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FINAL TECHNICAL PROGRESS REPORT

COLORADO SCHOOL OF MINES

LOW ENERGY NUCLEAR PHYSICS PROJECT

UNITED STATES DEPARTMENT OF ENERGY GRANT

DE-FG02-87ER40342

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Summary

This report summarizes the accomplishments of our project "Studies of nuclear reactions at very low energies". This project, supported by the U.S. Department of Energy grant DE-FG02-87ER40342 was undertaken in 1987 and completed in 1993. All but one of the major objectives of this study have been accomplished. Specifically we have completed our investigation of the (p,γ) on light nuclei, a study of the Oppenheimer-Phillips effect, a measurements of the astrophysically interesting reaction $D(\alpha,\gamma)^6Li$ at low energies and an extension of the reaction $D(d,\gamma)^4He$ to lower energies than previously observed. Preliminary investigation of the reaction $^7Li(^3He,p)^9Be$ was begun and is continuing under a separate DOE grant.

In addition to these tasks, we have completed some very interesting projects which were not included in our original proposal. These include a study of the (d,γ) reactions on ^6Li, ^7Li and ^{10}B and an investigation of the possibility of observing terrestrial antineutrinos from the beta decay chains of U and Th as a diagnostic of terrestrial heat flow.

Table of Contents

1. Progress on proposed investigations

The major goals outlined in our original proposal consisted of five separate investigations.

a. Radiative capture of protons on light nuclei. F.E. Cecil, D. Ferg, H. Liu, J.C. Scorby, J.A. McNeil and P.D. Kunz.* The first goal was a completion of a multiyear effort in which the (p,γ) reactions on the nuclei ^{6}Li, ^{7}Li, ^{9}Be and ^{11}B were measured from energies of about 40 to 180 keV. This work has been published [CE92a] and a reprint is attached to this report. Except fpr the low energy resonance in the $^{11}B(p,\gamma)^{12}C$ reaction at 163 keV, all of the astrophysical S-factors were determined to be nearly constant with energy. Direct capture calculations with no free parameters were able to duplicate the measured cross sections with the exception of the reaction $^{6}Li(p,\gamma)^{7}Be$ for which multi-step effects are suspected. Together with the recent measurement of the reaction $^{10}B(p,\gamma)^{11}C$ [WI83], all of the (p,γ) reactions on stable light nuclei through carbon have now been determined at low energies. *University of Colorado.

b. A study of the Oppenheimer-Phillips effect. F.E. Cecil, H. Liu, J.S. Yan and G.M. Hale* The second major goal of our project was an investigation of the Oppenheimer-Phillips effect, in which deuteron induced reactions at low energies are affected by the electric polarization of the deuteron in the Coulomb field of the target. This investigation has been completed and published [CE93]. A reprint of this work is attached to this report. To summarize the results of this investigation, we measured the branching ratios of the reactions $d(d,p)t/d(d,n)^{3}He$, $^{6}Li(d,p)^{7}Li/^{6}Li(d,\alpha)^{4}He$ and $^{10}B(d,p)^{11}B/^{10}B(d,\alpha)^{8}Be$ down to center of mass energies of 3 keV, 20 keV and 58 keV respectively. The expected enhancement of the (d,p) reactions was not seen. In the case of the d-d reactions, our measurements agreed with exact R-matric calculations of the

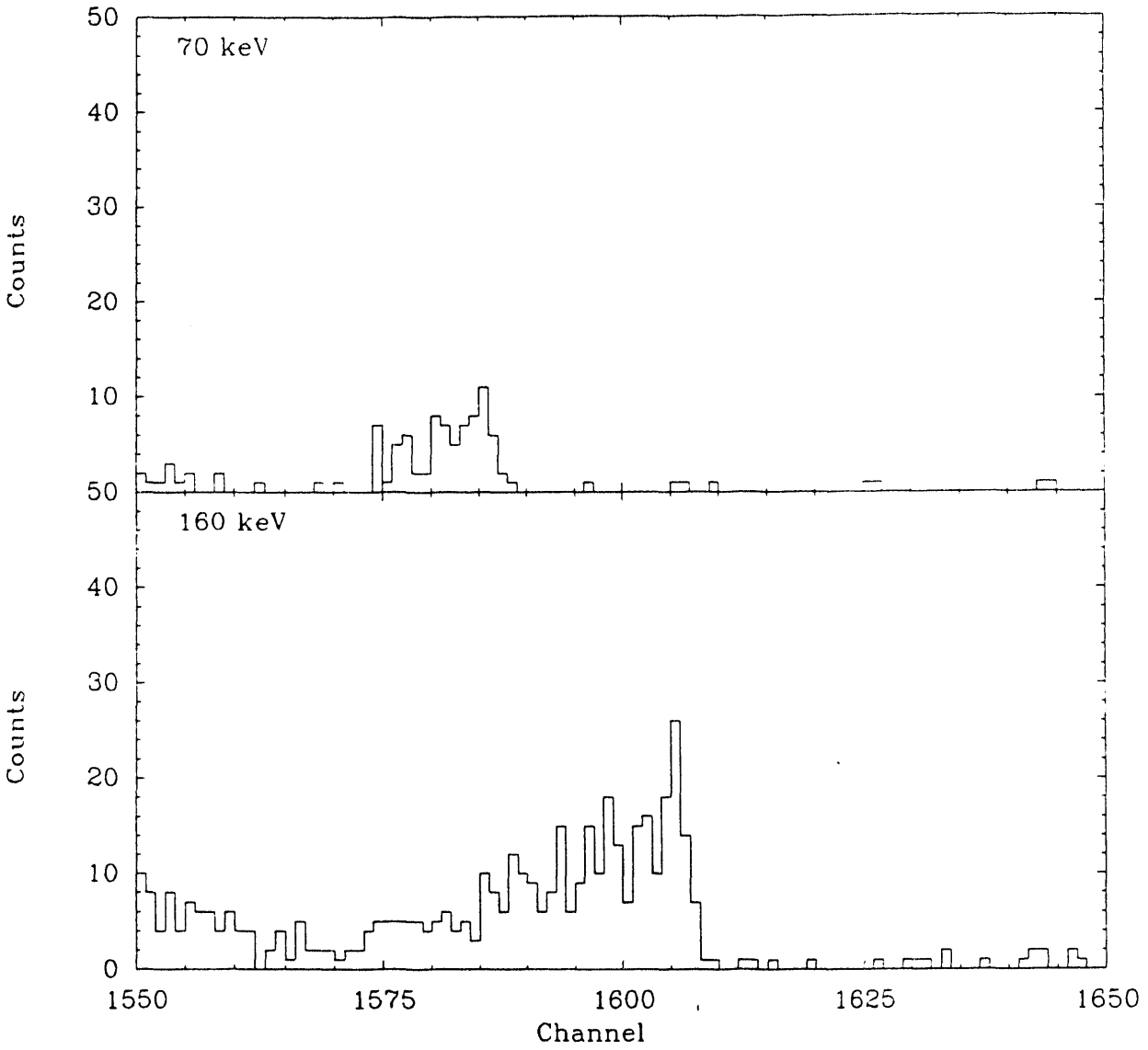
branching ratios. * Los Alamos National Labs.

c. A measurement of the D(α,γ)6Li reaction. J.S. Yan, F.E. Cecil and C.S. Galovich* The reaction D(α,γ)6Li continues to be the focus of considerable attention as a mechanism for the production of 6Li in primordial nucleosynthesis.[HE91], [KI91] and [HI92]. The only previous observation of this reaction was at an energy of 1 MeV and was carried out by observing the recoil 6Li nuclei in a magnetic spectrometer and then extrapolating the results to the more interesting astrophysical energies around 100 keV. [RO81]. We have attempted to measure this reaction at low energies by directly observing the capture gamma ray. Our experiment consisted of bombarding a cooled, thick target of deuterated polyethelene with a magnetically analyzed beam of 160 keV alpha particles and measuring reaction gamma rays with a large volume, high resolution gamma ray detector situated a few mm. from the target. A particularly surprising artifact was observed in our first attempts to observe this reaction. We observed a gamma ray line at an energy of 1.54 MeV, not present with the beam off, and nearly equal in energy to the expected capture gamma ray. This artifact was the result of a deuteron contaminant in the beam from deuterium, volatilized by beam heating, which was ionized in the accelerating column by the primary alpha particle beam. The result was a low level fast neutron background from the (d,d) reactions as the contaminant beam struck the target and the 1.54 MeV gamma ray was the result of 63Cu(n,n'γ) reactions on the copper in the housing of the HpGe detector. This artifact was eliminated by the installation of a second magnetic analysis system immediately up-stream from the target. We have previously suggested [CE90] as an explanation for cluster-impact-fusion. The experiment was calibrated with the reaction D(p,γ)3He, using the same targets, same detector and substituting a proton beam for the alpha particle beam. Spectra measured during these calibration runs are shown in Figure 1, where the kinematic dependence of the gamma ray energy on the beam energy and the slewing of the gamma ray

lines due to the slowing down of the protons in the thick CD2 targets is noted. The spectra measured during two alpha particle bombardments, one for 3 Coulombs of alpha particles and one for 2 Coulombs, are shown in Figure 2. The capture gamma ray from the α-d reaction is expected between channels 1037 and 1042. No evidence is seen for a gamma ray line in these channels. By comparing with the d-p calibration reaction, for which the low energy S-factor is well known to be about 2.5E-7 MeV-b, we are able to place an upper limit on the astrophysical S-factor for an alpha particle bombarding energy of 160 keV of about 1E-7 MeV-b. This is about a factor of 5 above the extrapolated value of Robertson [RO81]. It would be prohibitive to try to reduce this upper limit by a factor of 10 using the present experimental techniques. We are preparing a report of this work for publication. * University of Northern Colorado.

d. The reaction D(d,γ)4He at low energies. F.E. Cecil, H. Liu and J.S. Yan. The behavior of the D(d,γ)4He reaction at very low energies has been the subject of considerable theoretical attention following our original study [WI85]. We have extended this reaction to a center-of-mass energy of 20 keV and find the gamma ray to charged particle branching ratio to be constant. This result has been published [CE92b]. A reprint of this work is attached to this report.

e. A study of the reaction 7Li(3He,p)9Be. J.S. Yan and F.E. Cecil. The reaction 7Li(3He,p)9Be, astrophysically interesting as a mechanism for hopping over the A = 8 nucleosynthesis barrier, has been studied down to 500 keV by Rath et al.[RA90]. We are continuing our efforts to measure this reaction down to an energy of about 100 keV. We have completed the necessary development work for this study and expect to carry out the measurements in the next few months. The preparation has included fabrication of a scattering chamber allowing angular distributions to be measured and the development of a


70 keV
160 keV
Counts
Counts
50
40
30
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0
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Channel

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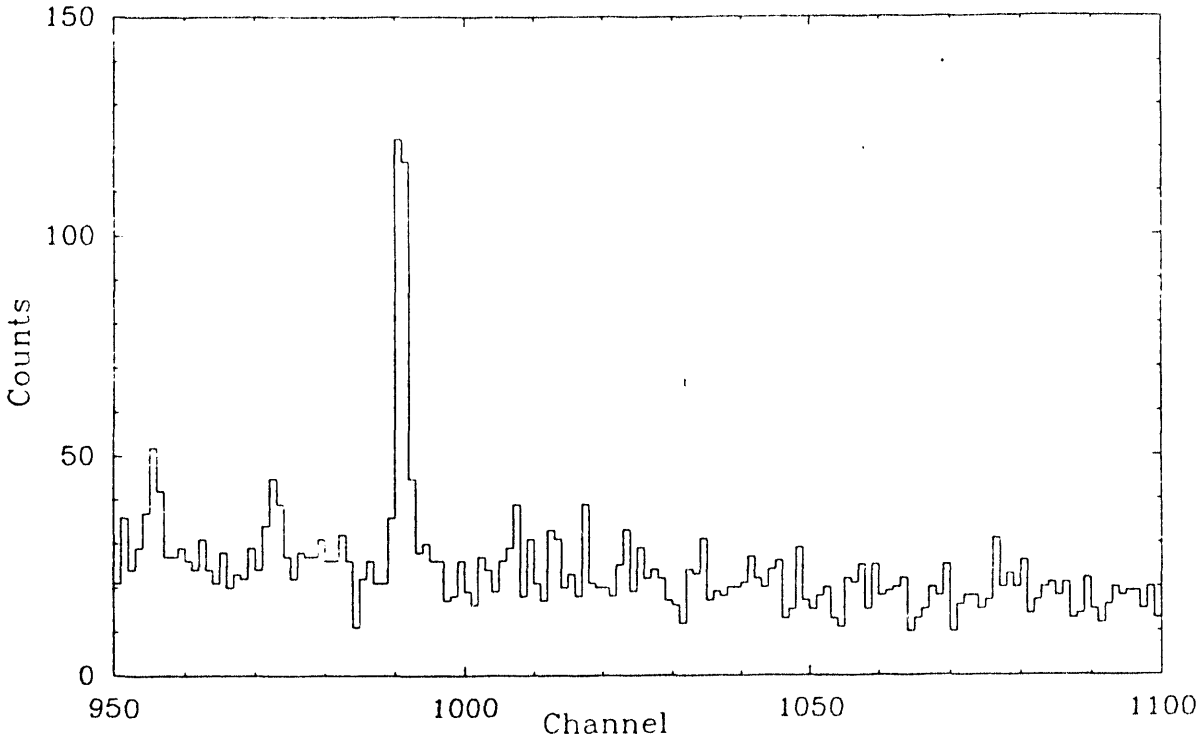

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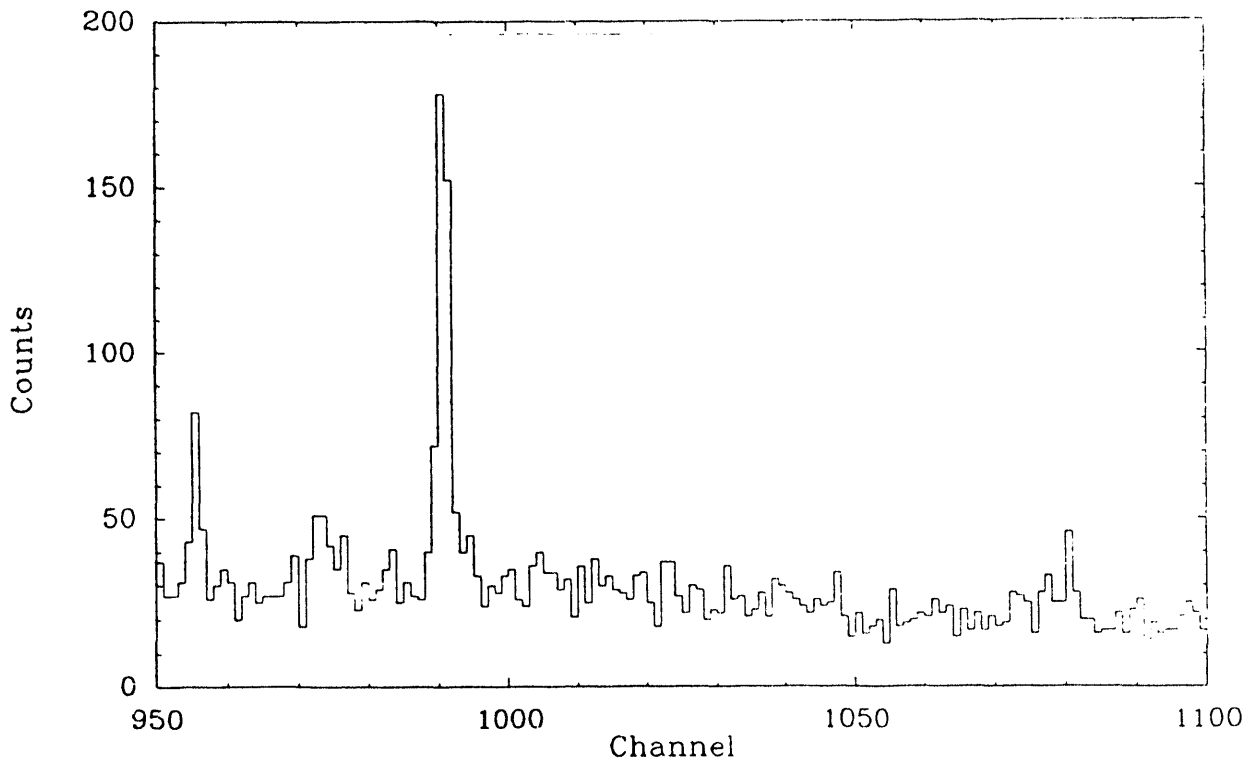
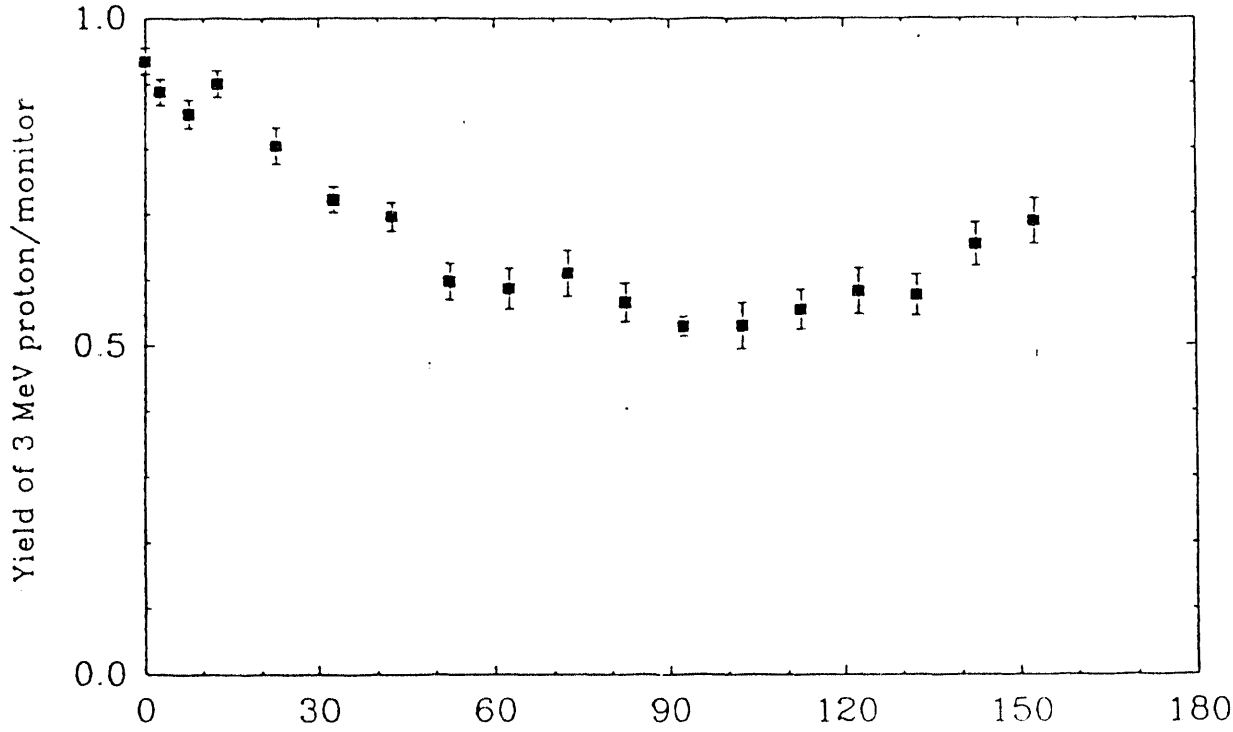


CAMAC system allowing for a two dimension particle identification system. As a test of these systems we have measured the angular distribution for the d-d reactions at energies of 20 and 70 keV. These angular distributions are shown in Figure 4. A test of the CAMAC particle identification system is shown in Figure 5 which shows the well separated proton groups corresponding to the ground and first two excited states in 11B from the reaction 10B(d,p)11B.

Angular dist. of 3 MeV proton from D(d,p)T Reaction
70 keV lab energy
Jan. 7, 1992



Angular dist. of 3 MeV proton from D(d,p)T Reaction
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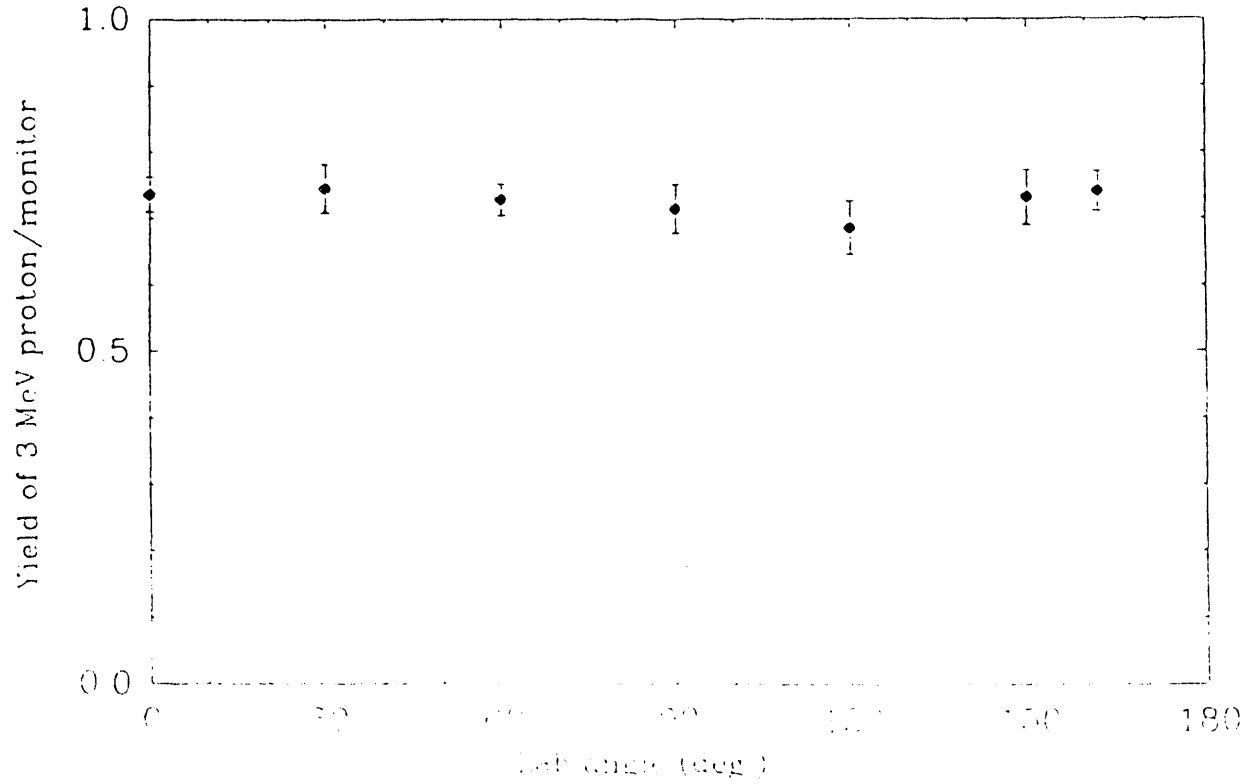
Jan. 8, 1992



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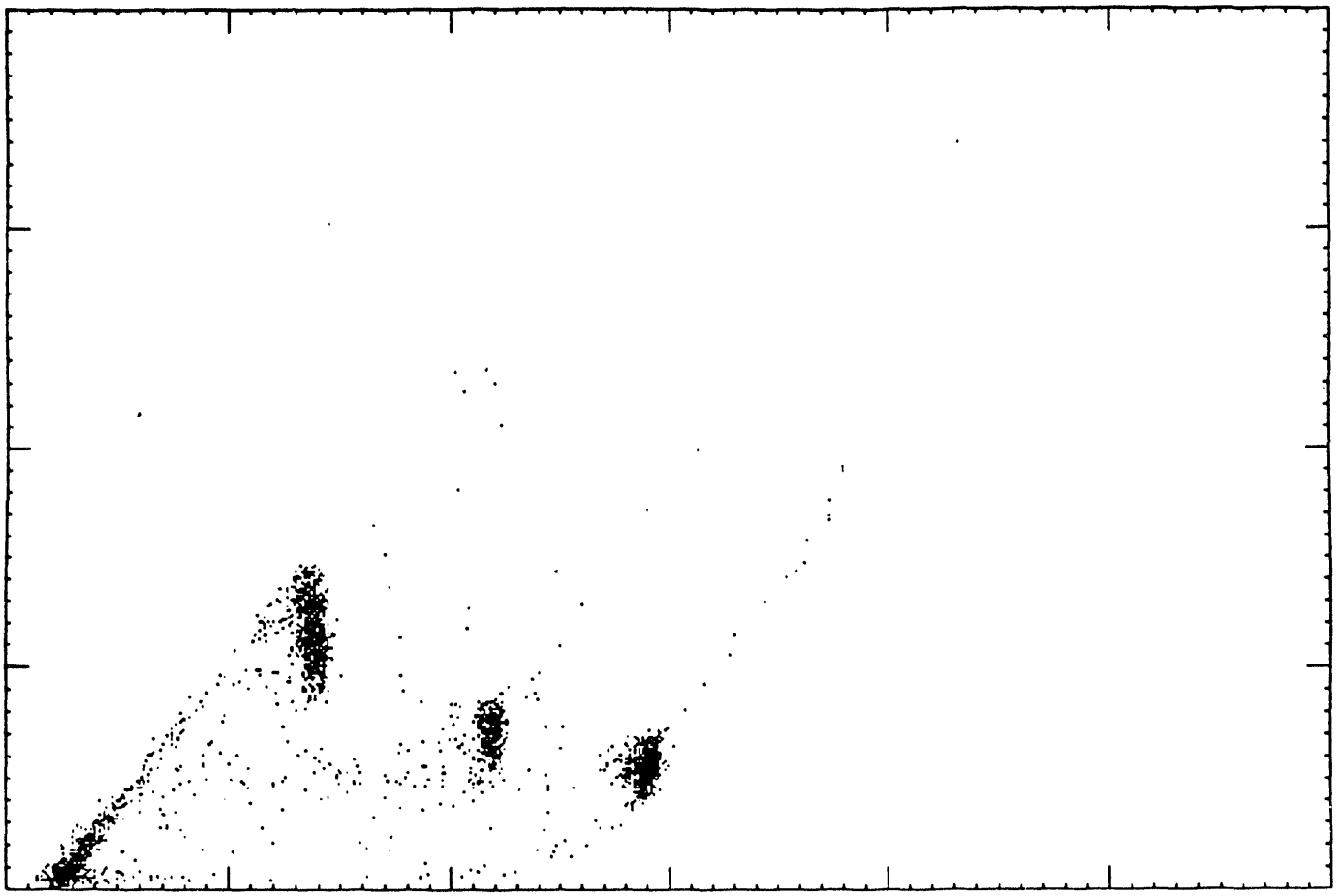


2. Progress on investigations not included in original proposal.

a. The reactions 6Li(d,γ)8Be, 7Li(d,γ)9Be and 10B(d,γ)12C. F.E. Cecil, H. Liu, J.C. Scorby and S.S. Medley. The gamma ray to charged particle branching ratios for the reactions 6Li(d,γ)8Be 12C have been established at low energies and appear roughly independent of deuteron bombarding energy. The values of the branching ratios have been published [CE92b] and a reprint of this publication is attached to this report. An upper limit of $1x10^{-6}$ for the branching ratio of the reactions 7Li(d,γ)9Be and 7Li(d,α)5He at low energies has likewise been determined [CE90].

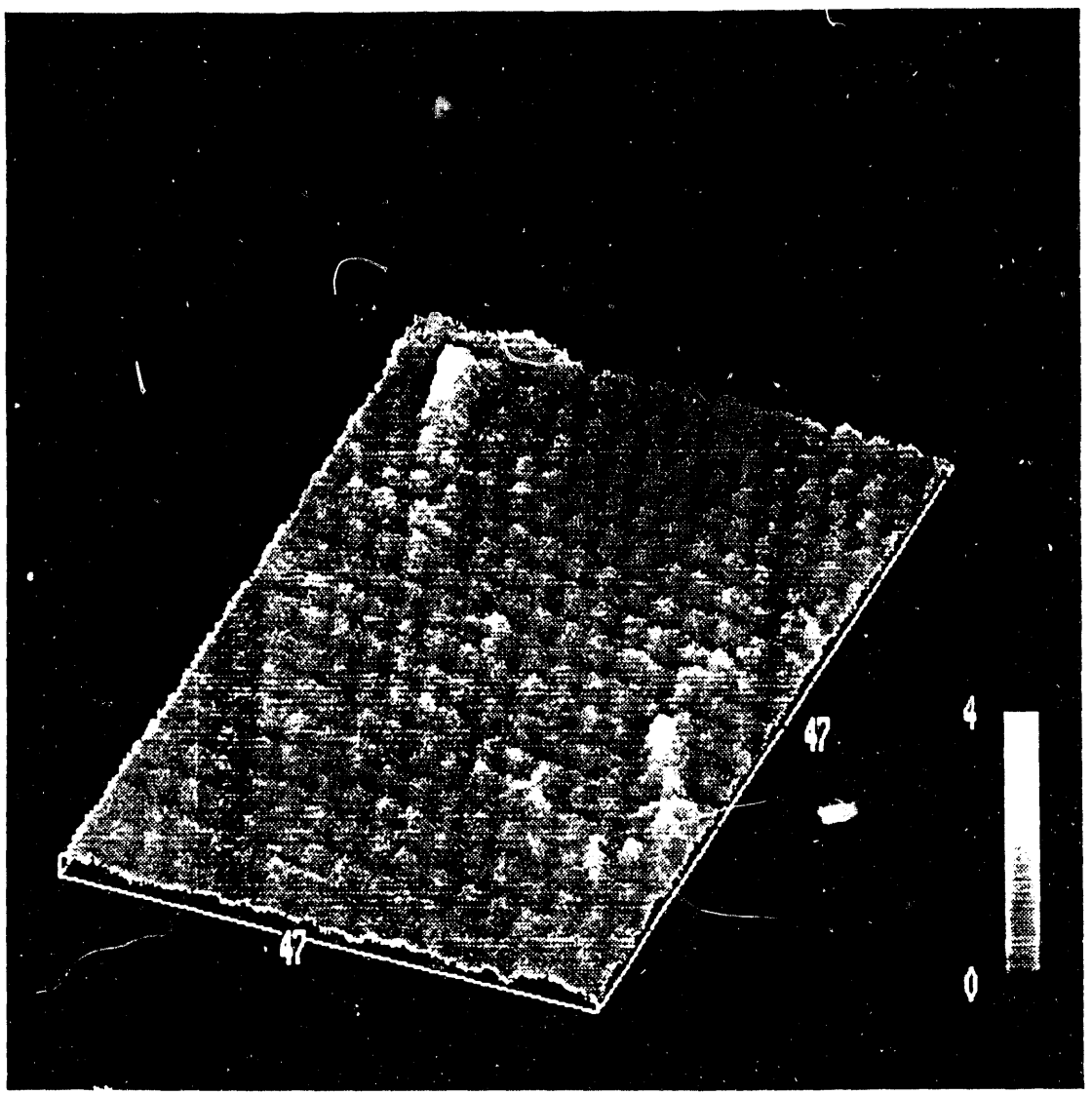
b. A proposed determination of radiogenic heating within the earth by measurement of the associated terrestrial antineutrino flux. J.C. Scorby and F.E. Cecil and Meridee Jones-Cecil*. The source of the Earth's surface heat flow, roughly 80 mW/m^2 and surprisingly uniform over the surface of the earth, represents one of the most challenging problems in contemporary geophysics. We have proposed a large underground scintillation detector, comparable in size and sophistication to the current generation of the proton decay, or large solar-neutrino detectors, which we believe would be capable of detecting the low energy terrestrial antineutrino flux from the β decays of the U-Th daughters associated with the radiogenic component of the heating. The detector would be based upon the $p + \nu \rightarrow n + e+$ reaction (the Cowan-Reines experiment) and, in addition, would possess a modest degree of directionality by virtue of the spatial separation of the e+ signal and the subsequent neutron capture signal. This directionality would allow the source of a detected antineutrino signal to be established as the earth's interior rather than an extra-terrestrial source of antineutrinos such as oscillations in the more prolific solar neutrino flux. Details of the proposed detector will be given in a forth-coming publication [SC93]. As part of this study, we have examined a two photo-tube, scintillation detector, utilizing the fast liquid

scintillator BC505. By comparing the arrival times at the two PMT's, the position of an event can be determined with a spatial resolution of about 2.7 cm (corresponding to a net time resolution of 150 ps.) A discussion of this technique has been published [CE92c] and a reprint is included in this report.* U.S. Geologic Survey.

c. Observation of surface damage to graphite crystals by energetic ions. Kevin Kelley, Tim Ohno and F.E. Cecil. We have bombarded cleaved graphite samples with low currents (≈10 nA) of 70 keV protons from our accelerator. Scanning tunneling micrographs of the sample prior to bombardment showed a featureless and regular array of carbon atoms. Micrographs taken following a bombardment of 4 C/cm^2 showed distinct "hillock" features. (see Fig. 6) We are continuing this work and plan to parameterize the observed features in terms of shape, dependence on ion energy and species, etc.

Kevin Kelly Senior Design

Ion induced damage on HOPG by 70keV H+ ions.



-DensityGraphics-

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CE92a. F.E. Cecil H. Liu, D. Ferg, J.A. McNeil and P.D. Kunz, Nuclear Physics, **A539**, **75** (1992).

CE92b. F.E. Cecil, H. Liu, J.S. Yan and S.S. Medley, Reviews of Scientific Instruments, **63**, 4854 (1992).

CE92c. F.E. Cecil and J.C. Scorby,Reviews of Scientific Instruments, **63**, 4559 (1992).

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HE91. J. Hesselbarth and K. Knopfle, Physical Review Letters, **67**, 2773 (1991).

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3. Cumulative bibliography of publications from project DE-FG02-87ER40342

1. F.E. Cecil and S.S. Medley "Gamma ray measurements during deuterium and 3He discharges on TFTR" Nuclear Instruments and Methods in Physics Research, **A271** (1988) 628.

2. F.E. Cecil, D. Ferg, R. King, B. Kriss, H. Liu and J. Scorby, "The low energy high current particle accelerator at Colorado School of Mines", "Proceedings of Tenth Conference on Applications of Accelerators in Research and Industry" Nuclear Instruments and Methods in Physics Research B, **40/41** 934, (1989)

3. M. Kopcewicz, D.L. Williamson and F.E. Cecil, "Proton irration and solid-state reaction of Fe-Zr multilayers". Hyperfine Interactions **56** 1599 (1990).

4. F.E. Cecil, D. Ferg, T.E. Furtak, J.A. McNeil and D.L. Williamson, "Study of energetic charged particles emitted from thin deuterated palladium foils subject to high current densities". Los Alamos Report LA-11686-C (1989) p.22 and Journal of Fusion Energy **9**, 195 (1990).

5. H.Hsuan, D.Manos, S.Cohen, S.Cowley, R.Motley, A. Roquemore, T. Saito, J.Timberlake, W.Ayers, Bennett, M.Bitter, F.Cecil, J.Cuthbertson, J.Dong, F.Dylla, J.Evans, H.Furth, L.Grisham, H.Hendel, K. Hill, R. Kulsrud, D. Meade, S. Medley, D. Mueller, E. Nieschmidt, R. Shoemaker and J. Thomas, "Lack of neutron and gamma radiation from PPL's cold fusion experiments"., Los Alamos Report LA-11686-C (1989) p.16.

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7. F.E. Cecil and J.A. McNeil, "Comment on cluster impact fusion", Physical Review Letters, **64** (1990) 2210.

8. F.E. Cecil, H. Liu, J.C. Scorby and S.S. Medley, "Prompt gamma ray diagnostics of advanced fuel fusion plasmas" in "Proceeding of Eighth Topical Conference on High Temperature Plasma Diagnostic", Reviews of Scientific Instruments, **61** (1990) 3223.

9. S.S. Medley, S.D. Scott, A.L. Roquemore and F.E. Cecil "Performance of the fusion gamma diagnostic on TFTR" in "Proceeding of Eighth Topical Conference on High Temperature Plasma Diagnostic", Reviews of Scientific Instruments, **61** (1990) 3226.

10. F.E. Cecil, D. Beddingfield, H. Liu and C.S. Galovich, "Observation of charged particles bursts from deuterium loaded thin Titanium foils" in "Proceedings of workshop on anamolous nuclear effects in deuterium-metal systems", Provo (1990). Editors: Steven E. Jones, Franco Scaramuzzi and David Worledge. American Institute of Physics Conference Proceeding **228** (1991) pp. 375-382.

11. F.E. Cecil, H. Liu, D. Ferg, J.A. McNeil and P.D. Kunz, "Radiative capture of protons on light nuclei at low energies". Nuclear Physics, **A539** (1992) 75.

12. D.H. Beddingfield, F.E. Cecil, C.S. Galovich, H. Liu and S. Asher, "Characterization of charged particle bursts from deuterium loaded thin titanium films" in "Proceedings of Second Annual Conference on Cold Fusion" Como, Italy (1991). Editors Tullio Bressani, Emilio Del Giudice and Giuliano Preparata (1992) p 99.

13. F.E. Cecil and G.M. Hale, "Measurement of D-D and D-^{6}Li nuclear reactions at very low energies" in "Proceedings of Second Annual Conference on Cold Fusion" Como, Italy (1991). Editors Tullio Bressani, Emilio Del Giudice and Giuliano Preparata (1992) p 271.

14. S.S. Medley, A.L. Roquemore and F.E. Cecil, "Absolute calibration of fusion gamma ray detector on TFTR" in "Proceeding of Ninth Topical Conference on High Temperature Plasma Diagnostics", Reviews of Scientific Instruments, **63**, 4857 (1992).

15. F.E. Cecil, H. Liu, J.S. Yan and S.S. Medley, "Gamma ray to charged particle branching ratios for the radiative capture of deuterons by ^{2}H, ^{6}Li and ^{10}B". "Proceedings of

Ninth Topical Conference on High Temperature Plasma Diagnostics", Reviews of Scientific Instruments **63**, 4854 (1992)

16. F.E. Cecil and J.C. Scorby, "Investigation of neutron detection properties of the fast liquid scintillator BC505" in "Proceedings of Ninth Topical Conference on High Temperature Plasma Diagnostics", Reviews of Scientific Instruments **63**,4559 (1992).

17. F.E. Cecil, H. Liu and J.S. Yan, "Recent measurements of nuclear reaction cross sections with ion beams at very low energies" in "Proceedings of Seventh International Conference on Low Energy Ion Beams" Loughborough UK (1992), Vacuum Technology and Ion Beams **44**, 181 (1993).

18. F.E. Cecil, H. Liu, J.S. Yan and G.M. Hale, "Measurement of branching ratios of low energy deuteron-induced reactions on ^{2}H, ^{6}Li and ^{10}B". Physical Review C **47**, 1178 (1993).

4. Personnel associated with grant projects

1. Ph.D.

F. Edward Cecil, Principal investigator, Colorado School of Mines

James A. McNeil, Colorado School of Mines

Tini R. Ohno, Colorado School of Mines

Don L. Williamson, Colorado School of Mines

P. Dale Kunz, University of Colorado

Cynthia S. Galovich, University of Northern Colorado

Gerry M. Hale, Los Alamos National Laboratory

Sid S. Medley, Princeton Plasma Physics Laboratory

2. Graduate students

David H. Beddingfield

Virginia D. Ferg

Harry He

Huaizhu Liu

Catherine Mader

John Scorby

5. Cumulative theses from project

1. Doctor of Philosophy

a. "Studies of nuclear reactions d-d, d-6Li and d-10B at low energies and charged particle emission from deuterium metal systems". Huaizhu Liu. Ph.D. in Applied Physics, May 1992

b. "A proposed determination of radiogenic heating within the earth by measurement of the associated terrestrial antineutrino flux". John C. Scorby. Ph.D. in Applied Physics, May 1992.

2. Master of Science

a. "The gamma ray reactivities for the reactions p-11B, p-7Li and p-6Li fusion reactions and applications as a temperature diagnostics of fusion plasmas". Huaizhu Liu, M.S in Physics, December 1989.

b. "Radiative capture of protons on light nuclei at low energies". Dale Virginia Ferg, M.S. in Physics, December 1989.

c. "Sub-coulomb deuteron-nucleus collisions using the Cayley equations" Catherine M. Mader, M.S. in Physics, December 1989.

d. "A beam optics study of the General Ionex Model 1545 linear particle accelerator. Lian Harry He, M.S. in Physics, December 1990.

e. "Preparation and characterization of Ti662-6Al-6V-2Sn hydrides and deuterides".

David H. Beddingfield, M.S. in Materials Science, May 1991.

3. Bachelor of Science

a. "Remote monitoring of power supplies in a 180 keV accelerator and some applications". Ross C. King, B.S. in Engineering Physics, May 1988.

b. "Instrumentation for identification of energetic charged particles from nuclear reactions" Ron Sidwell, B.S. in Engineering Physics, May 1989.

c. "A Compton suppressed HpGe gamma ray spectrometer" Ira Frosch, B.S. in Engineering Physics, May 1990.

d. "Deuterium loaded thin titanium foil charged particle emissions", Todd Kuhlmann, B.S. in Engineering Physics, May 1991.

e. "Cosmic ray distributions in underground environments", Deborah Dalby, B.S. in Engineering Physics, May 1992.

f. "The design and use of a low level gamma ray detection facility", Jonathon M. Hopkins, B.S. in Engineering Physics, May 1992.

g. "The correlation of radioactive contamination in trees with age." Erika Nelson, B.S. in Engineering Physics, May 1992.

6. Selected reprints of publications

1. F.E. Cecil, H. Liu, D. Ferg, J.A. McNeil and P.D. Kunz, "Radiative capture of protons on light nuclei at low energies". Nuclear Physics, **A539** (1992) 75.

2. F.E. Cecil, H. Liu, J.S. Yan and S.S. Medley, "Gamma ray to charged particle branching ratios for the radiative capture of deuterons by ^{2}H, ^{6}Li and ^{10}B". "Proceedings of Ninth Topical Conference on High Temperature Plasma Diagnostics ", Reviews of Scientific Instruments, **63**, 4854 (1992).

3. F.E. Cecil and J.C. Scorby, "Investigation of the neutron detection properties of the fast liquid scintillator BC505" in "Proceeding of Ninth Topical Conference on High Temperature Plasma Diagnostics", Reviews of Scientific Instruments, **63**, 4559 (1992).

4. F.E. Cecil, H. Liu, J.S. Yan and G.M. Hale, "Measurement of branching ratios of low energy deuteron-induced reactions on ^{2}H, ^{6}Li and ^{10}B". Physical Review C **47**, 1178 (1993).

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