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^{136}Xe(n,2n)^{135}Xe cross section between 9 and 15 MeV

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The cross section of the reaction ^{136}Xe(n,2n)^{135}Xe to both the ground state and the 526.6 keV isomeric states of ^{135}Xe was measured between 9.0 and 14.9 MeV. These data are important to guide evaluations and theoretical calculations aimed at estimating the importance of neutron-induced background effects in searches for neutrinoless double-β decay of ^{136}Xe.

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Among the three currently operating large-scale searches for the neutrinoless double-β ($0\nu\beta\beta$) decay [1–3], two of them use ^{136}Xe as the target medium. Very recently, the KamLAND-Zen [1] and EXO [2] collaborations reported lower limits for the half-life time $T_{1/2}$ of ^{136}Xe, from which an upper bound on the effective Majorana neutrino mass can be deduced. Although these experiments are mounted underground, muon-induced spallation neutrons are of concern, because they potentially could cause γ-ray events that are indistinguishable from those of interest at 2458 keV, the Q value for $0\nu\beta\beta$ of ^{136}Xe.

The ^{136}Xe(n,2n)^{135}Xe reaction ($Q = -8.079$ MeV) is of special interest, because the (n,2n) cross section for nuclei with large $(N\text{-}Z)/A$ ratios are known to be very large (up to 2000 mb). The reaction feeds either the isomeric $11/2^-$ state of ^{135}Xe at 526.6 keV, which decays with $T_{1/2} =$ 15.3 min to the $3/2^+$ ground state, or to the ^{135}Xe ground state directly, which in turn β decays to ^{135}Cs with $T_{1/2} = 9.14$ h [4].

Although there are not any deexcitation γ rays originating from ^{135}Xe and ^{135}Cs which directly interfere with the region of interest for $0\nu\beta\beta$, Compton scattering of γ rays with energies above about 2500 keV can create signals at 2458 keV if the Compton scattered γ rays escape the detection. Furthermore, the neutrons from the reaction ^{136}Xe(n,2n)^{135}Xe can capture on ^{136}Xe, producing the radioactive nuclide ^{137}Xe ($Q = 4.036$ MeV), which in turn β decays with $T_{1/2} =$ 3.82 min to ^{137}Cs, resulting in a variety of deexcitation γ rays, including the one at 2474.8 keV from the decay of ^{137}Xe. Given the 1.67% energy resolution of the EXO detector, this γ ray could produce a single-site event which would be indistinguishable from a potential $0\nu\beta\beta$ signal, if accompanying γ rays escape the detection. The ^{137}Xe levels at 2444.0 and 2452.4 keV do not decay directly to the ground state and therefore, are of less concern for EXO, because they should to be recognized as multisite events. However, the 2463.3 keV γ ray originating from the decay of the 3736.7 keV state in ^{137}Cs could be a potential problem for the EXO detector, again if accompanying γ rays are not detected. The KamLAND-Zen detector's energy resolution is about 4.2% in the energy region of interest. Therefore, three additional levels in ^{137}Xe can potentially contribute to events in the energy region of interest, if accompanying deexcitation γ rays escape. The excitation energies of these levels are 2422.7, 2474.8, and 2490.4 keV. On the other hand, the overburden and the active shielding of the KamLAND-Zen detector is more effective than those of the EXO detector, making the former less sensitive to spallation neutron-induced γ-ray events.

The ^{136}Xe(n,2n)^{135}Xe and ^{136}Xe(n,2n)^{135}Xe^m reaction cross sections were measured between 9 and 14.9 MeV using the activation technique [5,6]. Previous cross-section data do not exist below $E_n = 14$ MeV. The ^{2}H(d,n)^{3}He reaction initiated with a pulsed deuteron beam was used to produce quasimonoenergetic neutrons between 9.0 and 14.5 MeV. At 14.9 MeV the ^{3}H(d,n)^{4}He reaction was employed. A titanium sphere [7] of 10 mm outer diameter and 0.2 mm wall thickness, loaded to about 250 atm (725 mg) with ^{136}Xe (isotopically enriched to 99.9%) was positioned 2.5 cm from the end of a deuterium gas cell (see Fig. 1 of Ref. [8]). The deuterium gas pressure was adjusted to keep the neutron energy spread below $\pm$200 keV. For the 14.9 MeV measurements the deuterium gas cell was replaced by a tritiated target assembly, consisting of a 2 Ci tritiated titanium target with copper backing (see Fig. 1). As described in Ref. [8], a liquid scintillator based neutron monitor detector in combination with a Monte Carlo simulation was used to determine the neutron flux at the position of the titanium sphere. In addition, at selected neutron energies, thin Al and Au foils were attached to the front and back faces of the titanium sphere in order to check via the activation technique on the neutron fluence obtained from the neutron monitor detector. Both methods agreed within the combined uncertainty of the activation cross sections and the neutron detection efficiency of about 5%. The irradiation time was 45 min. The HPGe detector, the data-acquisition system, and the data analysis used to determine the yield of the 249.8 keV γ ray ($I_\gamma = 0.90$) from the decay of the first excited state of ^{135}Cs, and the 526.6 keV γ ray ($I_\gamma = 0.804$) from the decay of the ^{135}Xe isomeric state were identical to those referred to in Ref. [8]. In Figs. 2(a) and 2(b) typical γ-ray spectra obtained at $E_n = 12.9$ MeV are shown. In addition to the strong lines of interest at 526.6 keV in Fig. 2(a) and 249.8 keV in Fig. 2(b), in the latter figure the weaker ^{135}Cs

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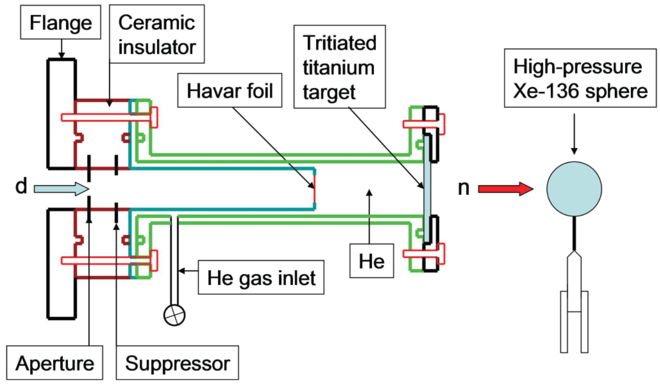

FIG. 1. (Color online) Schematic of experimental setup used for neutron activation measurements at 14.9 MeV, consisting of a tritiated titanium target for the $^{3}H(d,n)^{4}He$ reaction and a high-pressure ^{136}Xe cell.

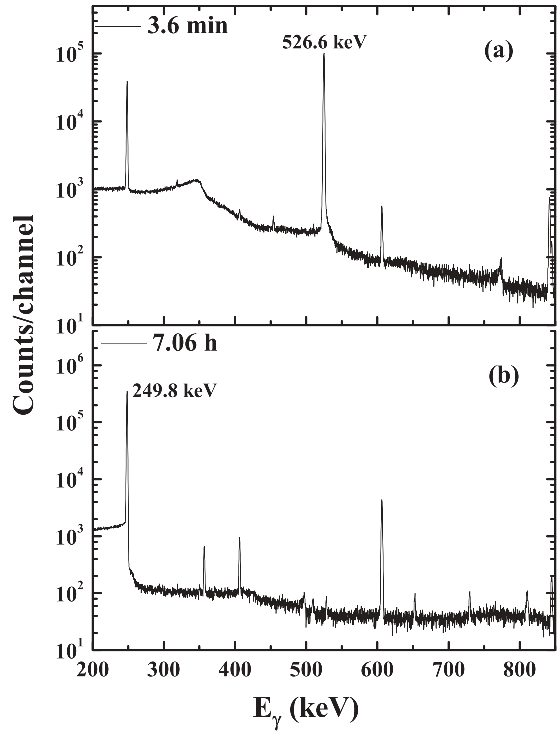

FIG. 2. Partial γ-ray spectra of $^{135}Xe^{m}$ and ^{135}Cs obtained with a 60% efficient HPGe detector at $E_n = 12.9$ MeV, (a) 3.6 min, and (b) 7 h after neutron activation of ^{136}Xe. The lines of interest are 526.6 keV in (a) and 249.8 keV in (b).

γ-ray transitions at 358.4 keV ($I_\gamma = 0.0022$), 408.0 keV ($I_\gamma = 0.0036$), 608.2 keV ($I_\gamma = 0.029$), 654.4 keV ($I_\gamma = 0.0005$), 731.5 keV ($I_\gamma = 0.0006$), and 812.6 keV ($I_\gamma = 0.0007$) are also indicated [4]. Figure 3(a) shows the decay curve for the 249.8 keV γ-ray line measured at $E_n = 14.5$ MeV, and Fig. 3(b) gives the decay curve for the 526.6 keV line obtained after irradiation with $E_n = 11.9$ MeV neutrons. As can be seen, there is good agreement between the measured and the literature half-life times. Runs were also taken with an identical but empty titanium sphere to check for background events in the relevant energy region, which turned out to be completely negligible.

Our cross-section results obtained for the $^{136}Xe(n,2n)^{135}Xe$ and $^{136}Xe(n,2n)^{135}Xe^{m}$ reactions are shown by the triangular symbols in Figs. 4(a) and 4(b), respectively. Table I gives the numerical values. The error bars include counting statistics, uncertainties in the neutron fluence determination, the uncertainty in the amount of ^{136}Xe, and finally the uncertainty in the absolute HPGe efficiency. All these uncertainties were added in quadrature. It is interesting to point out that about 50% of the $^{136}Xe(n,2n)^{135}Xe$ cross section is provided by the isomeric state transition. The previous data [9–11] are shown in Fig. 4 as well, indicating fairly good agreement for both transitions with the results found in the present work. The two curves shown in Fig. 4(a) are the ENDF/B-VII.1 (solid curve) [12] and TENDL-2011 (dashed curve) [13] predictions, which were fitted to the previous data. The present data are in very good agreement with the current evaluations.

We conclude by pointing out that the $^{136}Xe(n,2n)^{135}Xe$ cross section is very large, peaking at close to 2000 mb at about $E_n = 15$ MeV. Therefore, experiments searching for the $0\nu\beta\beta$ of ^{136}Xe must be operated very deep underground where the muon-induced spallation neutron flux will not cause a problem. Of course, the required depth depends on details of the experimental technique and shielding arrangement used in those searches. The present data also provide important guidance to theoreticians trying to calculate the $^{136}Xe(n,2n)^{135}Xe$ cross section at higher energies.

TABLE I. Summary of cross-section results. $\Delta\sigma_1$ = statistical uncertainty. $\Delta\sigma_2$ = total uncertainty.

E_n (MeV)	$^{136}Xe(n,2n)^{135}Xe$			$^{136}Xe(n,2n)^{135}Xe^{m}$		
	σ (mb)	$\Delta\sigma_1$	$\Delta\sigma_2$	σ (mb)	$\Delta\sigma_1$	$\Delta\sigma_2$
8.96 ± 0.09	265.09	1.50	12.12	21.71	0.33	0.99
9.46 ± 0.13	558.29	0.94	20.60	198.13	2.10	7.24
9.96 ± 0.13	746.97	1.10	24.90	290.01	3.40	10.48
10.95 ± 0.20	1344.73	1.3	40.01	552.44	3.21	17.64
11.94 ± 0.21	1630.47	3.98	44.50	763.13	2.72	20.26
12.94 ± 0.20	1751.34	3.20	40.95	864.13	2.33	22.04
13.75 ± 0.20	1813.19	2.22	33.11	870.56	1.51	15.05
14.45 ± 0.19	1794.11	2.45	40.02	848.85	1.78	18.70
14.85 ± 0.05	1727.85	2.66	53.15	845.42	1.81	25.58

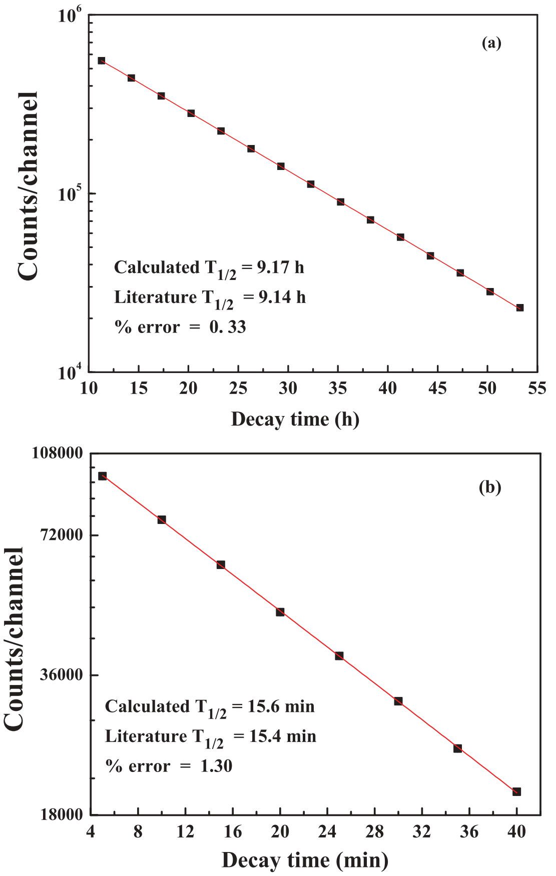

FIG. 3. (Color online) Decay curves for (a) the 249.8 keV γ-ray line of ^{135}Cs measured at $E_n = 14.5$ MeV and (b) the 526.6 keV line of ^{135}Xe obtained after irradiation with $E_n = 11.9$ MeV neutrons.

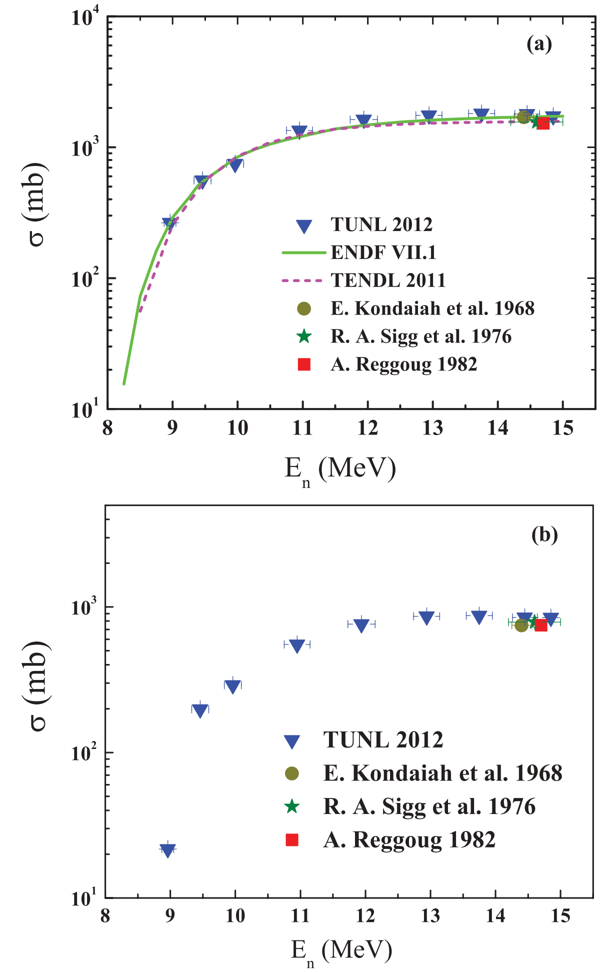

FIG. 4. (Color online) Cross-section results obtained for (a) the ^{136}Xe$(n,2n)^{135}$Xe reaction and (b) the ^{136}Xe$(n,2n)^{135}$Xe^m reaction are shown by the triangular symbols in comparison to previous measurements near 14.5 MeV, and recent evaluations [only for (a)].

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