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Search for ^{136}Xe Resonance Neutron Capture

R. L. Macklin

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SEARCH FOR ^{136}Xe RESONANCE NEUTRON CAPTURE

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SEARCH FOR ^{136}Xe RESONANCE NEUTRON CAPTURE

ABSTRACT

Evidence for neutron capture in ^{136}Xe at 2154-eV and 18.4-keV resonances is presented and quantified in terms of limits on Breit-Wigner single level parameters. Assuming the radiation width, 32 meV, found at the 18.4-keV resonance for all the reported resonances at higher energies, the Maxwellian average capture cross section is calculated for a range of stellar interior temperatures T. For kT=30 keV only 0.72 mb is found. Only one third of this comes from the resonances above 18.4 keV so an overall uncertainty at kT=30 keV of ±0.11 mb at the 68% probability level seems reasonable. Four resonances in ^{134}Xe were also found.

1. INTRODUCTION

Xe-136 with 82 neutrons in a closed shell is the heaviest xenon isotope. Its neutron binding energy, 4.025 MeV, is exceptionally low, leading to the expectation that its average neutron capture cross section may also be very small, enhancing its survivability in nucleosynthetic stellar environments. The next lightest xenon isotope ^{135}Xe decays too rapidly (half-lives of 1/4 h and 9h) for ^{136}Xe to participate significantly in the s-process[1] where neutrons are added at an average interval of tens of years. Only in galactic nucleosynthesis scenarios where the material must subsequently survive an s-process environment in secondary stars is the ^{136}Xe neutron capture probability likely to be significant. The 8.9% abundance of terrestrial ^{136}Xe can arise from the beta decay chain following r-process nucleosynthesis.

An earlier study[2] has identified 35 resonances between 18 keV and 500 keV. The work reported here suggests an additional weak resonance at 2.154 keV and estimates the average capture at stellar interior temperatures from kT=5 to 100 keV.

2. NEUTRON CAPTURE EXPERIMENT

A sample of high purity enriched xenon ^{136}Xe (93.6%) was used for the capture measurements. It was contained under pressure in a stainless steel cylinder with 0.12-mm walls which fitted into the Oak Ridge Electron Linear Accelerator (ORELA) pulsed neutron beam at the 40-m capture facility described earlier[3] and more recently illustrated.[4] The collimated neutron beam irradiated 2.72 g of the enriched xenon gas. Matching runs with the gas cell empty were made to allow subtraction of the many neutron resonance peaks due to constituents of the stainless steel. Prompt capture gamma rays were detected by C_6F_6 liquid scintillators at either side of the sample outside the neutron beam.

Pulse height and neutron time-of-flight data were recorded for computer processing to capture yield vs neutron energy as described earlier.[3] Calibration was done by the saturated resonance method using the 4.9-eV resonance of gold.[5] The accelerator ran 233 hours at 400 pulses per second of 24 ns duration giving 11 kW average electron power into the neutron producing target and moderator assembly. Usable capture data were collected from neutron energy 1 keV up to 25 keV.

3. RESONANCE ANALYSIS

Most if not all of the resonances previously identified[2] have been assigned as p-wave, $J=1/2^-$ and contribute negligibly to the laboratory thermal cross section. The direct capture process is probably responsible for most of the measured capture cross section (0.26 ± 0.02) mb at kT=0.025 eV.[6]

Thus the present data have been searched for possible resonances in the form of peaks with widths dominated by Doppler broadening and our experimental resolution. The strongest capture peak was found at 2154 eV and would normally be identified with the dominant isotope in the sample, ^{136}Xe. Because of the expectation of weak average capture

by this closed shell nucleus, additional evidence was sought. The transmission data[2] included natural xenon wherein the ^{136}Xe abundance is only 8.9%. Comparison of transmission dips near 2154 eV did not show the reduced dip area expected for a ^{136}Xe resonance. The authors[2] note the possibility that another of the stable isotopes of xenon might provide an obscuring resonance at that energy. As the capture gamma-ray data were accumulated in four pulse-height bins, and the boundary between the last two was at 4.6 MeV, it was possible to infer the isotopic assignment based on the available neutron binding energy as seen in Fig. 1.

The capture data were fitted to ^{136}Xe resonance parameters by least-squares adjustment[7] as shown in Fig. 2. The 2154 eV peak area corresponds to a capture kernel $g\Gamma_\gamma\Gamma_n/\Gamma$=30.1 meV with a statistical standard deviation of only 0.3 meV. Overall systematic uncertainties are estimated at 1.5 meV. The corresponding neutron width is thus about 250 times smaller than the smallest reported from the transmission study,[2] (8 ± 3) eV. The Doppler broadening of 2.2 eV FWHM and experimental resolution function of 3.6 eV FWHM would obscure a total resonance width less than 0.5 eV. The kernel sets a minimum total width at 0.12 eV. The same data were rescaled to effective ^{134}Xe capture cross section and a fit was attempted as shown in Fig. 3. Only the 2186-eV peak could be well fitted with ^{134}Xe parameters, giving a kernel of (188 ± 10) meV. Other ^{134}Xe resonances and their capture kernels were found at 6.315 keV (385 ± 19) meV, 7.260 keV (201 ± 14) meV, and 9.383 keV (385 ± 20) meV.

The first resonance reported[2] for ^{136}Xe near 18.3 keV with a neutron width of 25 eV was not seen clearly in the capture data as shown in Fig. 4. The radiation width found by least squares fitting was (32 ± 9) meV. The observed peak width is primarily due to the experimental resolution function, 50 eV FWHM. The nearby background was simultaneously fitted and an inverse correlation coefficient (-0.65) was found.

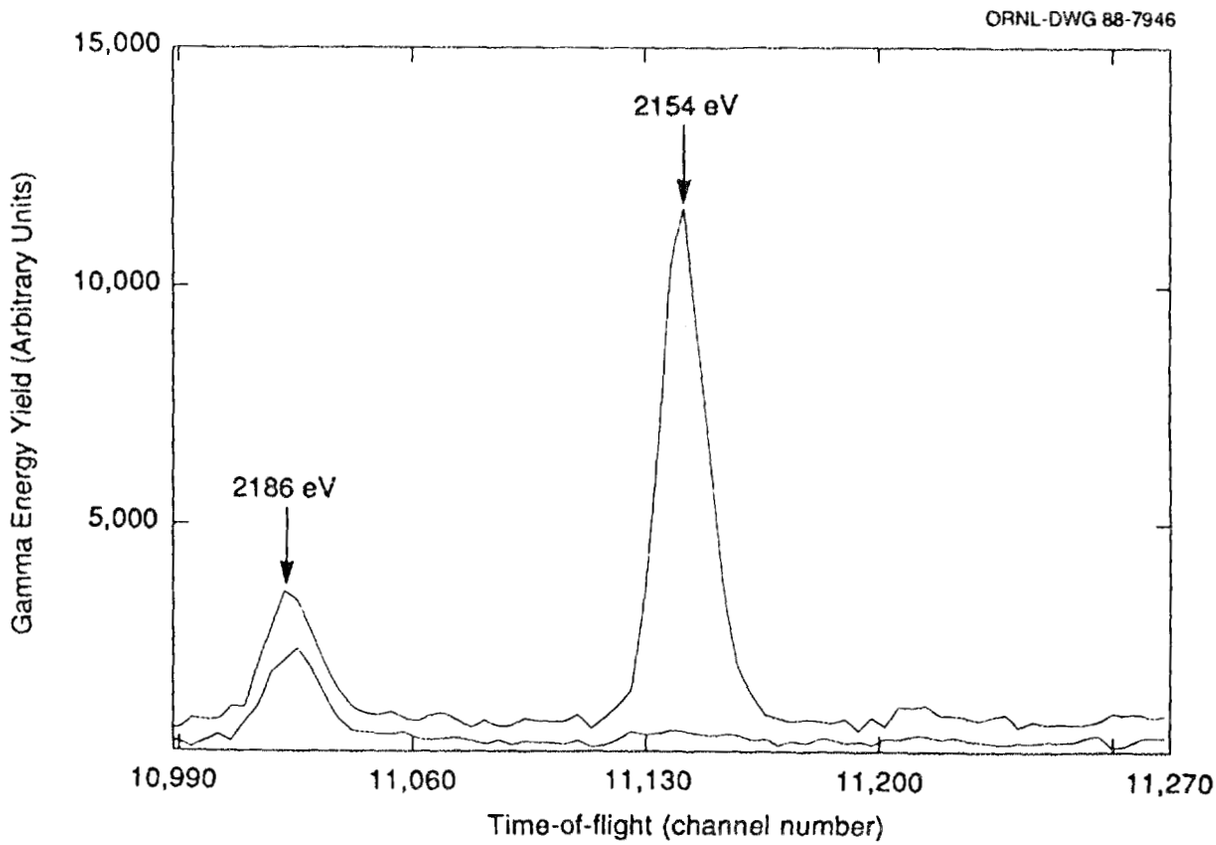

Figure 1. Weighted pulse height groups versus neutron time-of-flight. The upper curve includes pulse heights from 1.5 MeV to 4.6 MeV, and the lower curve includes pulses above 4.6 MeV. The behavior of the peaks is consistent with the one at 2186 eV being due to ^{134}Xe with its 6.45 MeV neutron binding energy and the one at 2154 eV being due to ^{136}Xe with its low 4.025 MeV neutron binding energy.

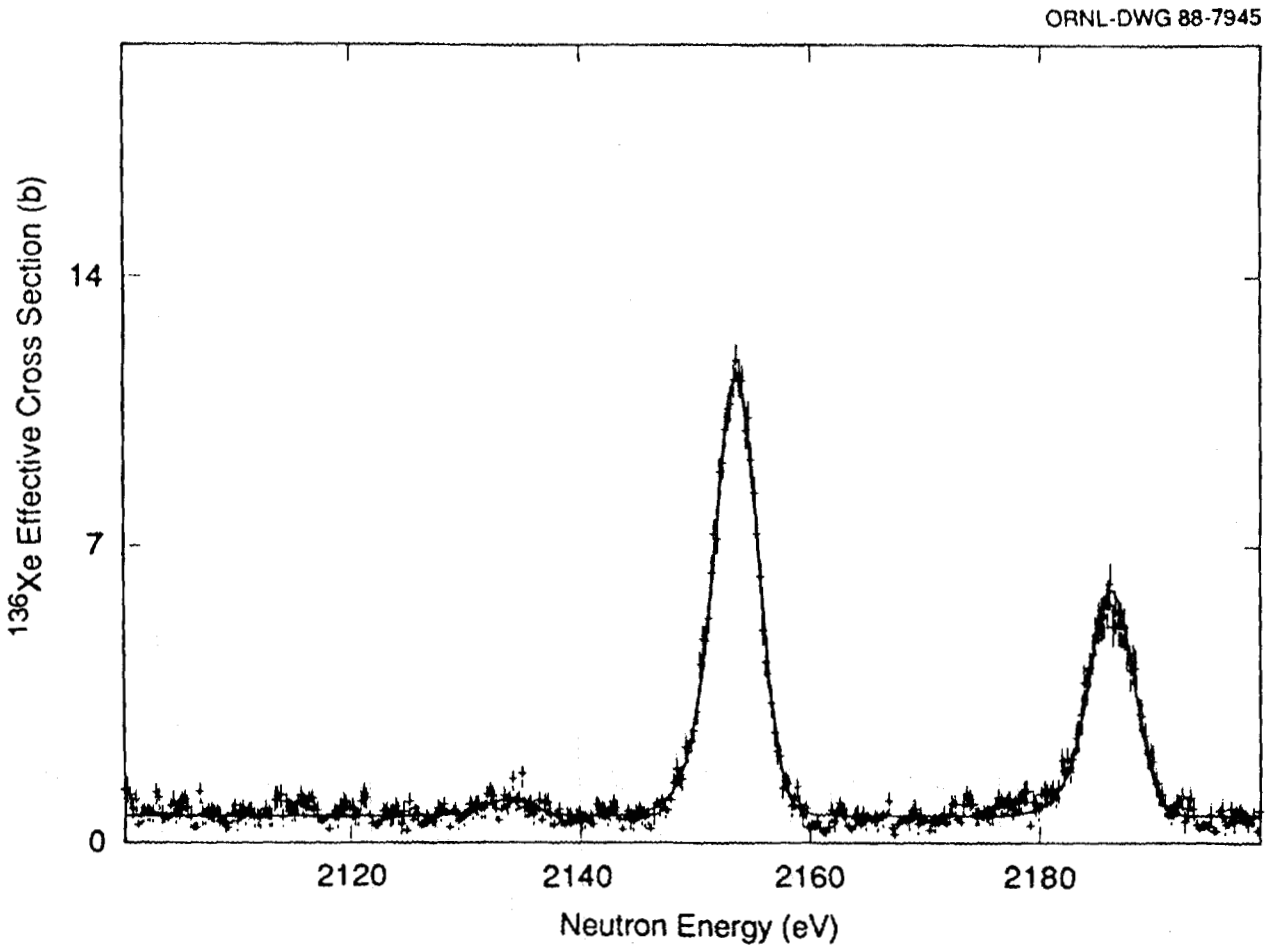

Figure 2. Least squares fit of ^{136}Xe parameters to the capture cross-section data. The largest peak area corresponds to a capture kernel of 30.1 meV with a statistical standard deviation of 0.3 meV. The small peak at 2133 eV is due to the stainless steel container used to contain the xenon sample.

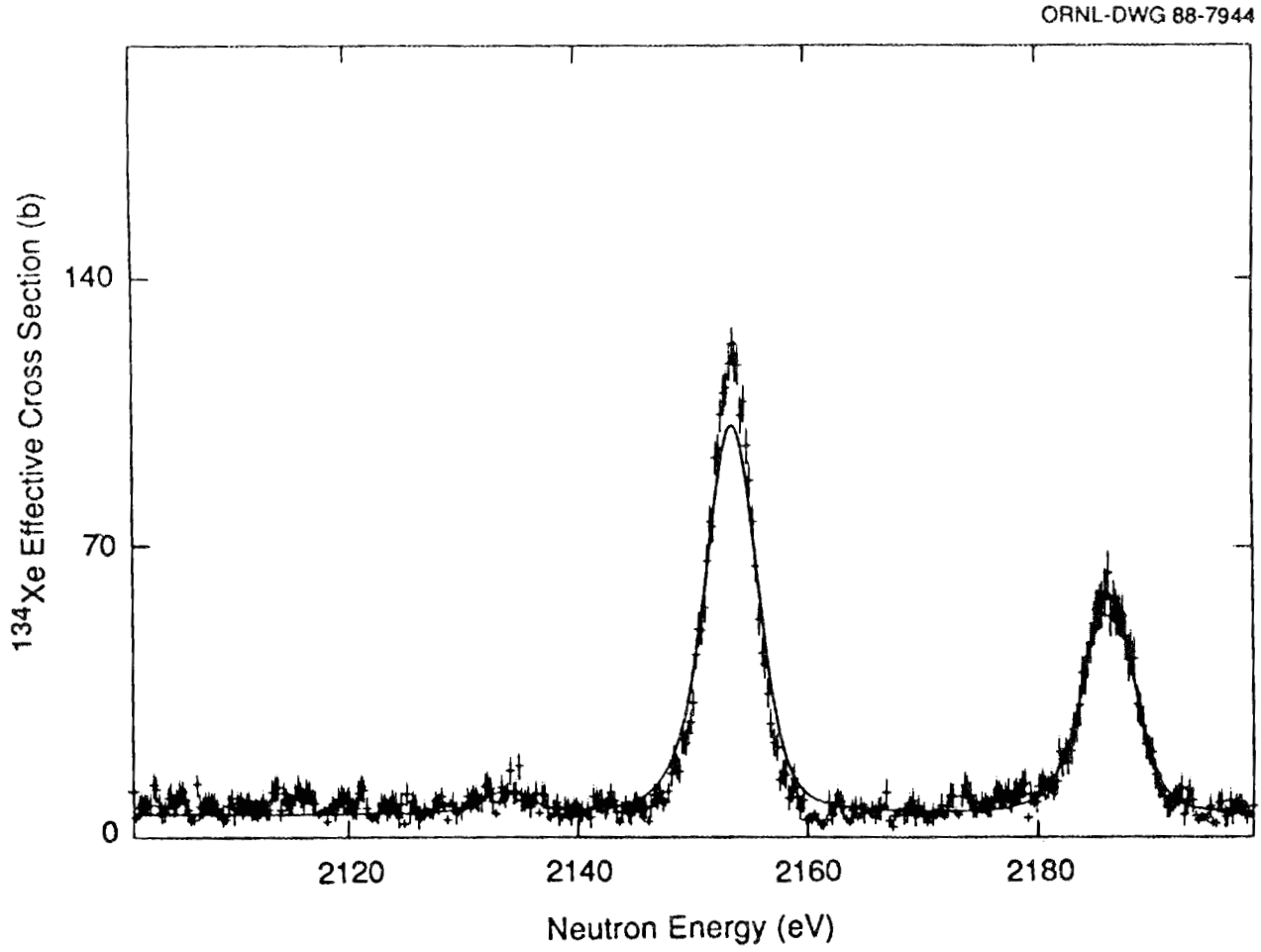

Figure 3. The same data (crosses) as in Fig. 2 rescaled and fitted to ^{134}Xe which comprised 5.7% of the sample. The 2186-eV peak is well described (curve) with a capture kernel of (188 ± 3) meV, while the large peak cannot be fitted as a resonance in the less abundant isotope.

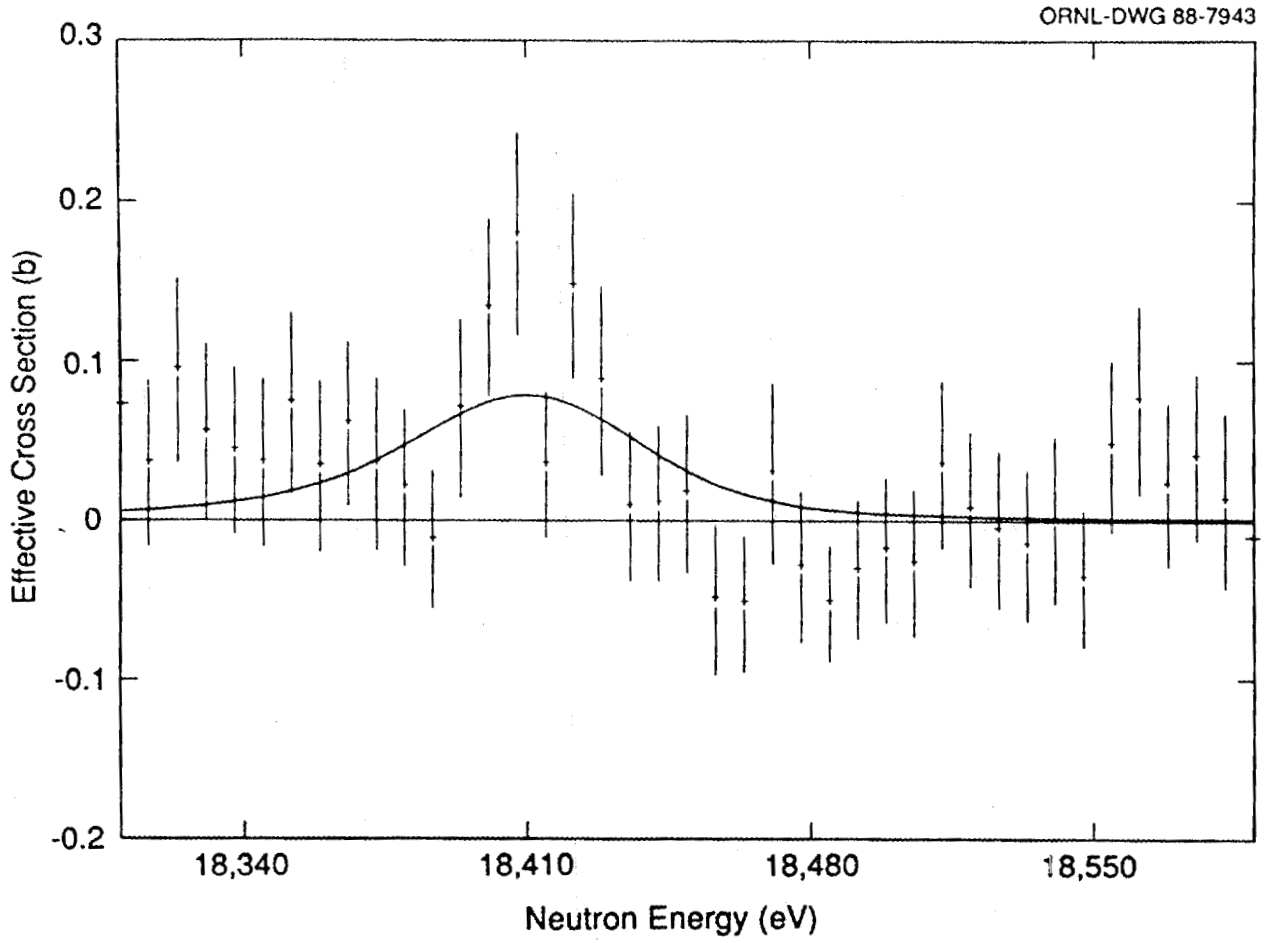

Figure 4. The excess capture yield in the neighborhood of 18.4-keV peak fitted as due to the 25-eV wide resonance found in the neutron transmission study.[2] The corresponding radiation width is (32 ± 9) meV, correlated inversely (-0.65) with the local background which was simultaneously fitted.

4. MAXWELLIAN SPECTRUM AVERAGE

The stellar velocity-weighted thermal cross-section was derived using the parameters for the 2.15 keV and 18.3 keV resonances found here, those resonances reported[2] above 35 keV assuming a constant radiation width of (32 ± 9) meV for them, plus the laboratory thermal capture value, (0.26 ± 0.02) mb.[6] A computer code MAXWL[8] was used for the calculation at a series of temperatures, kT=5 keV to kT=100 keV, appropriate to nucleosynthesis models. Results are shown in Fig. 5. The velocity-weighted average cross sections are reported in conventional form by dividing the average over the Maxwellian spectrum by the mean thermal velocity at each temperature. At the conventional temperature kT=30 keV the calculation gives (0.72 ± 0.11) mb. The resonances above 35 keV contribute one third of this value, and the indicated uncertainty of 15% is to allow for this assumption.

5. DISCUSSION

Earlier estimates of the ^{136}Xe stellar average neutron capture cross section at kT=30 keV are included in a recent evaluation.[9] Hauser-Feshbach calculations with global parameters[10] gave 2.6 mb, whereas a more recent calculation based on more detailed input information[11] gave 0.96 mb. The paucity of resonances near 30 keV make the Hauser-Feshbach approach unreliable for this target nucleus with its closed 82 neutron shell.

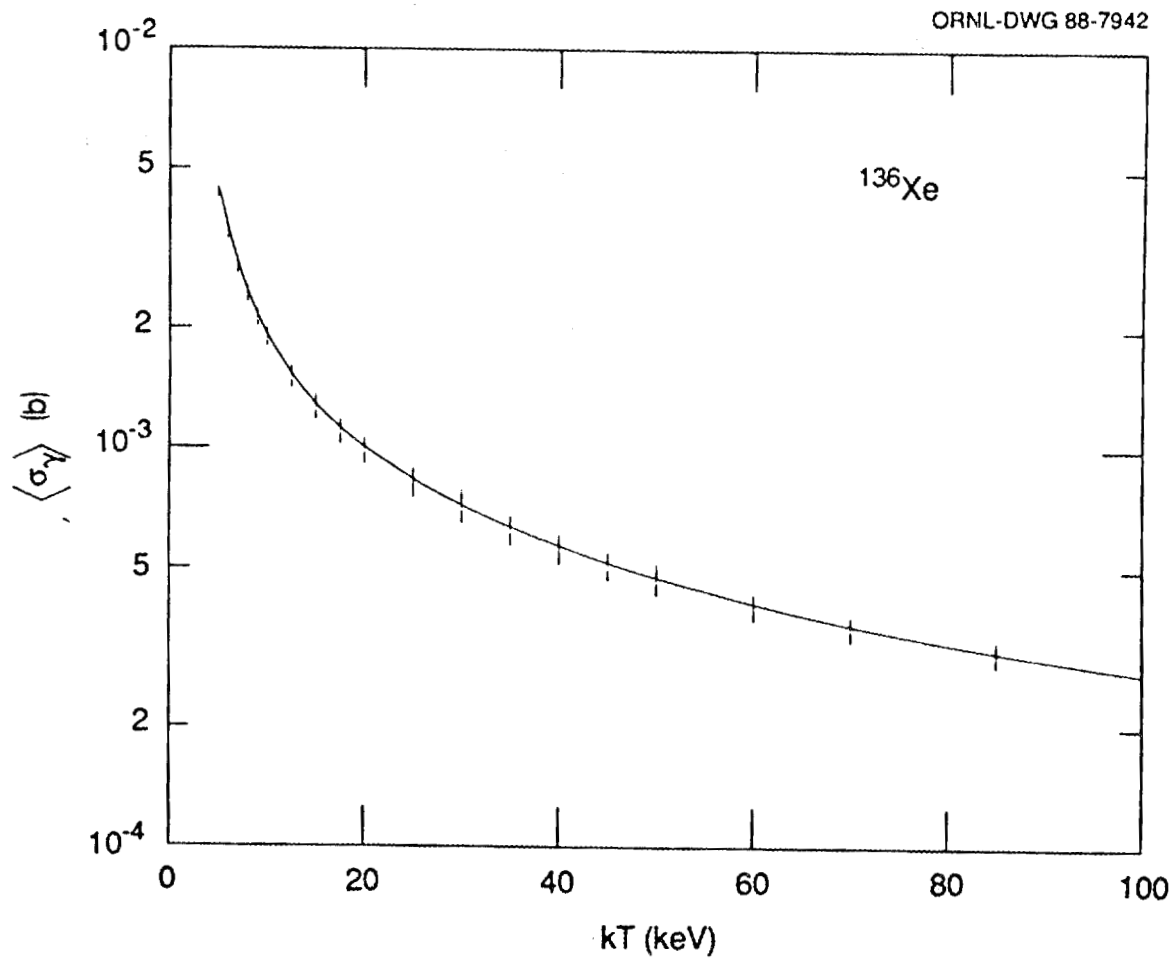

Figure 5. ^{136}Xe Maxwellian average capture calculated assuming a (32 ± 9) meV radiation width for the resonances reported[2] at and above 35 keV. These contribute one third of the total 0.72 mb found for a temperature of 30 keV.

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S. Raman kindly made the enriched gas sample available for the neutron capture measurements at ORELA and urged their analysis. B. Fogelberg suggested the pulse-height check for ^{134}Xe minor isotope peaks. The ORELA operators and engineers faithfully provided the pulsed neutrons used for the measurements.

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