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^{5}He ternary fission yields of ^{252}Cf and ^{235}U(n,f)

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The relative ^{4}He and ^{5}He ternary fission yields were determined from a careful analysis of the energy distribution of α spectra from a new measurement with a ^{252}Cf source and from published data on ^{252}Cf and ^{235}U(n,f). The kinetic energies of the ^{5}He and ^{4}He ternary particles were found to be approximately 11 and 16 MeV, respectively. ^{5}He particles contribute 10–20 % to the total alpha yield with the remainder originating from ^{4}He accompanied fission.

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Since the discovery of particle-accompanied fission by Alvarez in 1943 [1], the study of ternary spontaneous fission has been of much interest. This process is a rare one as it occurs about once in $\sim$500 spontaneous fission events. A helium atom is present in over 90% of all ternary fission events. In the case of ^{252}Cf, the relative yields of ^{4}He, ^{6}He, and ^{8}He have been measured to be 10^{4}, 393(60), and 25(5), respectively, with an absolute ternary ^{4}He yield of 3.82×10^{-3} [2,3]. The contribution of ^{5}He to the ternary helium fission yield is difficult to determine because of its breakup into the $\alpha+n$ channel with a half-life of 8×10^{-22} sec. The Q value and neutron energy associated with this process are 0.957 MeV and 4.0(3) MeV, respectively [4], e.g., $\langle E_{^{5}\mathrm{He}}\rangle=\langle E_{\alpha}\rangle+3\,(\mathrm{MeV})$. The presence of ^{5}He in the fission of ^{252}Cf was originally demonstrated by Cheifetz *et al.* [4], who measured the correlation between neutrons and α particles at 0° and 180°, and reported that approximately 11(2)% of the ternary α particles result from ^{5}He breakup. The average ^{5}He kinetic energy was measured to be 15.4 MeV, i.e., the associated α energy is 12.4(9) MeV [4]. The latter value should be contrasted with the *average* α energy of 15.7 MeV reported in Ref. [2].

In principle, an indirect estimate of the ternary ^{5}He fission yield can be derived from a calculation of the mean extra energy cost (E_c) required to emit a ternary particle [5]. This results in a $\sim$5% contribution to the total ternary α fission yield for ^{235}U(n,f). However, small changes in E_c impact the predicted yields significantly, and this approach can only serve as a rough guide [5,6]. A third, and possibly more reliable, estimate of the ternary ^{5}He yield comes from an attempt to understand the shape of the energy spectrum of the ternary α particles [6]. Remarkably, the energy spectra of *all* ternary particles are Gaussian (this observation is independent of the excitation energy of the fissioning system), except that of the α particles. In this case there is a low-energy tail which can be attributed to α particles originating from ^{5}He emission. The contributions from the breakup of the ^{6}He and ^{8}He can be neglected in this analysis since these processes will be less than 1%. In Refs. [6,7] this low-energy tail was established to correspond to a mean energy of $\sim$6 MeV and the associated yield was estimated to be 15.5% of the total α ternary particles for ^{252}Cf [7].

The results of Refs. [4–7] discussed above leave a number of open questions. The mean ^{5}He energy of $\sim$6 MeV extracted from the low-energy tail of the α spectra [6,7] differs significantly from the only direct measurement of 12.4 MeV [4]. Furthermore, the ^{5}He yield extracted from this tail, 15.5% [6,7], is barely consistent with the yield of 11% reported by Cheifetz *et al.* [4]. Additional uncertainties regarding the experimental situation come from the fact that the role of the neutron multiplicity was not considered in Ref. [4]. This multiplicity was determined later by Han Hongyin *et al.* [8]. Thus, it appeared worthwhile to revisit the issue. Hereafter, we present the results of a new analysis of α spectra from ternary fission. Data from a new measurement with a ^{252}Cf source as well as published data on ^{252}Cf and ^{235}U(n,f) have been analyzed. A consistent picture of the ^{5}He ternary fission yield appears to emerge.

The energy spectrum of α particles emitted in the spontaneous fission of ^{252}Cf was measured by using two ΔE-E Si detector telescopes installed at the center of the Gammasphere array [9] at Argonne National Laboratory. The ^{252}Cf source with a strength of the order of 30 μCi was sandwiched between two Au foils, each 19 mg/cm^{2} in thickness. These foils were used to stop the fission fragments so that problems associated with the Doppler shift of prompt fission γ rays were minimized. In addition, on each side of the source a 0.84 mg/cm^{2} Mylar foil was added to provide full absorption of α particles emitted in the radioactive decay of ^{252}Cf. This approach limited potential radiation damage to the Si detectors. Each ΔE-E telescope included one ΔE detector (of 15 μm thickness and 10×10 mm^{2} area) and one

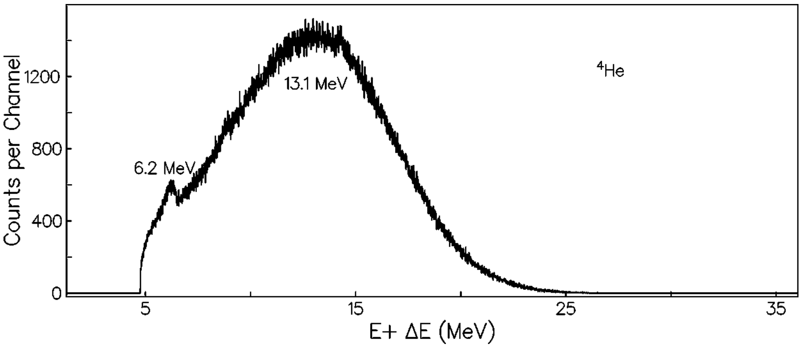

FIG. 1. The α energy distribution measurement in the ΔE-E Si strip detector with the correction of the energy loss through the Mylar.

strip detector. The strip detectors were 400 μm and 60×60 mm^2 in thickness and area, respectively and had 29 strips. The 2 mm strips were connected in pairs so that, for each strip detector, 15 signals could be obtained from 14 pairs and one single strip. This implied a 4 mm position resolution along the x axes of each strip detector, whereas there was no position resolution along the y axes. With the ΔE and E (strip) telescopes installed at distances of 6 and 40 mm from the source, respectively, the condition was fulfilled that all light charged particles detected by either of the strip detectors passed through the corresponding ΔE detector and gave ΔE signals. With the position resolution of the strip detector (4 mm wide strips and 1 mm resolution along each strip), the ΔE-E telescopes provided unambiguous Z and A identification for all the light charged particles of interest. The energy calibration of the telescopes was performed with ^{224}Ra and ^{228}Th radioactive sources and with the 6.2 MeV alpha peak from the decay of ^{252}Cf deposited on the surface of the Au foil (see below). This calibration automatically takes the presence of the Mylar foil into account. A software correction was applied for the energy loss in the Au foil. The latter was checked as an internal energy calibration was also obtained by using the average energy of 15.7 MeV of the broad ternary α peak as reported by Mutterer *et al.* [2].

The typical α spectrum from the present measurement is given in Fig. 1. As expected, a broad energy distribution was recorded. The small peak visible at 6.2 MeV comes from the α decay of ^{252}Cf. Its presence in the data is due to the accidental deposition of a small amount of source material on the surface of the Au foil. The observed mean energy of 13.1 MeV agrees well with the expected energy of 15.7 MeV [2], once the energy loss through the Au fold is taken into account. The α spectrum for the subsequent analysis, i.e., the spectrum corrected for energy loss and with the 6.2 MeV contamination removed, is shown in Fig. 2. No reliable data could be obtained below 9.0 MeV, the low energy cutoff of the measurement.

In order to disentangle the respective contributions of ^{5}He and ^{4}He to the alpha particle spectrum observed with the ^{252}Cf source, attempts were made to fit the data with two Gaussian functions. Two methods were used. In the first of these, the energy of the ^{5}He particles was kept fixed at the energy reported by Cheifetz *et al.* in Ref. [4], while all other parameters defining the two Gaussians were varied. In particular, in this approach the ^{4}He energy is a free parameter. The results are tabulated in the top rows of Table I and the quality of the fit can be judged from Fig. 2. The extracted yield for ternary ^{5}He emission is ~35% of the total α yield,

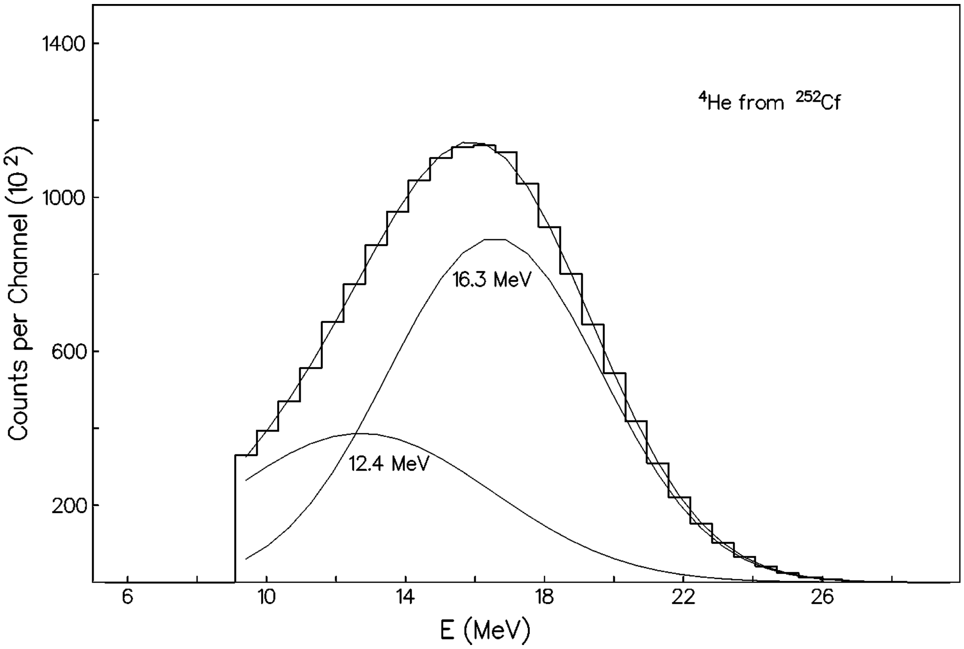

FIG. 2. The α energy distribution with the correction for the 6.2 MeV α decay and the energy loss through the Au foil.

TABLE I. Yield ratios extracted for the ternary ^{4}He and ^{5}He particles of ^{252}Cf in the present work. $\langle E_{^5\mathrm{He}}\rangle = \langle E_\alpha\rangle - Q + \langle E_n\rangle = \langle E_\alpha\rangle + 3$ (MeV).

	Ternary particle	$\langle E\rangle$ MeV	FWHM MeV	Yield ratio	χ^2/DOF
Method 1	^{4}He	$16.3^{+0.3}_{-0.3}$	$7.3^{-0.3}_{+0.1}$	$65.2^{-2.8}_{+2.8}$	0.065
	^{5}He	15.4[3]	$8.9^{-1.2}_{+1.3}$	$34.8^{+1.4}_{-1.8}$	
Method 2	^{4}He	$16.0^{+1.0}_{-0.5}$	$7.4^{-0.8}_{+0.4}$	$79.6^{-24.4}_{+12.0}$	0.068
	^{5}He	$13.9^{+1.1}_{-4.3}$	$7.4^{-0.8}_{+0.4}$	$20.4^{+21.9}_{-2.9}$	

TABLE II. Yield ratios extracted by using the method 2 for the ternary ^{4}He and ^{5}He particles from the α spectrum of ^{252}Cf [7] and ^{235}U(n,f) [6,10,11].

Nuclei	Ternary particle	$\langle E\rangle$ MeV	FWHM MeV	Yield ratio	χ^2/DOF
^{252}Cf	^{4}He	$16.0^{+0.3}_{-0.3}$	$9.7^{-0.3}_{+0.3}$	$78.9^{-4.1}_{+4.9}$	0.91
	^{5}He	$11.0^{+0.5}_{-1.0}$	$9.7^{-0.3}_{+0.3}$	$21.1^{+3.9}_{-4.5}$	
^{235}U	^{4}He	$15.8^{+0.4}_{-0.3}$	$9.1^{-0.3}_{+0.4}$	$87.7^{-5.4}_{+4.7}$	0.56
	^{5}He	$11.6^{+0.9}_{-1.4}$	$9.1^{-0.3}_{+0.4}$	$12.3^{+5.2}_{-4.5}$	

i.e., this process occurs roughly half as often as ternary fission involving ^{4}He. Hence, the ^{5}He intensity derived in this way is larger than that reported in Ref. [4] (11%). However, in the fitting process, the derived FWHM values for the two He isotopes are quite different. This result is at variance with the experimental observation [6] that, for ternary particles of the same charge, the widths of the energy distributions are independent of mass. Hence, this difference in the FWHM values is not reasonable. Furthermore, when method 1 is applied to the data of Loveland for ^{252}Cf [7] and of D'hondt *et al.* and Caitucoli *et al.* for ^{235}U(n,f) [10,11], where the α spectra extend to very low energy (~ 0.1 MeV), the derived ternary ^{5}He yields become much larger than the corresponding ^{4}He yields. Also, these fits result in very different widths distributions (FWHM) for the two He isotopes. These observations lead one to question the results of Ref. [4], and in particular the reported ^{5}He energy.

A second approach to the fitting procedure was then employed with the only requirement that the widths of the two Gaussian distributions be the same, hereby fulfilling the requirement derived from Ref. [6]. This approach neglects the fact that the breakup of ^{5}He contributes a small, additional spread in momentum to the distribution imparted by the ternary fission process. The results given in the lower part of Table I are presented under the assumption that ^{4}He ternary fission dominates the alpha particle spectra, i.e., that ^{5}He is associated with the component with the smaller intensity. The results of the fit are also displayed in the top part of Fig. 3. Under these fitting conditions, the results differ markedly from those obtained with method 1. The energies associated with the two particles are now quite different, even though the centroid of the low-energy Gaussian is determined with less than desirable accuracy. This is due to the low-energy cutoff of the present α spectra. This cutoff also impacts severely the accuracy with which the intensity of the two components can be determined. In other words, the low-energy cutoff of the present α spectra makes the errors large in the yields and energies as shown in Table I. These findings prompted us to then concentrate on the data of Loveland [7] and the results of a fit (with the same constraints) of the spectrum measured by this author are presented in Table II and the middle part of Fig. 3. Within the errors, the results of the two data sets are in satisfactory agreement. Furthermore, the effect of the low-energy cutoff in the new data was examined by arbitrarily truncating the data by Loveland [6]. It was found that the changes in the values of the fitting parameters remained within errors for cutoff energies varying from ~ 1 to 9.5 MeV; i.e., the values presented in Table II are quite stable and reliable. Thus, this analysis indicates that the average energies of the alpha particles associated with ^{4}He and ^{5}He differ by 3-6 MeV and that at least 80% of the total alpha yield is associated with ^{4}He originating from ternary

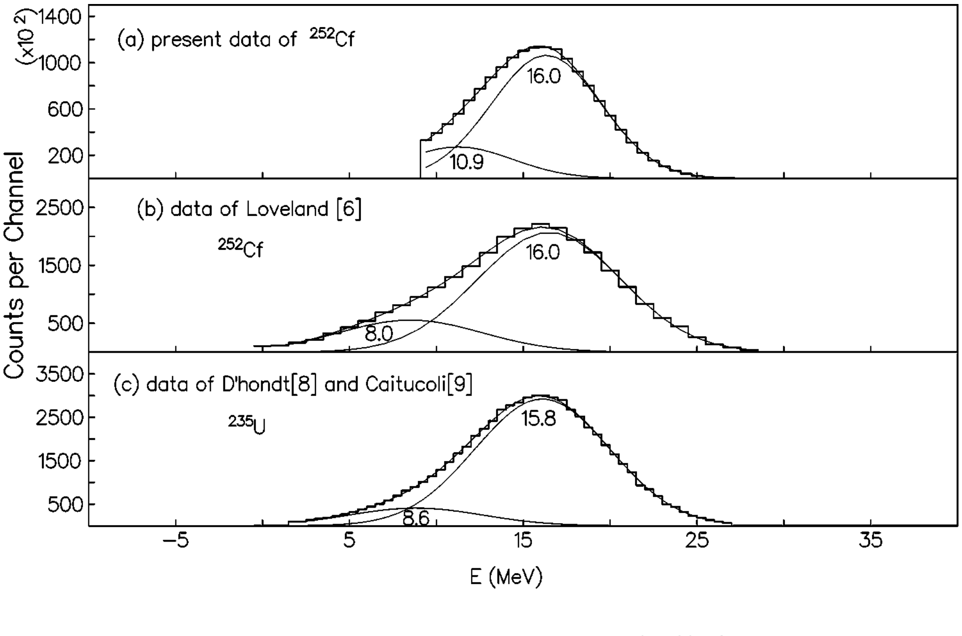

FIG. 3. Two Gaussian fits with the only condition of the same FWHMs for two Gaussians. The spectrum (a) is from the present work. (b) and (c) are the alpha spectra from data of Loveland for ^{252}Cf [7] and from data for ^{235}U(n,f) of D'hondt *et al.* [10] and Caitucoli *et al.* [11], respectively.

fission. Finally, a similar analysis of the ^{235}U(n,f) ternary fission data of Refs. [10] and [11] was also carried out. The results form the last entries to Table II. As can be seen the results are similar to those obtained for ^{252}Cf and a satisfactory understanding of the data appears to emerge. The agreement between the various data sets can be regarded as satisfactory, considering that the comparisons cover data obtained with independent instruments under different experimental conditions. The present yield of ternary ^{5}He for ^{235}U(n,f) is $12.3^{+5.2}_{-4.5}$% of that of ternary ^{4}He, which can be compared with the $\sim$5.0% predicted in the yield versus E_c plot by Halpern [5]. The present yield of $12.3^{+5.2}_{-4.5}$% is still within the range of the yield values which are expected from a simple statistical model of Halpern [5]. Considering the uncertainty in the calculated E_c values and the errors in the measured yields of the ternary particles (see Fig. 5 in Ref. [5]) the new results are consistent with that of Halpern's prediction. The previous ^{4}He yields are the summed yield of ^{5}He and ^{4}He. Relative yields for other ternary particles have to be increased a little, when this correction is taken into account.

To summarize, the direct yields of ^{4}He and ^{5}He particles from ternary spontaneous fission (SF) of ^{252}Cf have been obtained from a data set measured recently at Gammasphere. While the total α energy distribution cannot be fitted well with a single Gaussian distribution, it can be reproduced satisfactorily by assuming the presence of two components in the spectrum associated with ^{4}He and ^{5}He ternary fission, respectively. A consistent description of the present ^{252}Cf data as well as of the data of Ref. [7] for ^{252}Cf and of Refs. [10,11] for ^{235}U(n,f) was achieved. In all cases the energy of ^{5}He is determined to be around 11 MeV while the corresponding energy for ^{4}He is 16 MeV. 80–90 % of the total yield can be assigned the ternary fission accompanied by a ^{4}He particle. The remaining 10–20 % of the alpha yield is then assigned the breakup of ^{5}He.

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