tensor polarization is that possessed by those deuterons which became negative ions via metastable atoms. This tensor polarization is −0.23 ± 0.01. The ratio of these two tensor polarizations is consistent with that expected from a measurement of the counting rate with all the metastables quenched.

It was found that the measured values of tensor polarization were insensitive to cesium and argon pressures. No change in tensor polarization was observed over a pressure range on either side of the signal maxima great enough to give a factor of two drop in the metastable signal.

The tensor polarization of −0.23 for those deuterons made via metastables is to be compared with the expected value of −0.33. It was found that turning off the exponential transition field reduced the measured tensor polarization to −0.04. This observation is in agreement with estimates of the depolarization introduced by the fringing field of the solenoid. However, it appears that either our practical approximation to an exponentially decreasing field was inadequate, or that our numerical estimates of the depolarization introduced by this field are unrealistic. Neither of these possibilities can be ruled out at the present time. In the near future we plan to eliminate the problem by ionizing at high magnetic field. A more highly polarized deuteron beam will be produced by a method involving radio-frequency fields.

Finally, it should be mentioned that cesium vapor is also an efficient converter of incident deuterons into negative ions. At 1 keV as much as 25% of the positive-ion current is converted into negative-ion current at 10 mTorr cm of Cs. This effect has also been observed by Donnally.[6]

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TRANSITION RATES IN B^{10} AND THE β DECAY OF C^{10}†

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A recent measurement[1] of the lifetime of the lowest $T=1$ level of B^{10} at 1.74 MeV is incompatible with the known beta decay[2] of C^{10}. The transition between the 1.74-MeV and 0.72-MeV levels of B^{10} is the gamma-ray analog of the beta transition from C^{10} to the lower level. A comparison of the relevant matrix elements shows that the measured gamma-ray lifetime[1] of $(1.52 \pm 0.24)\times10^{-13}$ sec cannot be reconciled with the *ft* value[3] of 1000 for the C^{10} beta decay, unless there is a serious breakdown of isobaric-spin conservation. A specific calculation by Cohen and Kurath[4] predicts a gamma-ray lifetime 35 times shorter than the measured value. Measurements[1,5,6] have also been reported for the lifetimes of the levels of B^{10} at 2.15 and 3.59 MeV, but the large errors on the measurement[1] for the 2.15-MeV level warrant a remeasurement of the lifetime of this level; while the two measurements[5,6] for the 3.59-MeV level are in only fair agreement. The transition from the 2.15-MeV level to the 1.74-MeV level is the gamma-ray analog of the allowed but unobserved beta decay from C^{10} to the 2.15-MeV level.

The lifetimes of these three levels of B^{10} have been remeasured with the Doppler-shift-attenuation method using a Ge(Li) detector.

Table I. Summary of measurements on the 1.74-MeV state of B^{10}. All measurements were made with the reaction $Be^9(He^3,d)B^{10*}$ on the 1.02-MeV gamma ray, the first four measurements at $E_{He^3} = 2.0$ MeV, the last three at $E_{He^3} = 2.8$ MeV. The shifts were measured between $\theta = 0°$ and 150°.

Stopping medium	Shift (keV)	Vacuum shift (keV)	F_m	F
Al	18.60	20.90	0.890	0.95
Sc	19.50	20.90	0.933	0.99
Ni	18.97	20.90	0.908	0.97
Ir	17.70	19.05	0.930	0.99
Al	16.85	21.73	0.776	0.96
Ni	17.09	21.00	0.813	1.02
Ir	16.83	20.50	0.822	1.03
			Average	0.99 ± 0.04

The 1.74-MeV level. – The reaction $Be^9(He^3,d)B^{10*}$ was found to be the most suitable for studying this level. The technique employed was similar to that used previously[7] in measurements of the lifetimes of the first excited states of Li^7 and Be^7. Very thin targets of beryllium were bombarded with He^3 particles and the B^{10} nuclei recoiled into backings of iridium, nickel, scandium, or aluminum, or into vacuum. The attenuated Doppler shift of the 1.02-MeV gamma ray emitted by recoils stopping in a given medium was compared with the shift for recoils traveling in vacuum and the lifetime deduced from a knowledge of the stopping power of the medium.[8,9] It was not possible to work at a low enough bombarding energy to prevent entirely the simultaneous population of the 2.15-MeV state and the subsequent feeding of the 1.74-MeV level by means of the 0.41-MeV gamma transition. Observations were made at two bombarding energies, 2.0 and 2.8 MeV; at each energy the gamma-ray feeding of the 1.74-MeV level was accurately determined by measuring the relative intensity and angular distribution of the 0.41-MeV gamma ray. The measurements are summarized in Table I. The listed values of F are obtained from the measured shift ratios F_m by application of the feeding corrections. If we take $F > 0.95$ and apply corrections[7] for target thickness and nonlinearity of the stopping power curve, we obtain $F_c > 0.91$. For stopping in iridium, the relation

$$\tau = [(1 - F_c/F_c]\alpha,$$

where $\alpha = (2.6 \pm 0.2) \times 10^{-13}$ sec is the characteristic slowing-down time,[8,9] gives the result

$$\tau_{1.74} < 2.8 \times 10^{-14} \text{ sec.}$$

This limit is compatible with the ft value for the C^{10} beta decay. The value of the lifetime predicted by Cohen and Kurath,[4] 4.5×10^{-15} sec, is well below this limit. One of the runs in Table I is illustrated in Fig. 1.

The 2.15-MeV level. – Three reactions were used to study this level. With the reaction $Be^9(He^3,d)B^{10*}$, $E_{He^3} = 2.8$ MeV, the Doppler shift of the 0.41-MeV line resulting from the decay to the 1.74-MeV level was measured using nickel, scandium, aluminum, and beryllium as stopping media. The vacuum shifts were

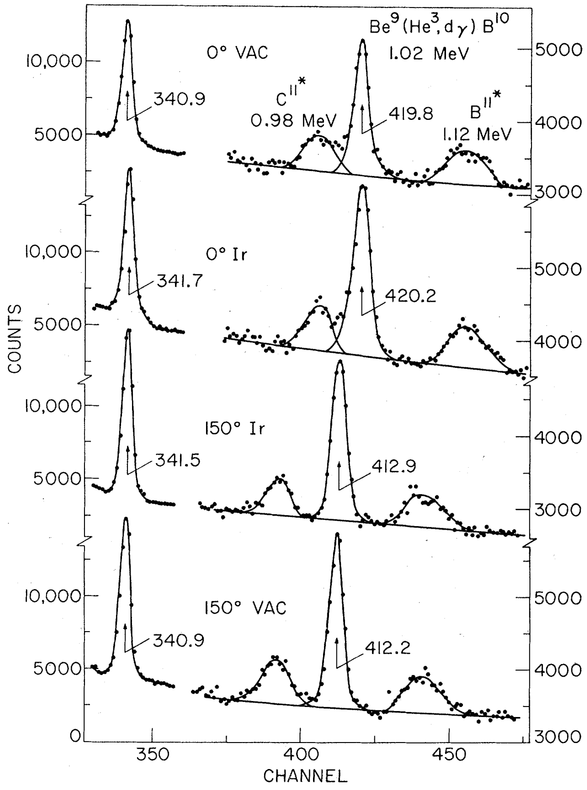

FIG. 1. Sequence of spectra obtained for the 1.02-MeV gamma ray emitted by the 1.74-MeV state produced in the reaction $Be^9(He^3,d)B^{10*}$ at $E_{He^3} = 2.0$ MeV. The reference line is obtained from the 0.835-MeV gamma ray from a Mn^{54} source. The two-escape peaks of the 2.00- and 2.14-MeV gamma rays from $Be^9(He^3,n)C^{11*}$ and $Be^9(He^3,p)B^{11*}$ also appear in the spectra. The lifetimes of these states are too short to produce attenuations in the Doppler shifts observed with the iridium backings. The arrows locate the calculated centroids.

either measured or calculated. The beryllium measurement was made with a thick beryllium target. The reaction $Be^9(d,n)B^{10}$, $E_d = 2.8$ MeV, was also used with a thick target. Both the 0.41- and the 1.43-MeV lines were measured, but the 1.43-MeV line could not be used to determine a lifetime because of the presence of the practically degenerate 1.43-MeV gamma ray from the 3.59-MeV level also populated in the reaction. Finally, the reaction $B^{10}(p,p')B^{10*}$, $E_p = 3.9$ MeV, was used with a carbon backing. Since the 3.59-MeV state is not produced at this bombarding energy, measurements could be made on the 1.43-MeV line without interference from the other gamma ray. All the measurements are summarized in Table II. In this table F_c is the value obtained after correction[7] for target thickness and departures from linearity of the stopping power curves. The average of the measured lifetimes is

$$\tau_{2.15} = (4.0 \pm 1.0) \times 10^{-12} \text{ sec}.$$

This result agrees with values obtained in the earlier experiments.[1,10] From the known branching ratios,[11] one obtains for the 0.41-MeV transition a lifetime 10 times longer than the theoretical value of Cohen and Kurath,[4] but this discrepancy can apparently be removed within the framework of their calculations.[12] It is interesting that this allowed ($M1$, $\Delta T = 1$) transition is actually relatively weak (0.06 Weisskopf units), although it has long been considered a good example of an allowed transition.[13] The observed strength of this transition is consistent with the failure to observe a beta branch from C^{10} to the 2.15-MeV state. This branch is less than 0.05% of all C^{10} decays.[2,14]

Table II. Summary of lifetime measurements on the 2.15-MeV state of B^{10}. The first five measurements were made on the 0.41-MeV gamma ray with the reaction $Be^9(He^3,d)B^{10*}$ at $E_{He^3} = 2.8$ MeV; the sixth measurement on the 0.41-MeV gamma ray with $Be^9(d,n)B^{10*}$ at $E_d = 2.8$ MeV; and the last one on the 1.43-MeV gamma ray with $B^{10}(p,p')B^{10*}$ at $E_p = 3.9$ MeV.

Stopping medium	Shift (keV)	Vacuum shift (keV)	F_m	F_c	τ (10^{-12} sec)
Be^a	0.60	6.6	0.091	0.110	4.2
Al	0.73	7.0	0.104	0.121	3.8
Al	0.71	7.0	0.101	0.118	4.0
Sc	0.75	7.0	0.107	0.125	5.3
Ni	0.46	7.0	0.066	0.076	3.1
Be^a	0.54	5.7	0.095	0.116	4.0
C	1.90	18.8	0.101	0.121	3.5
				Average	4.0 ± 1.0

^{a}Thick beryllium target.

Table III. Summary of lifetime measurements on the 3.59-MeV state of B^{10}. The measurements were made with the reaction $B^{10}(p,p')B^{10*}$ at $E_p = 5.0$ MeV on the two-escape peak of the 2.87-MeV gamma ray. The shifts were measured between $\theta = 30°$ and 150°.

Stopping medium	Shift (keV)	Vacuum shift (keV)	F_m	F_c	τ (10^{-13} sec)
C	32.0	39.6	0.81	0.79	1.29
W	26.9	39.6	0.68	0.68	1.35
				Average	1.33 ± 0.35

The 3.59-MeV level.—This level was produced with the reaction $B^{10}(p,p')B^{10*}$, $E_p = 5.0$ MeV, and Doppler shifts of the 2.87-MeV line (two-escape peak) were determined for carbon and tungsten backings and for vacuum. From Table III

$$\tau_{3.59} = (1.33 \pm 0.35) \times 10^{-13} \text{ sec}.$$

This value is in agreement with the previous measurements[5,6] of $(1.75 \pm 0.7) \times 10^{-13}$ and $(1.20 \pm 0.43) \times 10^{-13}$ sec. The partial widths of the transitions to the ground state and to the 0.72- and 2.15-MeV states are 7.5×10^{-4}, 3.5×10^{-3}, and 7.5×10^{-4} eV, respectively, as derived from the branching ratios.[11] These values are typical of $M1$, $\Delta T = 0$ widths or enhanced $E2$, $\Delta T = 0$ widths that are believed to be significant in these transitions.[6] The failure to detect[11] the transition to the 1.74-MeV level ($T = 1$) illustrates the suppression of $E2$, $\Delta T = 1$ transitions.[15] A detailed comparison of all these results with theoretical predictions, as well as other details, will be presented elsewhere.

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QUANTUM THEORY OF AN OPTICAL MASER*

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The theory of an optical maser due to Lamb[1-3] is generally accepted as giving a realistic account of laser oscillation. The laser radiation was described by means of classical electrodynamics while the atoms were treated quantum mechanically. In this way, phenomena such as frequency pulling, variation of intensity with cavity tuning, mode competition, etc., were successfully described. There has been considerable interest recently in a quantum theory of laser behavior. It is the purpose of this Letter to give an account of such a theory.

To simplify the presentation we consider only single-mode oscillation and ignore the effects of atomic motion and spatial variation of the cavity mode. We consider[4] the change in the density matrix for the radiation field which occurs due to the injection at time t_0 of a pumping atom in the upper state a of the two states a and b involved in the laser interaction. Working in the n representation this change is given by

$$\delta\rho_{n,n'}(t_0)=\rho_{n,n'}(t_0+T)-\rho_{n,n'}(t_0), \tag{1}$$

where T is a time which is long compared with the atomic lifetime, but short compared to the time characterizing the growth or decay of the laser radiation.

The states a and b of the atom are assumed to decay as in the Wigner-Weisskopf theory of radiation damping. For the state a, we introduce a group of states c, s where c is a level to which the atom decays with the emission of (nonlaser) radiation of type s. Similarly b decays to d, σ; the decay constants are denoted by γ_a and γ_b, respectively.

To obtain $\rho_{n,n'}(t_0+T)$ we must follow the time development of the combined atom-field system until the atom has decayed, and then trace over the states c, s and d, σ. We may obtain the rate of change of the density matrix due to many atoms, injected at random times t_0, by multiplying the $\delta\rho_{n,n'}$ resulting from one atom by the rate of injection r_a. To represent the effects of dissipation (finite cavity Q), we inject a different type of atom which is initially in the lower state b' and can make transitions to a higher state a'. These states are given very large damping constants in order to have a nonresonant dissipation mechanism.

Combining the effects of interaction with the active and dissipative atoms we are led to the following equations of motion for the laser radiation (written in the Schrödinger picture):

$$\dot\rho_{n,n'}=-i(n-n')\Omega\rho_{n,n'}-[(n+1)R_{n,n'}+(n'+1)R_{n',n}{}^*]\rho_{n,n'}+[R_{n-1,n'-1}+R_{n'-1,n-1}{}^*]$$
$$\times(nn')^{1/2}\rho_{n-1,n'-1}-\tfrac{1}{2}(\nu/Q)(n+n')\rho_{n,n'}+(\nu/Q)[(n+1)(n'+1)]^{1/2}\rho_{n+1,n'+1}, \tag{2}$$