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Delayed particles from the beta decay of ^{11}Be

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Heavy particles emitted in the β decay of ^{11}Be were studied by forming the activity in the ^{9}Be$(t,p)^{11}$Be reaction at $E_t = 3.4$ MeV and measuring the radiations by means of a helium-jet system together with Si and NaI(Tl) detectors. α particles and corresponding ^{7}Li recoil ions were observed both in singles and in coincidence with 478-keV γ rays. It is deduced that ^{11}Be branches 2.9 ± 0.4 % by β-ray emission to the 9875-keV $J^\pi = 3/2^+$ excited state of ^{11}B, which then decays by α emission 87.4 ± 1.2 % to the ground state of ^{7}Li and 12.6 ± 1.2 % to the 478-keV excited state. The experimental log*ft* of 4.04 ± 0.08 for the ^{11}Be β branch to the 9875-keV state agrees with a theoretical estimate of $\simeq$4.0, and the ambiguity in an earlier result is thereby resolved. The α branching intensity to the ^{7}Li 478-keV state is in reasonable agreement with a theoretical estimate.

[RADIOACTIVITY ^{11}Be; measured delayed α, ^{7}Li, and α-γ coin; He-jet system, Si and NaI(Tl) detectors; deduced β and α decay branches; compared with theory.]

I. INTRODUCTION

The parity of the ground state of ^{11}Be is even whereas odd would have been most simply expected. In 1971 the history of the experimental establishment of this situation was traced in a paper[1] in which studies into the β decay of ^{11}Be that had begun in 1959[2] were continued. It was previously shown[3] that, in fact, the even parity and the spin $(J = \frac{1}{2})$ of ^{11}Be could be easily understood semiempirically from consideration of the systematics of the excitation energies at which, *de facto*, the $2s_{1/2}$- orbital first shows up in nuclei of the $1p$ shell. More recently[4] it has been shown that this surprising situation can be understood quantitatively on the basis of direct computation of level structures using variational calculations with deformed wave functions through the projected Hartree-Fock method. This "absolute" approach to the relative energies of the odd-parity and even-parity states does not quite succeed in predicting that the ground state of ^{11}Be should have even parity but it comes within 3 MeV or so of this and since the calculation is manifestly incomplete in certain respects we may assume that no qualitative mystery remains.

In parallel with the absolute studies just referred to, calculations have been carried out on nuclei of mixed $1p$-shell and $(2s, 1d)$-shell configurations using the method of effective particle-particle and particle-hole interactions[5]. This permits the prediction of detailed level schemes and also of dynamical properties such as β-decay and γ-decay rates. In particular, Teeters and Kurath[6] have treated $A = 11$ and have compared the resultant predictions as to the β decay of ^{11}Be with experiment[1]. So far as the level scheme of the positive parity states of $A = 11$ goes, the quality of agreement between theory and experiment is excellent for the first dozen or so states which are all for which comparison is possible. As always, sharper tests come from the dynamical quantities. The higher-energy β transitions from ^{11}Be are first forbidden. Of them, that to the $J^\pi = \frac{5}{2}^-$ state at 4445 keV is unique first forbidden and so susceptible to relatively simple theoretical analysis. It was a feature of the earlier work[1] that this transition is unusually slow ($\log f_1 t > 10.9$) and it is pleasing that the theoretical wave functions[6] agree with this ($\log f_1 t \simeq 10.5$) although the experimental strength is at least a factor of 2 or so lower still. (This transition has now been found with a strength approximately equal to the earlier established limit.[7]) Nonunique first-forbidden β-ray transitions are extremely complicated in that they depend on a number of nuclear matrix elements. Nevertheless, the theoretical and experimental strengths[7] of the transitions in question (to the $J^\pi = \frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{3}{2}^-$ states at 0, 2125, and 5021 keV, respectively) agree within a factor of 2. This leaves the allowed β decays which are to the $J^\pi = \frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{3}{2}^+$ states at 6793, 7978, and 9875 keV, respectively. (Throughout this paper we designate the state on which our work centers as the 9875-keV state, following the most recent literature[8]; however, as we discuss below, its apparent excitation energy and width will depend on how it is observed.) It is interesting that, experimentally, the first two of these three allowed transitions are quite slow—$\log ft \simeq 5.9$ and 5.6, respectively. Theoretically, cancellations indeed arise but are not quite adequate in the first case, which has the theoretical value $\log ft \simeq 4.9$, and are a little too great in the second case, which has the theoretical value $\log ft \simeq 5.9-6.5$. On the basis of the earlier experimental work[1] the situation with respect to the third of these important allowed transitions was ambiguous; the preferred result was $\log ft = 4.03 \pm 0.15$ which compared very well with the theoretical[6] $\log ft \simeq 4.0$ but there was an alternative solution of $\log ft = 3.33 \pm 0.15$ which would have disagreed strongly with theory. It was a primary objective of the present work to resolve this ambiguity; resolution in favor of the previously preferred solution would set the seal on a basically satisfactory theoretical account of this interesting mixed-shell situation in $A = 11$.

The reason for the ambiguity to which we have just referred is as follows: experimentally the β decay of ^{11}Be was observed to one or more α-emitting states of ^{11}B by detecting the α particles following the breakup of that state, or states, to ^{7}Li. Because the sources were thick to the emitted α particles there was considerable uncertainty in the shape analysis of the continuum-type spectrum as to just what states of ^{11}B were involved. The states at 9875, 10 260, and 10 380 keV were all thought to be possible candidates. The reasonable assumption was adopted that it was only the $J^{\pi} = \frac{3}{2}^{+}$ 9875-keV state that was populated in the β decay, although this was not backed up by firm experimental proof. Furthermore, there was no experimental indication of the branching ratio for α decay as between the ground state of ^{7}Li and its first excited state at 478 keV. Coincidences between α particles and γ rays of 478 keV were searched for, but none were detected and it was concluded that fewer than 5% of the observed particles were in coincidence with γ rays. Because of the degradation of α-particle energy in the source the upper limit on α-γ coincidences was not considered to be very meaningful since the sought-for events might have been at low enough α energy to occur below the detector bias. The alternate value of $\log ft = 3.33$ assumed the inelasticity favored by the analysis of Cusson[9] of the reaction ^{7}Li$(\alpha, \alpha)^{7}$Li through the state of ^{11}B in question; that is to say, the branching ratio as between the ground and first-excited states of ^{7}Li for deexcitation of the state in ^{11}B by alpha-particle emission. This latter case thus involved the assumption that the α branching was mainly to the 478-keV excited state but that the corresponding strong α-γ coincidence yield was not being observed because of instrumental reasons.

The present experiment was designed to resolve the ambiguity by detecting the emission of the α particles from a source, thin compared with their range and, furthermore, in such a way that coincidence with the γ rays of 478 keV following α decay to the first excited state of ^{7}Li, if such there be, could be put in evidence.

II. EXPERIMENTAL METHODS

As noted above it was not possible in previous experiments[1], involving the activation of thin Be targets in the ^{9}Be$(t, p)^{11}$Be reaction, to produce sources thin enough to resolve the line structure of the particle spectrum coming from the β decay of ^{11}Be. This was due to the penetration of the ^{11}Be recoil nuclei into the target backing thereby making the source effectively thick with respect to the emitted particles which are of energies < 1 MeV. In order to solve this problem, as well as to provide an instrument that could be used in a general program of radioisotope studies at the Brookhaven MP Tandem Van de Graaff, a helium-jet system[10] was designed and fabricated. It was already known that with such a device sources can be made very thin due to the small amount of material deposited and the negligible penetration of the active nuclei into the collecting surface because of the transport and deposition of these nuclei at sonic velocities.

The application of the He-jet system to the ^{11}Be problem is shown schematically in Fig. 1. Tritons of 3.4 MeV from the 3.5-MV Van de Graaff enter a 3-cm long gas cell through a 1.0-mg/cm^2 thick Ni window. At a distance of 5 mm from the window a 0.5-mg/cm^2 thick Be foil target is held in a frame. Recoil ^{11}Be nuclei from the foil are stopped in a helium plus aerosol mixture supplied by a bubbler system. A 50-50 mixture of water and isopentyl alcohol is used in the bubbler and the cell is operated at a pressure of ~1.1 atm, sufficient to stop the most energetic ^{11}Be recoils in less than 2.5 cm. The activity is swept out of the cell, through a 1.1-mm i.d. capillary, to the source-deposition and tape-transport unit located in the control room.

After the activity is deposited in a spot of ~1.5 mm diam the tape is moved on command from a timer programmer. One of the control options is to move the spot the full distance of 30.5 cm in 0.2 s, bringing it to the detector position. However, in the present case ^{8}Li ($T_{1/2} = 0.84$ s) is produced in the ^{9}Be$(t, \alpha)^{8}$Li reaction and since ^{8}Li emits a broad spectrum of α particles it is necessary to wait for the nearly complete decay of this activity before measuring the delayed particles from the ^{11}Be activity ($T_{1/2} = 13.8$ s). As a means of increasing the time-integrated counting effici-

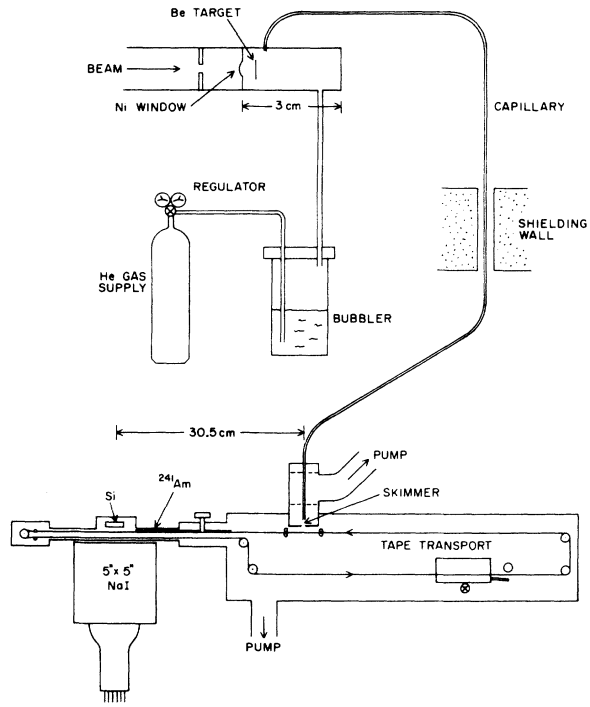

FIG. 1. Schematic diagram of the helium-jet system, including a source-deposition and tape-transport unit, as applied to the study of delayed particles from the β decay of ^{11}Be.

ency another option built into the control circuit is to move the tape 15.2 cm each time, i.e., just halfway to the detector[11]. Thus, while a given source is being counted at the detectors the next one is in a stand-by position for decay of the ^{8}Li, and the one after that is being deposited at the jet. For a cycle time of 14 s the ^{8}Li decays in the intermediate position by more than 16 half-lives. This scheme also has the advantage of depositing only half as much aerosol material on a given spot as one would have for a cycle of 28 s if the tape were moved the full distance and if a wait of 14 s were to be followed by a 14-s counting period.

At the detector position a removable brass box holds a standard Si detector so as to measure delayed particles from the spot of activity. For most of the work the detector was 31 μm thick and 8 mm in diameter. Its surface was 9 mm from the tape. For energy calibration of the detector a 0.1 μC source of ^{241}Am, emitting α particles of 5486 keV, is mounted on a frame which allows it to be moved directly in front of the detector. On the opposite side of the tape a standard 12.5 cm $\times$12.5 cm NaI(Tl) γ-ray detector is located. The overall source-to-crystal distance was 2.3 cm. All of the electronic components, including amplifiers, coincidence circuitry, and pulse-height analyzer, were of standard design.

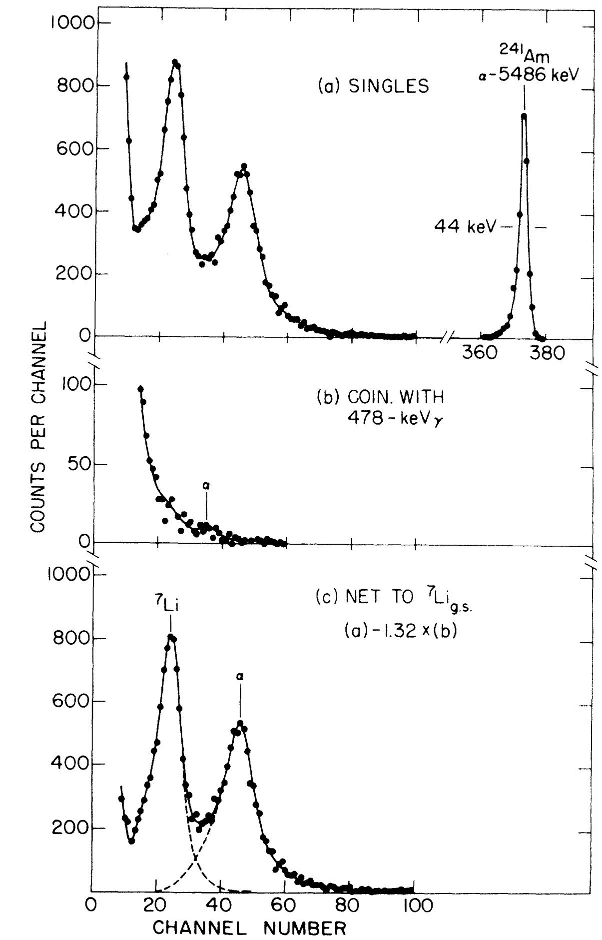

FIG. 2. Curve (a): singles spectrum of particles measured in a 31-μ-thick Si detector following the β decay of ^{11}Be, with the addition of an α energy calibration line from an ^{241}Am source. Curve (b): particles in coincidence with γ rays detected in the 12.5 cm$\times$ 12.5 cm NaI(Tl) crystal gated with a window centered at $E_\gamma = 478$ keV. Curve (c): net spectrum of particles corresponding to the α decay to the ^{7}Li ground state as obtained from curves (a) and (b) with appropriate normalization. The peak energies agree with the expected 770 keV for the α and 440 keV for the ^{7}Li due to the breakup of the ^{11}B 9875-keV state to the ^{7}Li ground state.

III. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 2(a) shows the charged-particle spectrum observed in the Si counter. This was a 50-min run at a triton beam current of 140 nA using the 14-s cycle as described above. A crude check on the decay of the spectrum, made by the multiscaling technique, gave a half-life of 15.0 ± 1.5 s, thus verifying that the particles were associated with the 13.8-s ^{11}Be activity. The two prominent peaks in Fig. 2(a) around channel numbers 45 and 25 correspond, respectively, to the α particles leading to the ground state of ^{7}Li following the breakup of the 9875-keV state of ^{11}B and to the ^{7}Li recoils associated with that same breakup. However, some α branching to the 478-keV excited state of ^{7}Li must be anticipated. This can be put in evidence through the charged-particle spectrum observed in coincidence with γ rays of 478 keV; this is shown in Fig. 2(b), a run of 9 h duration. Appropriate subtraction of curve (b) from curve (a) gives curve (c) which then represents the decay to the ground state of ^{7}Li alone. In this subtraction the normalization factor of 1.32 was obtained from a combination of factors representing the absolute photo-peak efficiency of the NaI(Tl) detector for 478-keV γ rays, corrections for γ-ray absorption, and the relative integrated beam charges for the runs of curves (a) and (b). The error in the normalization factor is estimated to be small compared with other errors in the final results.

In the analysis of the net spectrum of Fig. 2(c) the dashed lines were obtained by assuming similar shapes for the high-energy edges of the ^{7}Li and α-particle peaks. Net areas under the two peaks were equal to within 5% and this gives us confidence in the procedure by which curve (b) was subtracted from curve (a).

It is evident from Figs. 2(a) and 2(b) that some, although small, branching takes place from the 9875-keV state of ^{11}Be to the first excited 478-keV state of ^{7}Li. This is clearly demonstrated by the γ rays observed in coincidence with the charged particle spectrum of Fig. 2(a); this is shown in Fig. 3, where a clear peak at $E_\gamma = 485 \pm 10$ keV is seen. The α-particle branching ratio to the first excited state of ^{7}Li derived from Fig. 2(b) and similar data is 11.0%; that derived from Fig. 3 is 14.2%; we quote (12.6 ± 1.2)%. The previously measured upper limit[1] on α-γ coincidences is not in conflict with the present result, in view of the considerable uncertainties in that work[1] due to source thickness effects, as noted earlier.

It is immediately clear that the 1971 assumption[1] of essentially 100% branching to the ground state of ^{7}Li is correct and that the inelasticity suggested by Cusson[9] as discussed in the Introduction, namely an approximately 3:1 branching in favor of the 478-keV excited state, does not obtain. It remains to extract the β-branching ratio of ^{11}Be decay to the 9875-keV state which we do by comparing the data already presented with observations, simultaneously made, of the 2125-keV γ ray which follows ^{11}Be decay directly to that state of ^{11}B plus various cascades as revealed in the earlier work[1] and shown in Fig. 4. From these comparisons we derive a β branch to the $J^\pi = \frac{3}{2}^+$ state of ^{11}B at 9875 keV of (2.9 ± 0.4)% which is to be compared with the earlier[1] figure of (3.0 ± 0.7)% (the latter assuming 100% branching of the 9875-keV state to the ground state of ^{7}Li, but the former incorporating our present quantitative knowledge as to that branch).

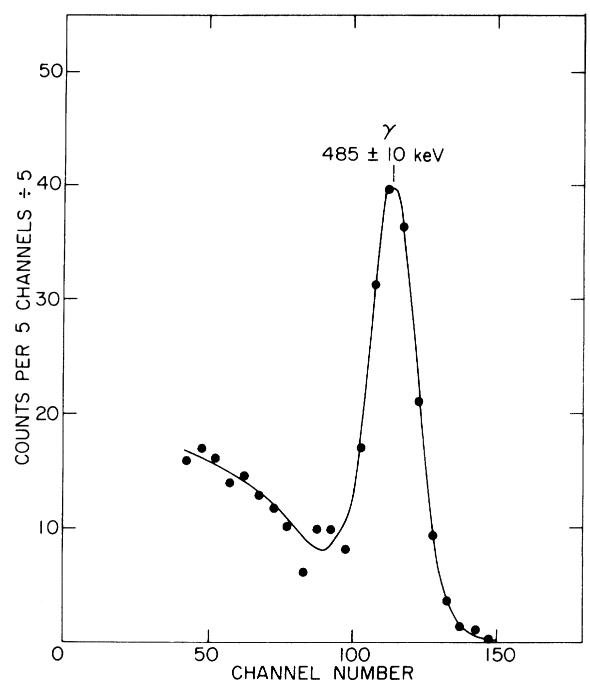

FIG. 3. Spectrum of γ rays from the NaI(Tl) detector in coincidence with heavy particles from the decay of ^{11}Be.

The particle energies expected for the decay of the 9875-keV state of ^{11}B to the ^{7}Li ground state (total decay energy 1210 keV) are 770 keV for the α particle and 440 keV for the corresponding ^{7}Li recoil ion. For the decay branch to the 478-keV excited state of ^{7}Li the expected particle energies are 466 and 266 keV for the α and ^{7}Li, respectively. We have so far simply asserted the identification of the α-particle and ^{7}Li groups of Fig. 2. Our experiment was not designed for accurate charged-particle energy measurement; we made, for example, no careful measurement of the dead-layer effect in the Si counter such as would have been essential had we wished to report accurate energies, nor did we make careful resolution measurements such as would have been essential had we wished to report accurate widths. However, using the manufacturer's data as to the counter dead layer and making appropriate allowance for pulse-height defect we find, from data such as in Fig. 2(c), an acceptable ratio of α particle to ^{7}Li energies, namely 1.73 ± 0.03 against the expected 1.75. Expectation as to the observed energies of the charged particle groups is more difficult to discuss because of the considerable Coulomb barrier

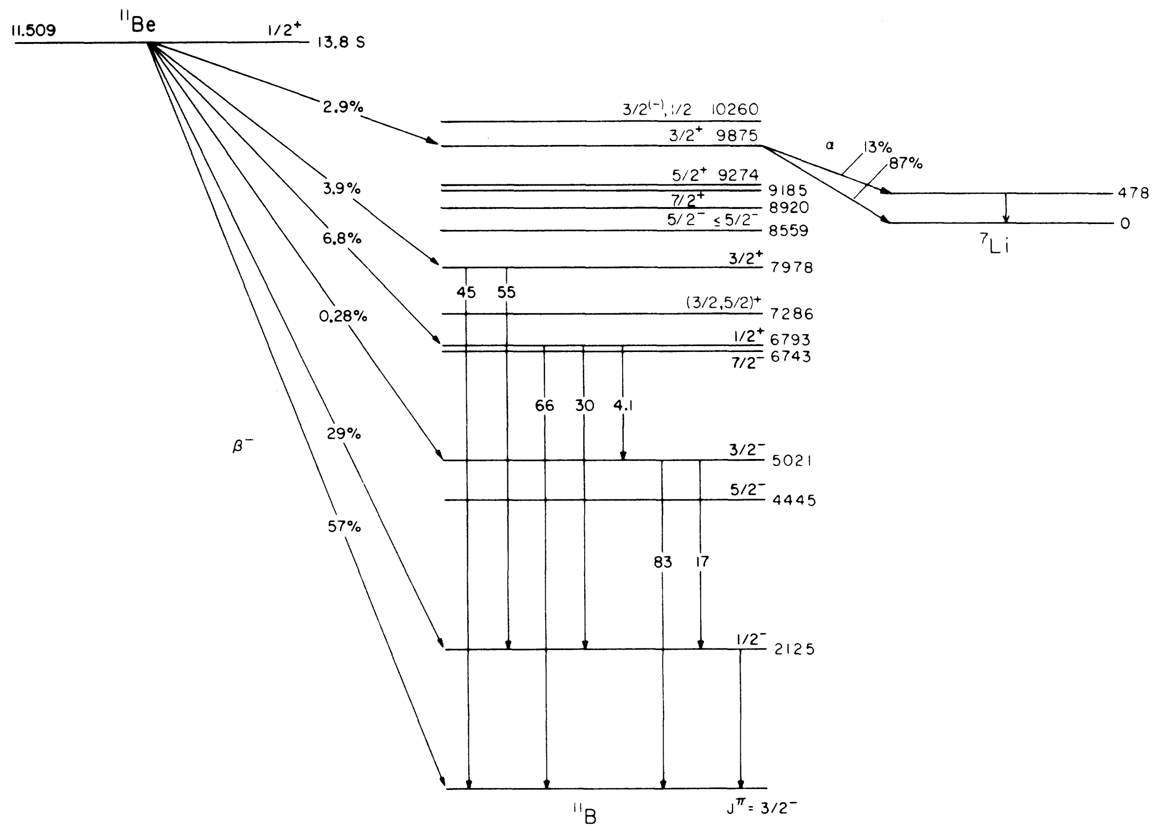

FIG. 4. Proposed decay scheme of ^{11}Be. New information from the present work includes the β-ray branching intensity to the 9875-keV state and α branching ratios to the ground and 478-keV states of ^{7}Li.

effects obtaining in the only charged-particle reactions accurately studied, namely ^{7}Li(α,α)^{7}Li and ^{7}Li(α,α')^{7}Li*, and also because of the shift to be expected in our present experiment due to the significant change of the phase-space factor in the β-particle feeding across the width of the ^{11}B state in question. However, the observed energy of the α-particle group as seen in Fig. 2(c) agreed with expectation to within the 20 keV uncertainty in that expectation because of the factors just enumerated. The energy of the α-particle peak in Fig. 2(b) agrees, also within 20 keV, with that expected for breakup to the 478-keV excited state of ^{7}Li. In this case the corresponding ^{7}Li recoil particles of 266 keV are not clearly separated from noise and other background at low pulse heights, although there seems to be a slight shoulder in the curve of Fig. 2(b) around channel 20 that might be associated with these ^{7}Li ions.

Similar uncertainties to those just discussed inhibit a close discussion of the observed widths of the α-particle and ^{7}Li groups of Fig. 2. Several tests were made in which the source deposition time, and thus the amount of aerosol, was varied over a range of values, and other Si detectors of various thicknesses were used to record the spectrum. All such tests suggest that the shapes of the α and ^{7}Li peaks in Fig. 2 are genuinely characteristic of the activity and were not caused by source thickness or other instrumental effects. Evidently the instrumental full width at half maximum of 44 keV obtained for the ^{241}Am α-particle calibration peak in Fig. 2(a) contributes negligibly to the observed widths of the peaks in the ^{11}Be spectrum. Figure 5 shows a profile of the feeding of the 9875-keV state of ^{11}B as deduced from data such as those of Fig. 2(c) both with and without allowance for the weighting by the β-decay phase space factor. For the former case we find a full width at half maximum of 324 keV and for the latter 334 keV (both with an uncertainty of about 20 keV). These widths are considerably greater than that of 130± 30 keV in the literature[8] but this difference cannot be interpreted significantly in view of our remarks about the very different type of reaction involved (and also our lack of direct measurement of Si counter performance at the energies in question). In curve b of Fig. 5 no significance should be attached to the upturn at energies > 1.7 MeV since the statistical accuracy was not sufficient

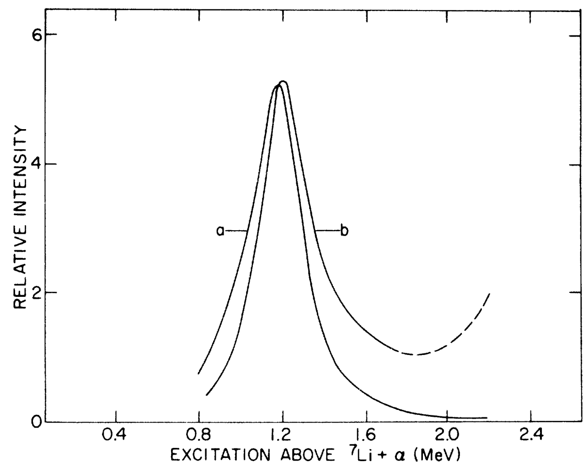

Fig. 5. Profile of the feeding of the 9875-keV state of ^{11}B. Curve (a) without allowance for weighting by the β-decay phase space factor; curve (b) includes the phase space factor.

to establish the shape in this region experimentally.

The present data exclude the significant involvement, in ^{11}Be β decay, of any state of ^{11}B above that at 9875 keV, a possibility which had to be left open in the earlier work[1].

IV. DISCUSSION

The proposed revision of the ^{11}Be decay scheme is shown in Fig. 4. Our present experiment resolves the ambiguity left by the earlier work[1], as discussed above, in favor of the assumption made at that time. We can now quote for ^{11}Be β decay to the $J^{\pi}=\frac{3}{2}^{+}$ state of ^{11}B at 9875 keV; $\log ft = 4.04 \pm 0.08$. The mass and lifetime input data behind this number are from the literature[8]. The effective f value derives from integration across the profile of the 9875-keV state (as currently determined from Fig. 5). As remarked in the Introduction this number agrees very well with the theoretical value[6] of $\log ft \simeq 4.0$ which strengthens our confidence in the theoretical account of the even-parity states of the $A=11$ system.

To obtain a theoretical estimate of the α branching of the 9875-keV state of ^{11}B to the ^{7}Li ground and 478-keV states we first use the wave functions of Teeters and Kurath[6] for the decaying $\frac{3}{2}^{+}$ state and of Cohen and Kurath[12] for the final ^{7}Li states to compute four particle spectroscopic factors. The spectroscopic factor is computed[13] for a $p^3(sd)$ configuration projected onto internal S states for the group; i.e., in the harmonic oscillator model the ^{7}Li-α relative wave function has a node structure given by $2N_{\alpha} + L_{\alpha} = 5$. The results of the calculation are given in Table I. To provide a basis

TABLE I. Four particle spectroscopic factors.

$J^{\pi}_{n}(^{11}B)$	E_{exc} (keV)	$J^{\pi}(^{7}Li)$	L_{α}	S_{α}
$\frac{3}{2}^{+}_{1}$	7978	$\frac{3}{2}^{-}$	1	0.115
			3	0.011
		$\frac{1}{2}^{-}$	1	0.284
$\frac{3}{2}^{+}_{2}$	9875	$\frac{3}{2}^{-}$	1	0.0093
			3	0.071
		$\frac{1}{2}^{-}$	1	0.030
$\frac{5}{2}^{+}_{1}$	7286	$\frac{3}{2}^{-}$	1	0.402
			3	0.028
		$\frac{1}{2}^{-}$	3	0.046

for comparison the spectroscopic factors for the first $\frac{3}{2}^{+}$ and $\frac{5}{2}^{+}$ levels of ^{11}B are also given. The spectroscopic factors involving the $\frac{3}{2}^{+}_{2}$ level are small and thus subject to greater uncertainties than the larger spectroscopic factors.

The effect of barrier penetration has been estimated as a ratio of Coulomb penetrabilities calculated for a radius of 4 fm. For $L_{\alpha}=1$ the ratio of penetrabilities for excited state to ground state decay is not very sensitive to the value chosen for the radius and has a value ~ 0.11. The ratio $L_{\alpha}=3$ to $L_{\alpha}=1$ penetrabilities for the ground state is ~ 0.014. Although this ratio depends more strongly on the radius the $L_{\alpha}=3$ penetrability is so small that it has little effect on the calculated branch to the 478-keV state. Another estimate for the barrier penetration was made by solving the Schrödinger equation for a complex energy eigenvalue using a standard Woods-Saxon potential with a radius $R=3.23$ fm and a diffuseness $a=0.72$ fm. The depth of the well was varied to obtain the imaginary part of the eigenvalue (a width) as a function of the real part. For $L_{\alpha}=1$ the ratio of the "single particle" widths for the excited state to ground state decay was 0.11 in excellent agreement with the estimate from Coulomb penetrabilities.

For the 9875-keV level the spectroscopic factor ($L_{\alpha}=1$) for the decay of the excited state of ^{7}Li is favored over the ground state by a factor of ~3.0. With the barrier penetration factor included the branch to the 478-keV state is expected to be ~24% of the total. This can be said to be in fair agreement with the observed 13% branch.

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