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SUPPLEMENT 6

APOLLO 17 MISSION REPORT

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CALIBRATION RESULTS FOR GAMMA RAY SPECTROMETER SODIUM IODIDE CRYSTAL

National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
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FINAL REPORT

GAMMA-RAY SPECTROMETER EXPERIMENT

APOLLO 17: NaI(Tl) DETECTOR CRYSTAL ACTIVATION

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FINAL REPORT
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PREFACE

This report summarizes the significant experimental results from the Apollo 17 crystal activation experiment. We have also included some preliminary interpretations to indicate the significance of the results and possible direction for future experimentation. The experimental results have been obtained as a cooperative effort of a large group of investigators We list the names and institutions at the beginning of this paper and we express our gratitude for their participation and help in this program. We wish to thank the Apollo 17 flight crew for their support in the performance of this experiment. A special debt of gratitude is due to the recovery team under the direction of Dr. Stullken of Johnson Space Center. We thank F. Martin of NASA Headquarters and W. Eickelman of JSC for coordinating this effort, and M. Fong of the Jet Propulsion Laboratory for pre-flight testing. Finally, we thank E. G. Stassinopoulos of the Goddard Space Flight Center for his trapped radiation dosage estimates.

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INTRODUCTION

A major difficulty in medium energy gamma-ray remote sensing spectroscopy and astronomy measurements has been the high rate of unwanted background resulting from the following major sources:

1. Prompt secondary gamma-rays produced by cosmic-ray interactions in satellite materials.

2. Direct charged-particle counts.

3. Radioactivity induced in the detector materials by cosmic-ray and trapped protons.

4. Radioactivity induced in detector materials by the planetary (e.g., earth or moon) albedo neutron flux.

5. Radioactivity induced in the detector materials by the interaction of secondary neutrons produced throughout the spacecraft by cosmic-ray and trapped proton interactions.

6. Radioactivity induced in spacecraft materials by the mechanisms outlined in 3, 4, and 5.

7. Natural radioactivity in spacecraft and detector materials.

The Apollo gamma-ray spectrometer experiments carried aboard Apollo 15 and Apollo 16 were designed: to minimize effect (1) and (6) by placing the gamma-ray detector on a boom twenty-five feet away from the spacecraft, to eliminate effect (2) by use of an active charged-particle shield (Harrington, et al., (1974)); and to determine the magnitude and nature of effect (7) by surveying the spacecraft prior to launch (Metzger and Trombka (1972)). The purpose of this experiment was to obtain information on effects 3, 4, and 5, and from this information start developing calculational methods for predicting the background induced in the crystal detector in order to correct the Apollo gamma-ray spectrometer data for this interference.

EXPERIMENT PROCEDURE

A NaI(Tl) crystal assembly physically identical to that flown aboard Apollo 15 and 16 was used in this experiment (Harrington, et al., 1974). The assembly aboard the Apollo 17 CSM did not include the photo-multiplier, the proton anti-coincidence mantle, and the thermal shield. The detector was a 7 cm x 7 cm right cylindrical crystal. A glass plate was optically sealed to the crystal. MgO was used as the optical reflector inside the crystal assembly. This type of assembly permitted the crystal to be hermetically sealed, and allowed for a simple procedure for optically coupling the crystal assembly to a photo-multiplier tube after flight. The crystal and reflector were enclosed in a steel jacket. An identical second crystal assembly which was not flown was used as a control throughout the measurement program. After splashdown, the flight (i.e., activated) crystal was returned to the recovery ship and optically mounted on a photo-multiplier tube and pulse height spectra were obtained. The activated crystal was counted in a large steel low-level shield. The crystal counting started about one and a half hours after the Command Module re-entered the earth's atmosphere. Before splashdown the control (unactivated) crystal was optically sealed to a photo-multiplier tube and the background was determined in the steel shield. The same photo-multiplier tube was used to count the activated and control crystal assemblies. After 30 hours of counting aboard the recovery ship, the detector was flown back to the Oak Ridge National Laboratory (ORNL) where measurements were continued. This permitted observation of the decay of longer-lived induced activities. Direct measurements of the induced activities were made by again, optically sealing a photo-multiplier tube to the activated crystal. Indirect measurements using both Ge(Li) detectors and a large scintillation 4π detector in a low level counting system at ORNL (Eldridge, et al.,) were performed in order to determine the spectral distribution and intensity of the emitted radiations. The 4π scintillation counter is divided into two halves. Both halves can be operated so as to require that there be coincident events in both halves before an event is analyzed and recorded (coincidence spectra) or both halves can be operated without the coincidence requirement and events independent of their coincidence can be analyzed and recorded (singles spectra). The counting of the crystal was continued at the Oak Ridge National Laboratory and at the Goddard Space Flight Center for about a year in order to determine long-lived nuclear species produced by irradiation during space flight.

COMPUTATION SCHEME FOR INDUCED ACTIVITY

It is essential both for correction of Apollo 15 and 16 data and for background assessment in future missions that an extensive computation scheme be developed. In-flight data can then be adequately interpreted and used to improve the model. Such a model is being developed by Dyer and Seltzer at GSFC and is summarized in the flow diagram of Figure 1. A fuller description is in preparation. The method is basically that described in Dyer and Morfill (1971) but using greatly improved input data. Spallation cross-section data are accumulated from a number of sources including the semi-empirical estimates of Silberberg and Tsao (1973), and the Monte Carlo intranuclear cascade codes of Bertini, et al., (1971). A photon transport code is used to compute a library of energy-loss spectra of decaying nuclides inside detector materials as updated decay-scheme data become available from the ORNL Nuclear Data Center. Because of particle-gamma and gamma-gamma coincidences, such spectra are very different from those produced by external photon sources. Examples of such spectra computed for the Apollo-sized crystal, are given in Figures 2 and 3 for two isotopes which are of significance for the Apollo 17 data. Iodine - 124 is an example of neutron deficient species in which the underlying continuum is produced by the β^+ - branches and the line features by electron-capture modes. The Na-24 response is typical of β^- decay in which the β^- spectrum is shifted by coincidence with one or more gamma rays. Thus far response functions have been computed for 70 isotopes. This is sufficient to cover trapped radiation effects and the bulk of cosmic-ray activation.

Programs have been developed which take input particle spectra, modify for ionization energy loss, and calculate the production and decay rates of radioactive nuclides under appropriate dosage models. Daughter and granddaughter species are followed where necessary.

It is hoped to improve the cross-section estimates by comparison with controlled monoenergetic beam irradiation results and the entire scheme by comparisons with in-flight and return data. At present this scheme considers only primary cosmic ray and trapped protons. However, it can be readily interfaced with codes which predict the spectra of cascade particles produced in heavy spacecraft. In view of the results presented below, development of such codes would seem to be of considerable importance.

RESULTS AND INTERPRETATION

The methods outlined above have enabled qualitative identification of the following nuclear species: I_{126}, I_{125}, I_{124}, I_{123}, Xe_{127}, Te_{125m}, Te_{123m}, Te_{121m}, Te_{121}, Na_{24}, Na_{22}. There is also possible indication of I_{128} in a component of half-life about 28 mins. in the range 0.2 - 1 MeV obtained from internal monitoring carried out on board the carrier.

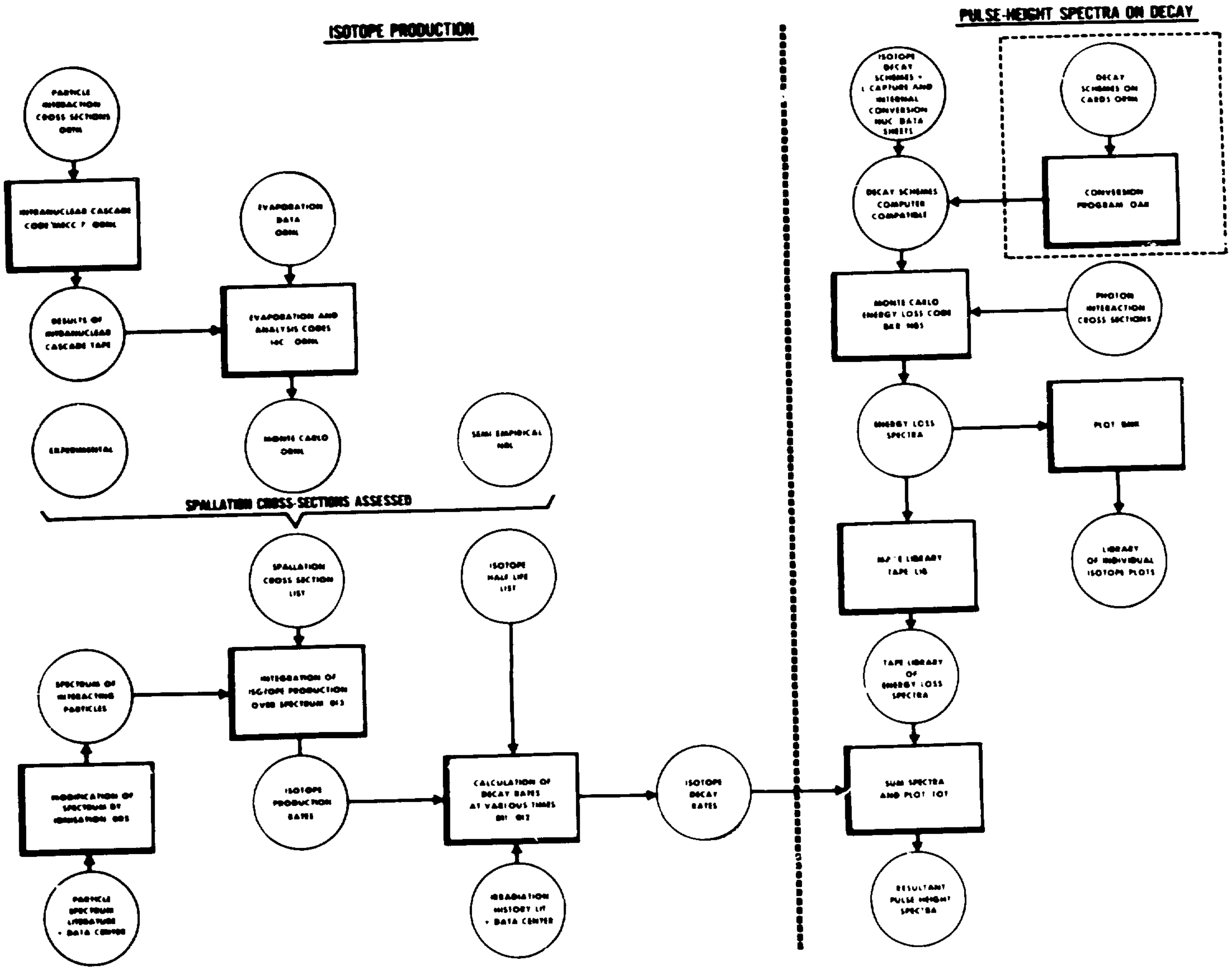

Figure 1. Flow Diagram of Spallation Activation Computation

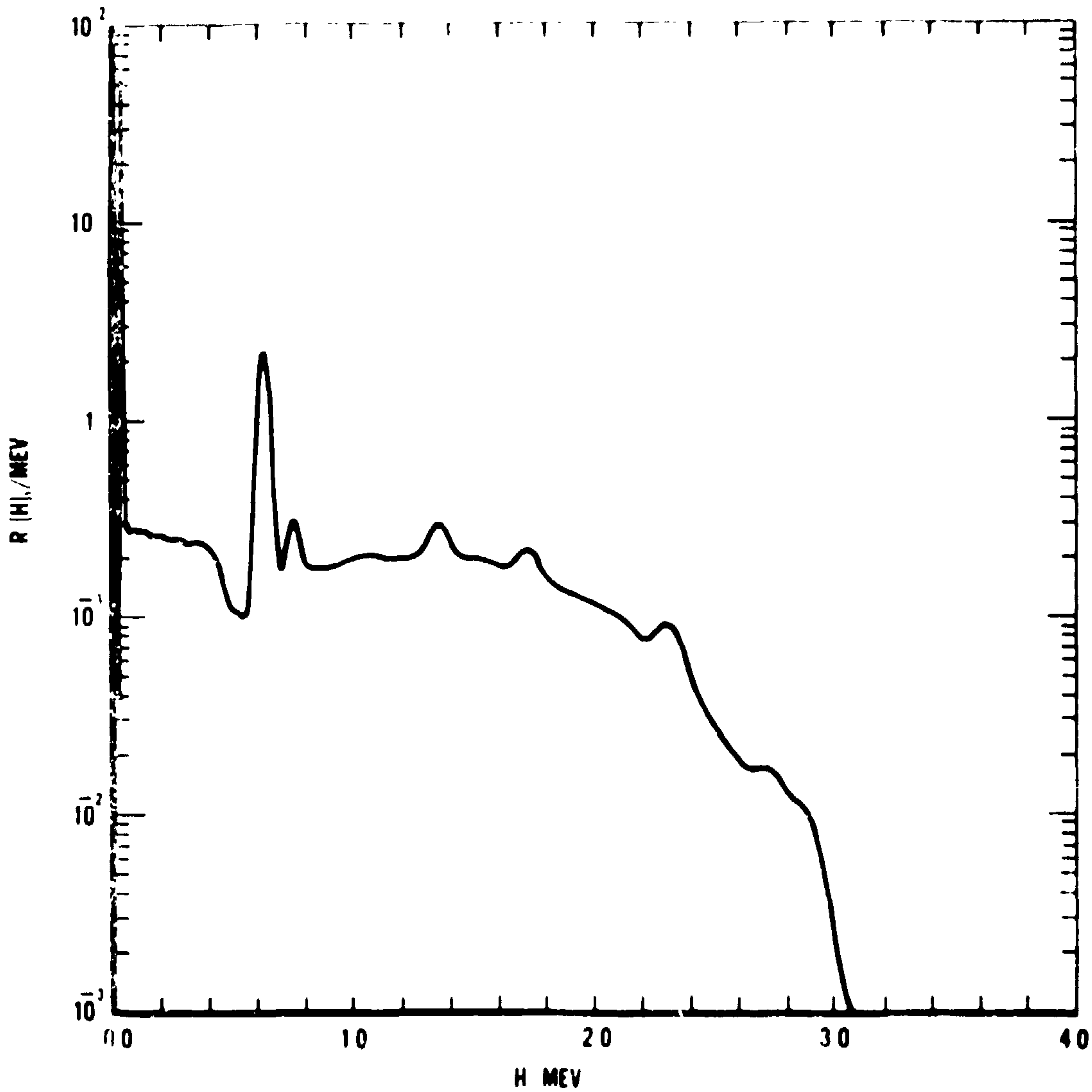

Figure 2. Computed Response Function for I_{124} Decay Inside Apollo 17, NaI(Tl) Crystal. The Underlying Continuum Results From Several β^+ Branches While Line Features Result From Electron Capture Modes

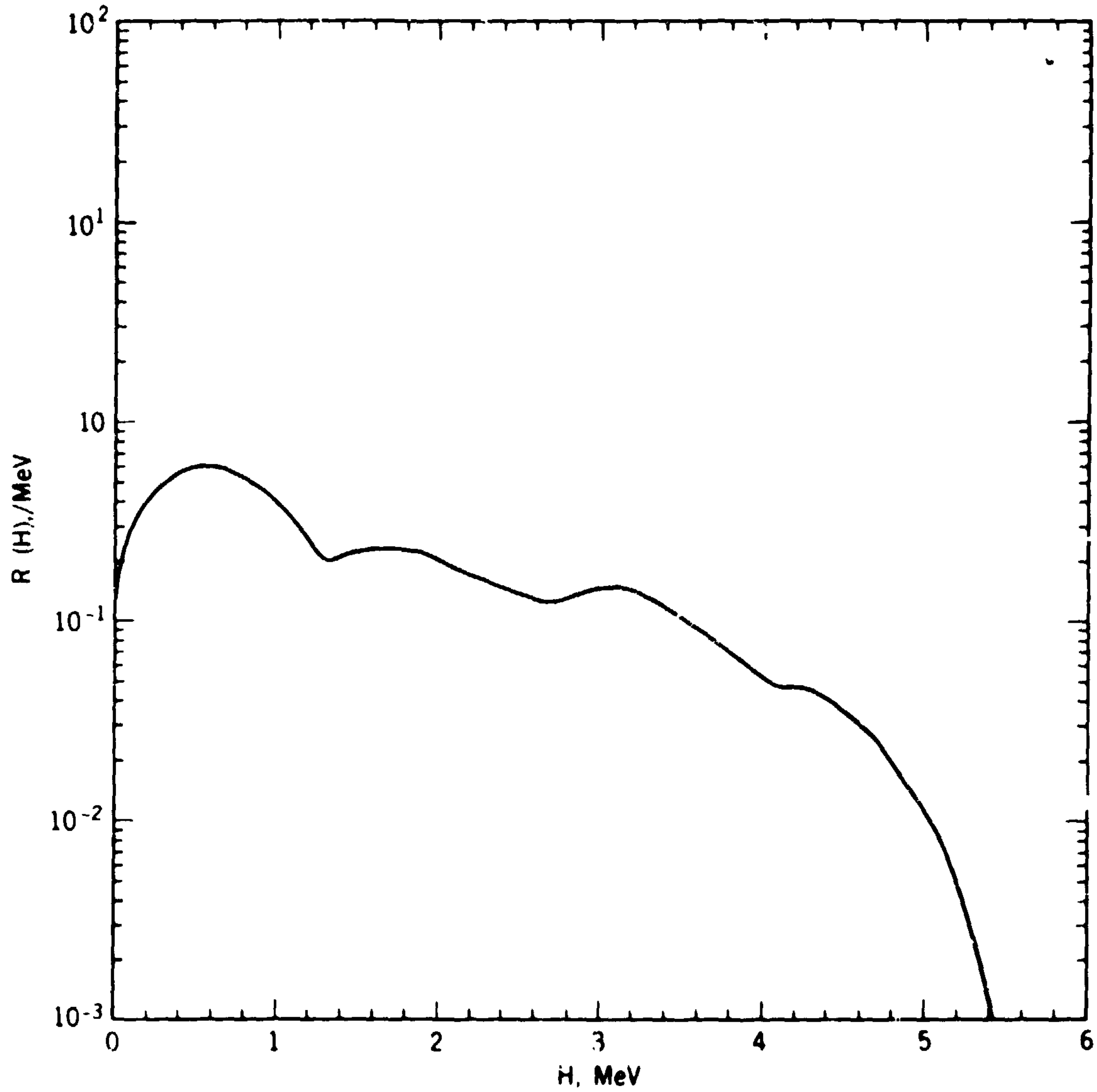

Figure 3. Computed Response Function for Na_{24} Decay Inside the Detector Crystal. A Continuum Results From β^- Spectra Shifted by Coincidence with One or More Gamma-Rays

The earliest spectrum was obtained 1 1/2 hrs. after re-entry and is shown in Figure 4 with identification of the major line features. Comparison is made with estimated and applied spallation corrections. It can be seen that the level is a factor of two higher than the correction applied to Apollo 15 in-flight data. The spallation calculations of Dyer and Morfill (1971) show that the in-flight equilibrium level will decay by about a factor of two after 1.5 hrs. so that the Apollo 17 return activation is clearly a factor 2 to 4 higher than expected. In order to assess any possible activation contribution arising from trapped radiation dosages received on launch and/or landing, accurate trajectory integration of dosages has been carried out by Stassinopoulos at the GSFC Data Center. Results for Apollos 15 to 17 are presented in Table 1 and compared with the accumulated cosmic ray dosage. A mean amount of shielding of about 18 gm cm^{-2} sets an energy threshold of 100 MeV for activating protons. Clearly the landing dosage is likely to be of little significance but the launch dose requires further investigation.

Table 1

Proton Dosages

(Dosage in Protons cm^{-2} >100 MeV)

Mission	Launch	Landing
Apollo 15	3.6×10^2	Crystal not returned
Apollo 16	2.5×10^6	Crystal not returned
Apollo 17	2.7×10^6	2.7×10^4

cf mission integrated cosmic-ray dosage ~ 3.2×10^6

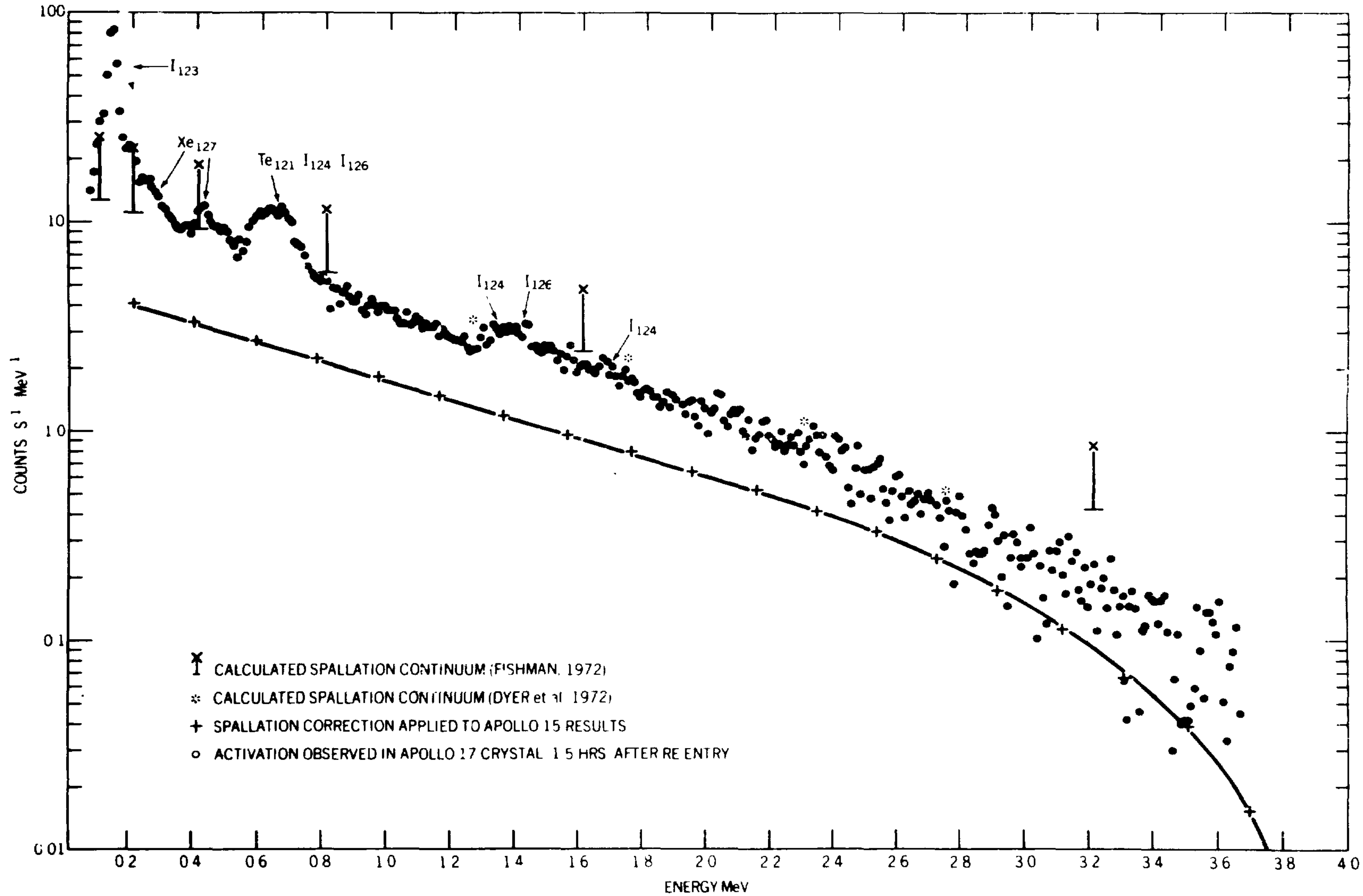

Figure 4. Activation Observed by Direct Internal Counting of Apollo 17 Crystal 1.5 Hrs. After Re-entry. Counting Time was 30 Minutes and Background has been Subtracted. Line Features have been Identified Where Possible Using Computed Response Functions and Later Observations of Their Decay

Coincidence measurements made using the 4π counter have enabled quantitative measurement of the isotopes I_{126}, I_{124}, Na_{24}, Na_{22}. The results extrapolated to splashdown are given in Table 2 and compared with predictions based on the various dosages. Also included are the predicted decay rates of certain long-lived isotopes which are observed internally. Figure 5 shows such a spectrum observed internally in the return crystal at the Oak Ridge low background facility 43 days after splashdown. The gain of the spectrometer was adjusted to look at the low energy portion of the pulse-height spectrum and background has been subtracted. Comparison is made with prediction based on the launch dose numbers of Table 2 decayed to 43 days. Although the shapes are well predicted there is almost an order of magnitude discrepancy in intensity. This discrepancy can also be seen in the externally measured decay rates. At present the calculation should certainly be good to a factor 2 and so an alternative explanation must be sought. It should be noted that although the trapped proton dosage on launch is comparable with the cosmic ray dosage, the former is less efficient at producing activation because energy-loss by ionization removes particles before they can interact. An important clue for interpretations of these results comes from the high measured value for Na_{24} decay. This isotope is a major contribution to the spectrum of Figure 4 and gives nearly all the counts in the 3-5 MeV region. The decay curve in this energy region clearly shows the appropriate 15 hr. half-life. The results imply that the Apollo 17 return crystal must have been subjected to a flux of thermal neutrons ($<$2eV) of about 1.5 $cm^{-2}Sec^{-1}$ throughout the mission. This flux level is similar to thermal neutron dosage estimates obtained from personnel dosimeters carried by the astronauts (English, et al., 1973). The high level of activation could then be due to a significant flux of energetic secondary neutrons produced in the heavy spacecraft. A flux of 10 to 100 MeV neutrons of about 5 $cm^{-2}Sec^{-1}$ throughout the mission would be required to give the observed quantities of the isotopes presented in Table 2.

Important features in the low energy activation results of Figure 5 are peaks at around 30 KeV, 40 KeV and 68 KeV. The latter two peaks are characteristic of I_{125} decay inside detector material. The 30 KeV peak is a superposition of K-capture decay lines and decays faster as can be seen from Figure 6 taken after 80 days. Similar low energy features have been observed to follow 155 MeV irradiation of CsI scintillator (Carpenter and Dyer, 1973) and are seen in background data from the UCSD, hard x-ray telescope on OSO-7 (McKay, Ulmer and Peterson; private communication).

Table 2

Measured and Predicted Decay Rates

Isotope	4π Measurement Decays Per Min.	Predicted Decay Rates From		
		1) Cosmic Rays	2) Launch	3) Landing
			Trapped Radiation	
Na_{22}	2.6 ± 1.4	0.26	0.15	0.002
Na_{24}	100.0 ± 40	Evidence for thermal neutrons		
I_{124}	300.0 ± 80	21.1	3.94	0.31
I_{126}	300.0 ± 150	27.0	11.2	0.22
Xe_{127}	Observed internally	0.15	1.4	0.02
I_{125}	Observed internally	4.7	6.5	0.08
Te_{125m}	Observed internally	1.41	1.0	0.01
Te_{123m}	Observed internally	0.71	0.38	0.004
Te_{121m}	Observed internally	0.55	0.23	0.002
Te_{121}	Observed internally	4.2	2.6	0.03

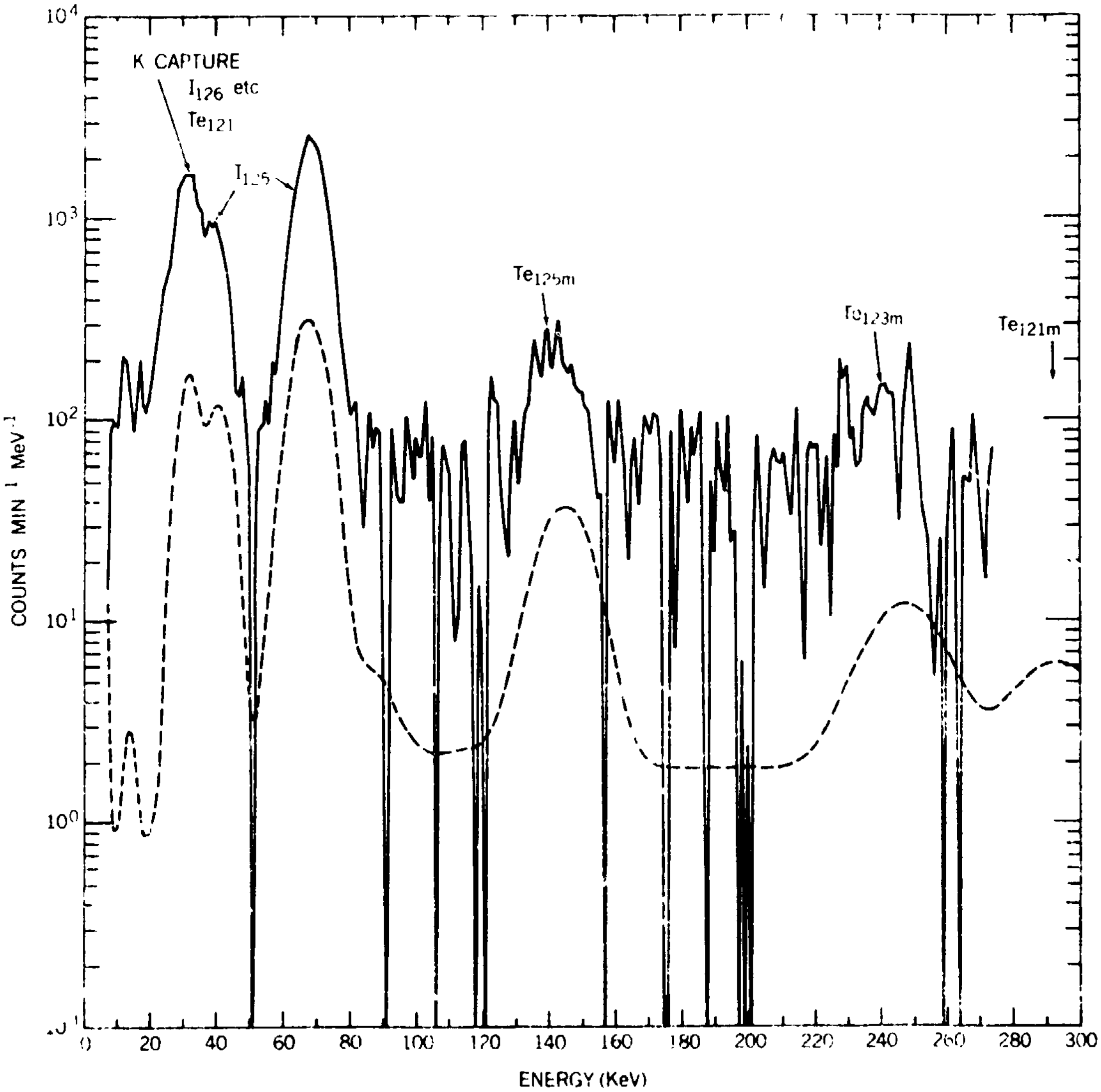

Figure 5. Low Energy Spectrum of Induced Activation Obtained by Internal Counting 43 Days After Splashdown. Comparison is Made with a Predicted Spectrum Based on the Isotopes and Launch-dose Decay Rates of Table 2. The Features are Well Predicted and the Discrepancy in Intensity would seem to be due to a High Flux of Secondary Neutrons Produced Throughout the Heavy Spacecraft

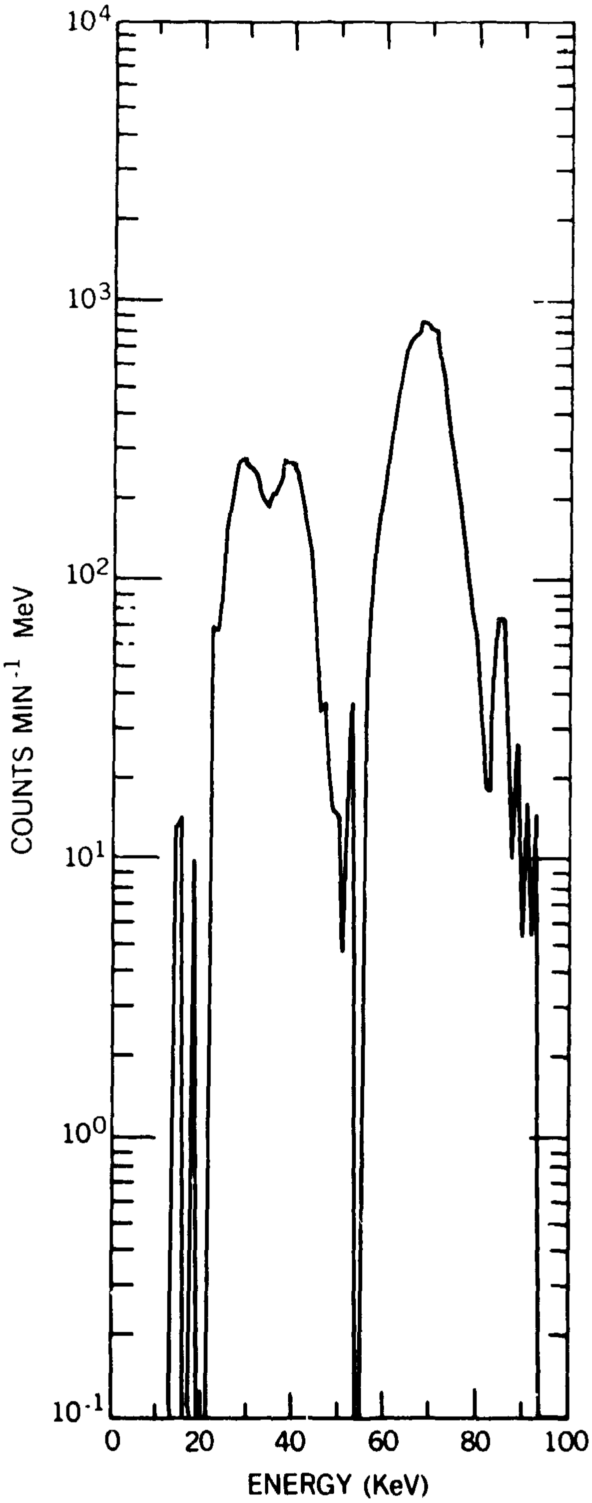

Figure 6. Peaks at 40 KeV and 68 KeV Persist in an Internal Spectrum Accumulated 80 days After Splashdown, and are Attributable to I_{125} Decay (τ 1/2 = 60 days). The Peak at Around 30 KeV is due to Other K-Capture Isotopes and is Seen to Decay More Rapidly

DISCUSSION OF IMPLICATIONS

The Apollo 17 return crystal results have shown the importance of activation effects resulting from secondary neutrons. Future work must determine the extent to which such effects were present in the Apollo 15 and 16 crystal spectrometers which were carried in the service module. Preliminary work on looking for decay rates following boom extension suggests that the thermal neutron flux must have been considerably lower in this location. However, the energetic neutron flux could have been comparable. Preliminary results from foils carried on Skylab IV (Fishman, 1974) show thermal neutron fluxes lower by at least an order of magnitude than the Apollo 17 fluxes. However, there may have been considerable fluxes of high energy neutrons (J. Baum, private communication). Neutron dosages and spectra would seem to be both spacecraft and location dependent. Because of the very high rates of background which can result from such effects, it is of crucial importance that spectrometers and passive foils be flown and returned on the Apollo-Soyuz mission.

A wealth of data from the Apollo 17 mission has now been assembled. Using computed response functions it should be possible to obtain useful information on the secondary neutron spectrum. It is also hoped that monoenergetic beam irradiation experiments can be performed to measure the short half-life isotopes which are missed in such return procedures.

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