A source of 3.85-MeV gamma rays for testing Ge(Li) detectors

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Mono-energetic 3.85-MeV gamma rays, and lower energy gamma rays, have been produced in a source consisting of an intimate mixture of ^{10}B and PuO_2. Levels in ^{13}C are excited by the $^{10}B(\alpha,p\gamma)^{13}C$ reaction and the Doppler broadening of gamma rays from the 3.85-MeV level is attenuated, since its lifetime is long compared with the slowing-down time of ^{13}C ions in the source material. When observed with a particular 15-cm^3 Ge(Li) detector, the 3.85-MeV full-energy peak had a width of 4.5 keV (FWHM), consistent with no Doppler broadening. The measured energy of the gamma ray from the third excited state of ^{13}C is 3854 $\pm$ 1 keV. The branching ratios $I(3854 \to 3090)/I(3854 \to 0) = 2.5 \pm 0.5 \times 10^{-2}$ and $I(3854 \to 3685)/I(3854 \to 0) = 0.55 \pm 0.03$ have been determined using the source.

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A source of mono-energetic 3.85-MeV gamma rays, and lower energy gamma rays, has been produced by using $^{10}B(\alpha,p\gamma)^{13}C$ reactions occurring in an intimate mixture of ^{10}B and PuO_2. The $^{10}B(\alpha,p)^{13}C$ reaction has a Q value of 4.07 MeV and the first three excited states at 3.09, 3.68, and 3.85 MeV in ^{13}C (Ajzenberg-Selove and Lauritsen 1959) are populated when ^{239}Pu alpha particles are used. The 3.85-MeV level decays to the ground state (64% branch) giving rise to a 3.85-MeV gamma ray.

Although the excited ^{13}C nuclei are produced with high recoil velocity ($v/c \simeq 1\%$), the Doppler broadening of the gamma rays from the 3.85-MeV level is almost completely attenuated since the lifetime, $\tau_m = 7.5^{+3}_{-2}$ ps (Simpson *et al.* 1962, see also Fisher *et al.* 1967[2]), is long compared with the slowing-down time of the recoils in the solid source material. Thus nearly all the decays from the 3.85-MeV level occur from nuclei at rest. The 3.85-MeV gamma ray from the Pu^{10}B source, observed with a 15-cm^3 Ge(Li) detector, has a width of 4.5 keV (FWHM), which is the system resolution.

In comparison, $^9Be(\alpha,n)^{12}C$ reactions in a mixture of Pu and Be have often been used to produce a convenient fast neutron and high energy gamma-ray source. The 4.43-MeV gamma rays from ^{12}C, however, are Doppler broadened to a width of $\sim$1% because the alpha-particle direction is undefined and the recoiling $^{12}C^*$ ions have not sufficient time to slow down before emitting the gamma rays. The large Doppler broadening makes the Pu^{9}Be source unsuitable for testing Ge(Li) detectors.

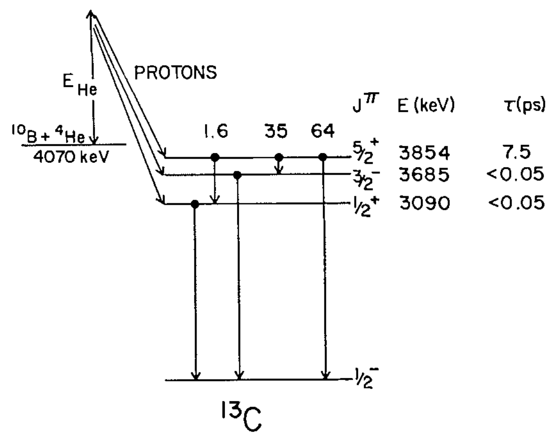

FIG. 1. The low-lying levels of ^{13}C showing the main gamma-ray decays. The energies shown are from the present investigation. The lifetimes are from Simpson *et al.* (1962) and Fisher *et al.* (1967).

Figure 1 shows the first three excited states of ^{13}C and indicates how the levels are populated by the $^{10}B(\alpha,p\gamma)^{13}C$ reaction. The main gamma-ray decay modes, the mean lifetimes, and the spin-parity values of the levels are shown. It is found with the Pu^{10}B source that the 3.85 and 3.68-MeV levels are fed most strongly. This is fortunate since the 3.09-MeV level gives rise to Doppler-broadened gamma rays. The $^{10}B(\alpha,n)^{13}N$ reaction, Q = 1.065 MeV, competes with the $^{10}B(\alpha,p)^{13}C$ reaction and fast neutrons are produced (Geiger and Jarvis 1962), but the former reaction is less probable.

The source contains 10 g of ^{10}B (>96%) powder and 3 g of $^{239}PuO_2$. The finely ground powders were mixed together and compacted

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[2]$\tau(3.85)$ = 8 ps is quoted.

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into a cylindrical pellet 2.29 cm in diameter by 1.68 cm long (Norlock 1968). The pellet was sintered and encapsulated in a double-walled aluminium container. For the measurement reported here, the source was also surrounded by $\frac{1}{8}$ in. of lead and $\frac{1}{8}$ in. of copper to reduce the intensity of low energy pulses. The total intensity of 3.09, 3.68, and 3.86-MeV gamma rays was estimated to be approximately 1.1×10^5 γ/s, this intensity being shared in the ratios I(3.85 MeV):I(3.68 MeV):I(3.09 MeV) 1:2.9:0.43. The efficiency for producing these gamma rays is 1.6×10^{-5} gamma rays per alpha particle. From the data of Bonner *et al.* (1956), the value of the integrated cross section is 2.8×10^{-25} MeV$-$cm^2 for alpha particles up to 5 MeV assuming their differential cross-section measurement at 45° gives the average $d\sigma/d\Omega$ over 4π. Using this, the expected number of gamma rays per alpha particle is estimated to be about 1.7×10^{-5} γ/α. The agreement is better than one would expect, considering the crudeness of the estimates involved.

The neutron yield from neutron producing reactions was measured as 3×10^4 neutrons/s, which gives 4.4×10^{-6} neutrons per alpha. This can be compared with the value obtained by Geiger and Jarvis (1962), who obtained 5×10^{-6} neutrons/α using a Po–^{10}B source produced by a different preparation technique.

Sources using ^{241}Am as the alpha emitter have also been successfully made and produced a similar gamma-ray spectrum with approximately the same yield of gamma rays per alpha particle. One disadvantage is the presence of the intense 59-keV gamma-ray line from ^{241}Am.

Figure 2 is a spectrum obtained with a 15-cm^3 coaxially drifted Ge(Li) spectrometer fabricated at Chalk River by Malm and Fowler (1966, 1968). The 3.85-MeV line has a full width at half maximum (FWHM) of 4.5 keV.

The 3.68-MeV full-energy peak is interesting since its shape is complex, reflecting the two possible ways the 3.68-MeV level is populated. This level is fed either by the 169-keV cascade transition from the 3.85-MeV level or directly following proton emission as indicated in Fig. 1. This gives rise to a sharp component due to the 35% branch from the 3.85-MeV level and a Doppler-broadened component due to direct feeding of the 3.68-MeV level, which has a short lifetime ($\tau < 0.05$ ps (Fisher *et al.* 1967)). The importance of attenuating the Doppler broadening to produce a gamma-ray line suitable for testing Ge(Li) detectors is evident.

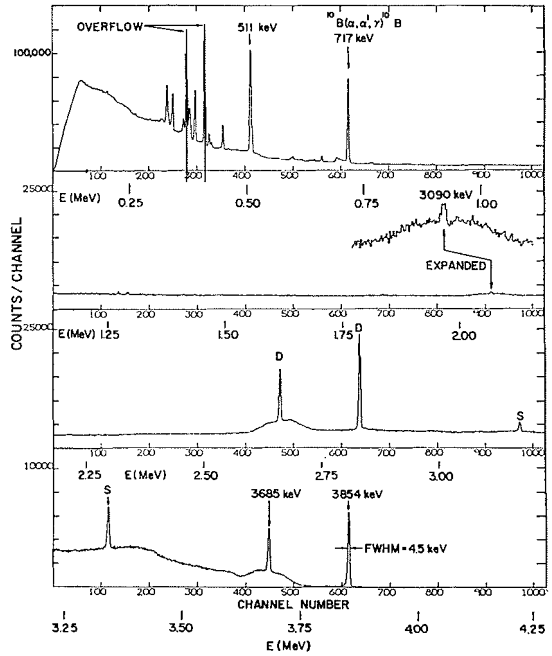

FIG. 2. A 4096-channel spectrum obtained with a 15-cm^3 Ge(Li) detector showing the 3.854 and 3.685 and 3.090-MeV gamma rays from the Pu^{10}B source. The 717-keV gamma ray from the ^{10}B(α,α′γ)^{10}B reaction is observed as well as the gamma rays from the reaction ^{10}B(α,pγ)^{13}C. The peaks labelled S and D are single and double escape peaks of the 3854-keV and 3685-keV gamma rays.

In Figure 2, the region around the energy of the double-escape peak of the 3090-keV transition has been expanded to show that a small component of the intensities (i.e. the small sharp peak) of this transition arises from cascade transitions from the 3854-keV level.

The branching ratios of the 3854-keV level have been measured by Pixley *et al.* (1960) who obtained $R_1 = I(3854 \rightarrow 3090)/I(3854 \rightarrow 0) = 9.3 \pm 2.0 \times 10^{-3}$ and $R_2 = I(3854 \rightarrow 3685)/I(3854 \rightarrow 0) = 0.32 \pm 0.07$. From the data in Fig. 2, and correcting for the weak branching of the 3685-keV level to the 3090-keV level (6×10^{-3}), it is found that $R_1 = 2.5 \pm 0.5 \times 10^{-2}$ and $R_2 = 0.55 \pm 0.03$. The error in R_1 includes an uncertainty of a factor of two in the 3685 → 3090 branching ratio. In the present measurements, the efficiency of the detector does not have to be known over a wide energy range, in contrast to previous determinations. Taking $\tau = 7.5$ ps for the lifetime of the 3854-keV level and the present branching ratio measurement, the enhancement of the 3854 → 3090 keV, E2 transition is 3.4 Wu.

The spectrum of gamma rays below 1.5 MeV is complex and arises from other nuclear reactions in the source and in the Ge(Li) detector as well as from the PuO_2 alpha-particle source. By comparing the observed spectrum with that obtained from a Pu^9Be source, identification of those gamma rays common to both could be made. Table I lists and identifies the origin of the lines above 250 keV observed from the $Pu^{10}B$ source. The only line with appreciable intensity which is present in the $Pu^{10}B$ source and not in the Pu^9Be source is the 717-keV gamma ray from the first excited state of ^{10}B excited in the $^{10}B(\alpha,\alpha'\gamma)^{10}B$ reaction. Several lines common to both spectra are due to inelastic neutron scattering in the Ge(Li) detector and were identified by their energy (Chasman *et al.* 1965).

Some applications of a $Pu^{10}B$ source are (1) testing the energy resolution of Ge(Li) detectors,

TABLE I

Gamma rays from $Pu^{10}B$ source

E_γ (keV)	Also in Pu^9Be spectrum	Remarks
269		
299	√	
313	√	
324		
334	√	^{239}Pu
347	√	
~370	√	Very weak
376	√	^{239}Pu
395	√	
415	√	^{239}Pu
425	√	
452	√	
511	√	Annihilation rad.
599	√	$^{74}Ge(n,n')$
661		
695	√	$^{72}Ge(n,n')$
717		$^{10}B(\alpha,\alpha')$
744		Very weak
767		Very weak
802		Very weak
837		$^{72}Ge(n,n')$, weak
844		$^{27}Al(n,n')$, weak
1016		$^{27}Al(n,n')$, weak
1044		$^{70}Ge(n,n')$, weak
1291		^{41}A background
1455		^{40}K background
3090		$^{10}B(\alpha,p\gamma)^{13}C$
3685		$^{10}B(\alpha,p\gamma)^{13}C$
3854		$^{10}B(\alpha,p\gamma)^{13}C$

(2) calibrating the response of detectors up to 3.85 MeV, and (3) calibrating the detector efficiency at 3.85 MeV. The source has been used to test the performance of a pair and escape-suppressed spectrometer (Alexander *et al.* 1968).

It is a considerable advantage to have a convenient source of mono-energetic gamma rays at 3.85 MeV to measure the energy resolution of Ge(Li) detectors. Charge collection efficiency in the detector and gain instabilities in the electronics are both percentage effects and therefore as the energy of the gamma ray is high, the quality of the Ge(Li) detector and its associated electronics are critically tested.

An accurate value for the energy of the 3.85-MeV full-energy peak may be obtained by comparing it with existing lower energy sources such as radiothorium ($E_\gamma = 2614.5$ keV), since the $E_\gamma - 2m_0c^2$ peak lies 1022 keV lower in energy. The energy we have measured is 3854 ± 1 keV and it should be possible to improve the accuracy by careful measurements. The 3.854-MeV line can then be used as an energy calibration in experiments involving high energy gamma rays.

Since the source of 3.85-MeV gamma rays is long lived, (half-life of $^{239}Pu = 2.4 \times 10^4$ years), the intensity of the gamma rays from the source remains fixed, assuming no physical changes occur in the source pellet. Once the intensities are calibrated for a fixed geometry, the source can be used to measure the efficiency of Ge(Li) detectors. The fact that the 3.85-MeV line is sharp increases the accuracy with which this can be done.

Previously, reactions induced by beams of particles from accelerators had to be used for testing and calibrating at energies greater than 2.75 MeV. Recently, ^{56}Co has been used as a calibration source up to 3.5 MeV for gamma-ray detectors (Barker and Conner 1967). ^{56}Co can be produced by the $^{56}Fe(p,n)^{56}Co$ reaction and has a half-life of 77.3 days. In many applications, the use of a $Pu^{10}B$ source could be more convenient and less expensive than using either reaction gamma rays or short-lived radio activities produced by accelerators. There is the possibility of using the $^{13}C(\alpha,n\gamma)^{16}O$ reaction in a similar source to produce mono-energetic 6.13-MeV gamma rays, since the $(\alpha,n\gamma)$ reaction is energetically possible using source alpha particles from radioactive sources and since the lifetime of the 6.13 MeV level in ^{16}O is 25 ± 2 ps (Alexander and Allen 1965).

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