

Lawrence Berkeley National Laboratory

Lawrence Berkeley National Laboratory

Title

BETA DECAY MEASUREMENTS OF NEUTRON DEFICIENT CESIUM ISOTOPES

Permalink

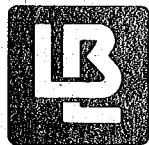
<https://escholarship.org/uc/item/5sr734tb>

Author

Parry, R.F.

Publication Date

1983-03-01



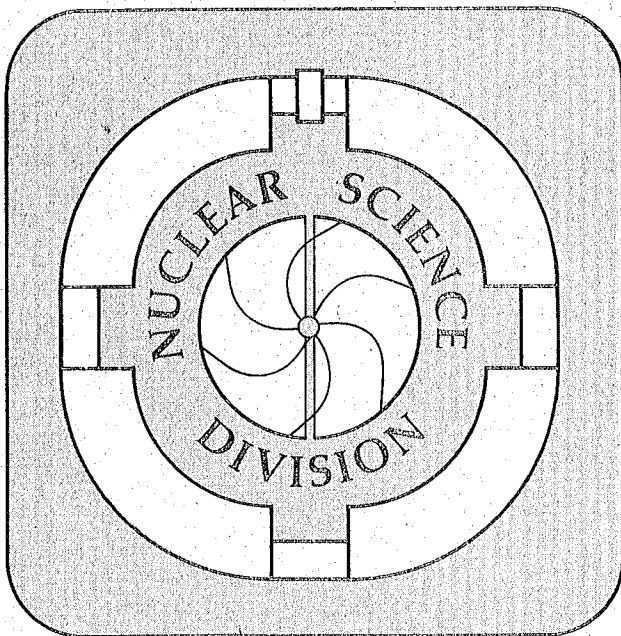
Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

BETA DECAY MEASUREMENTS OF NEUTRON DEFICIENT CESIUM ISOTOPES

Roger Franklin Parry
(Ph.D. Thesis)

March 1983



LEGAL NOTICE

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

BETA DECAY MEASUREMENTS OF NEUTRON DEFICIENT CESIUM ISOTOPES

by

Roger Franklin Parry

Department of Chemistry and
Lawrence Berkeley Laboratory
University of California
Berkeley, CA. 94720

Beta Decay Measurements of Neutron Deficient Cesium Isotopes

Table of Contents

Abstract

I.	Introduction	1
II.	Theory	5
	A. The collective model	5
	B. Beta decay	13
	1. Allowed transitions	13
	2. Forbidden transitions	17
	3. Log ft	20
	4. Electron capture	22
	5. Effects of deformation on beta decay	22
III.	Experimental	25
	A. Isotope production	25
	B. Mass separation - RAMA	28
	C. Tape transport	31
	D. Detection instrumentation	35
	E. RAMA computer system	40
IV.	Analysis of beta spectra	48
	A. Fermi-Kurie	49
	B. Stretch fitting	55
V.	Results	65
	A. ^{123}Cs	65
	B. $^{122\text{m,g}}\text{Cs}$	69
	C. ^{121}Cs	76

D. ^{120}Cs	80
E. ^{119}Cs	84
VI. Discussion	89
VII. Summary and Conclusions	103
Acknowledgements	106
Appendix A - Wapstra xenon and cesium mass excess values	108
Footnotes	110
References	111

BETA DECAY MEASUREMENTS OF NEUTRON DEFICIENT CESIUM
ISOTOPES

Roger Franklin Parry

Department of Chemistry and
Lawrence Berkeley Laboratory
University of California
Berkeley, CA. 94720

ABSTRACT

The study of nuclei far from beta stability provides information on nuclear binding energies and nuclear structure. However, as one progresses away from the valley of stability, the associated half-lives and production cross sections decrease with increasing interference from the decays of adjacent nuclei. An experimental solution to these problems was the use of the He-jet fed on-line mass separator, RAMA. This instrument provided a fast and selective technique for the mass separation necessary for the investigation of exotic nuclei. Using this device, a beta decay Q-value study of the neutron deficient cesium isotopes, $^{119-123}\text{Cs}$, was conducted.

Beta decay endpoint energy measurements of the neutron deficient cesium isotopes were done using an energy spectrum shape fitting technique. This was a

departure from the typical method of endpoint energy analysis, the Fermi-Kurie plot. A discussion of the shape fitting procedure and its improved features are discussed.

These beta endpoint measurements have led to total decay energies (Q_{EC}) of the neutron deficient $^{119-123}\text{Cs}$ isotopes. The total decay energies of ^{122m}Cs ($Q_{EC} = 6.95 \pm 0.25$ MeV) and ^{119}Cs ($Q_{EC} = 6.26 \pm 0.29$ MeV) were new measurements. The total decay energies of ^{123}Cs ($Q_{EC} = 4.05 \pm 0.18$ MeV), ^{122g}Cs ($Q_{EC} = 7.05 \pm 0.18$ MeV), ^{121}Cs ($Q_{EC} = 5.21 \pm 0.22$ MeV), and ^{120}Cs ($Q_{EC} = 7.38 \pm 0.23$ MeV) were measurements with significantly improved uncertainties as compared to the literature. Further, a combination of the energy levels derived from previous literature gamma-gamma coincident measurements and the experimental beta-coincident gamma decay energies has supported an improved level scheme for ^{121}Xe and the proposal of three new energy levels in ^{119}Xe .

Comparison of the experimental cesium mass excesses (determined with our Q_{EC} values and known xenon mass excesses) with both the literature and theoretical predicted values showed general agreement except for ^{120}Cs . This isotope displayed a deviation of ~ 800 keV in both comparisons with the experimental value. Possible explanations for this deviation are discussed.

I. Introduction

The study of mass excesses of nuclei far from stability, or exotic nuclei, provides information on binding energies and nuclear structure. Determination of mass excesses of these nuclei provides a means for extrapolation to unknown regions of the associated mass surfaces as well as additional data for establishing better theoretical models predicting systematic and structural trends in other unknown nuclei. These measurements complement other investigations into independent particle models examining shell trends, collective features highlighting binding energy differences due to deformation effects, and the effect of various nuclear configurations on radioactive decay, such as the population of high spin states, and forbidden decay modes.

Several methods exist for determination of mass excesses. Recent experimental techniques have focused on application of mass spectroscopy to provide information leading to mass excesses. These methods have involved time-of-flight (ROB77) and direct mass measurement (EPH79) procedures. Another technique involves measurement of reaction Q-values, in which multinucleon transfer reactions, such as $(p, {}^6\text{He})$, $({}^3\text{He}, {}^6\text{He})$, and $({}^4\text{He}, {}^8\text{He})$, provide information on both particle unbound and bound

exotic nuclei (SAN76). These methods yield precise masses for a considerable number of nuclei.

A common method for studying heavier exotic nuclei is the measurement of decay Q-values. Beta decay, alpha decay, and beta-delayed particle decays are used, some in conjunction with gamma ray studies, to deduce mass excesses using previously known masses. Decay Q-value measurements also provide additional information for nuclear structure studies with respect to determination of spins, excited states, and nuclear forces (as in the case of the weak interaction in beta decay).

The experimental study of exotic nuclei poses many problems. One must contend with significantly short half lives, from seconds to milliseconds, reduced production cross sections, and large numbers of associated competing reactions that produce products whose decays can mask the specific nuclide of interest.

The experimental solution to these problems has been directed towards a system which provides directly A and/or Z selectivity on line, or ISOL (Isotope Separator On Line) device. A typical example of such a system is the ISOLDE facility at CERN (KJE70). This ISOL system contains an integrated target-ion source configuration such that product recoil nuclei diffuse out of the target into the source. Z selection is accomplished by elemental specific ion sources in which diffusion times range on the order of 50 to 500 milliseconds depending on target material and

ion source temperature. Coupled to a mass separator, the facility provides a fast and selective means for isolation and study of exotic nuclei.

Another approach to the ISOL system has been the use of a He-jet to couple the recoils produced in the target chamber to the ion source of a mass separator system. The Recoil Atom Mass Analyzer, RAMA, at the 88 inch cyclotron of Lawrence Berkeley Laboratory (MOL80a, MOL80b, MOL81) exemplifies this type of system. It has the direct A (and minor Z selection by judicious choice of light and heavy ion fusion reactions) needed to study nuclei far from stability. Numerous other mass separation facilities have been constructed using both of these techniques in a variety of environments. A discussion of these facilities and the problems and physics involved are found in several review articles (HAN79, RAV79, HAM81).

Initial experiments with the RAMA system investigated the beta-delayed proton emission of several light, $A=4n$, $T_z = -2$, nuclei for the application of the isobaric multiplet mass equation (AYS79, MOL79a, AYS81) and determination of mass excesses, through beta decay Q-value measurements, of the light indium isotopes near the doubly magic nuclide ^{100}Sn (WOU83). These studies have been expanded as discussed here to include neutron deficient cesium isotopes (five protons in excess of the $Z=50$ proton shell closure). Numerous prior investigations have studied these cesium nuclei and found the region

especially interesting due to the deformed nuclear shapes and the occurrence of rotational spin isomerism (GAR78, CH078). The light cesium isotopes have also been investigated using a new direct mass measurement technique using ISOLDE (EPH79,AUD82). However, questions as to the accuracy of some of these prior measurements have arisen. Experimental investigation of the light cesium beta decay Q-values then provides an independent assessment of the light cesium mass excesses.

II. Theory

This section will present a brief description of the pertinent theory describing the rotational characteristics of the cesium isotopes along with the occurrence of spin isomerism. Following this discussion will be a summary of allowed beta decay as it relates to the analysis of the endpoint measurements of the neutron deficient cesium isotopes. An expanded section will continue concerning the beta decay of nuclei with first forbidden characteristics. The conclusion of this section will summarize briefly the effects of the collective nuclear motion on the beta decay process.

A. The collective model

A general description of the nuclear properties expected in the cesium isotopes is obtained by examining the nuclei in light of the collective model. One expects spherical shapes close to the shell closures in both $50 \leq (N, Z) \leq 82$, where simple shell model descriptions are adequate. However, as one progresses away from these shell closures, increasing deformation from the classical spherical shape can be expected (DES74).

A maximum of deformation would be expected in the center of the nuclidic region bounded by the respective

shell closures. The surface between the $Z=50$ and $N=82$ shell closures and this maximum has been denoted a transition region (ARS69) where there exists both rotationally deformed and spherical nuclear shapes. The neutron deficient cesium isotopes consequently are described as transition nuclei. A description of the intrinsic structure for the distorted cesium isotopes and the spin isomerism is approached from collective motions that lead to a deformed nuclear internal wavefunction constructed with independent-particle wavefunctions in a deformed potential.

The general method of generating these deformed particle states is to develop wavefunctions from a modified spin-dependent central potential. The Hamiltonian used includes an intermediate form of the shell-model harmonic oscillator potential with terms that lead to a tailing square-well potential with increasing deformation (PRE62). The Hamiltonian has included in it a spin-orbit interaction term, $l \cdot s$, and a l^2 term which artificially produces the splitting between levels with different values of l . These terms simulate the transition in the distorted particle wave function potential from a harmonic oscillator where all the l values within a major shell are degenerate, to a square-well potential where higher l -levels in a major shell are of lower energy than the lower l -levels.

A Hamiltonian that results from this treatment is the

Nilsson Hamiltonian (NIL55)

$$\begin{aligned}
 H &= H_0 + V_{\text{osc}} + V_{\ell,s} \\
 &= -\hbar^2/2M \sum_i \nabla_i^2 + 1/2M \sum_i (w_x^2(x_i^2+y_i^2) + w_z^2 z_i^2) + \\
 &\quad (A \sum_i \ell_i \cdot s_i + B \sum_i \ell_i^2)
 \end{aligned}$$

The first two expressions specify a 3-dimensional harmonic oscillator Hamiltonian and the third the spin-orbit interaction and the angular momentum level splitting terms.

At very large deformations, the $V_{\ell,s}$ term can be neglected in comparison to V_{osc} term. This leads to the asymptotic quantum numbers

$$\Omega, (N, n_z, \Lambda)$$

which are derived from the solution of the 3-dimensional harmonic oscillator Hamiltonian. The value of N is given as $n_x+n_y+n_z$ where $n_{x,y,z}$ are the three harmonic oscillator quantum numbers. For any given value N and n_z , the z -projection of the two-dimensional orbital angular momentum that is, Λ , takes on the values

$$\Lambda = \pm n, \pm(n-2), \pm(n-4), \dots, \pm 1, \text{ or } 0 \text{ for } n = N - n_z$$

since the states in a harmonic oscillator shell have the same parity. Ω , the z-projection of the total angular momentum of the particle level follows

$$\Omega = \Lambda \pm 1/2$$

and is two-fold degenerate. The parity of the state is given simply as

$$\pi = (-1)^N$$

and the z-oscillator quantum number satisfies

$$n_z \leq N.$$

The deformation in the harmonic oscillator potential is established by introducing the quadrupole deformation parameter ϵ and a frequency ω_0 (DAV68)

$$\omega_z^2 = \omega_0^2(1-4/3\epsilon) \quad \omega_x^2 = \omega_y^2 = \omega_0^2(1+2/3\epsilon)$$

with the restriction of constant nuclear volume, $\omega_x \omega_y \omega_z =$ constant, or

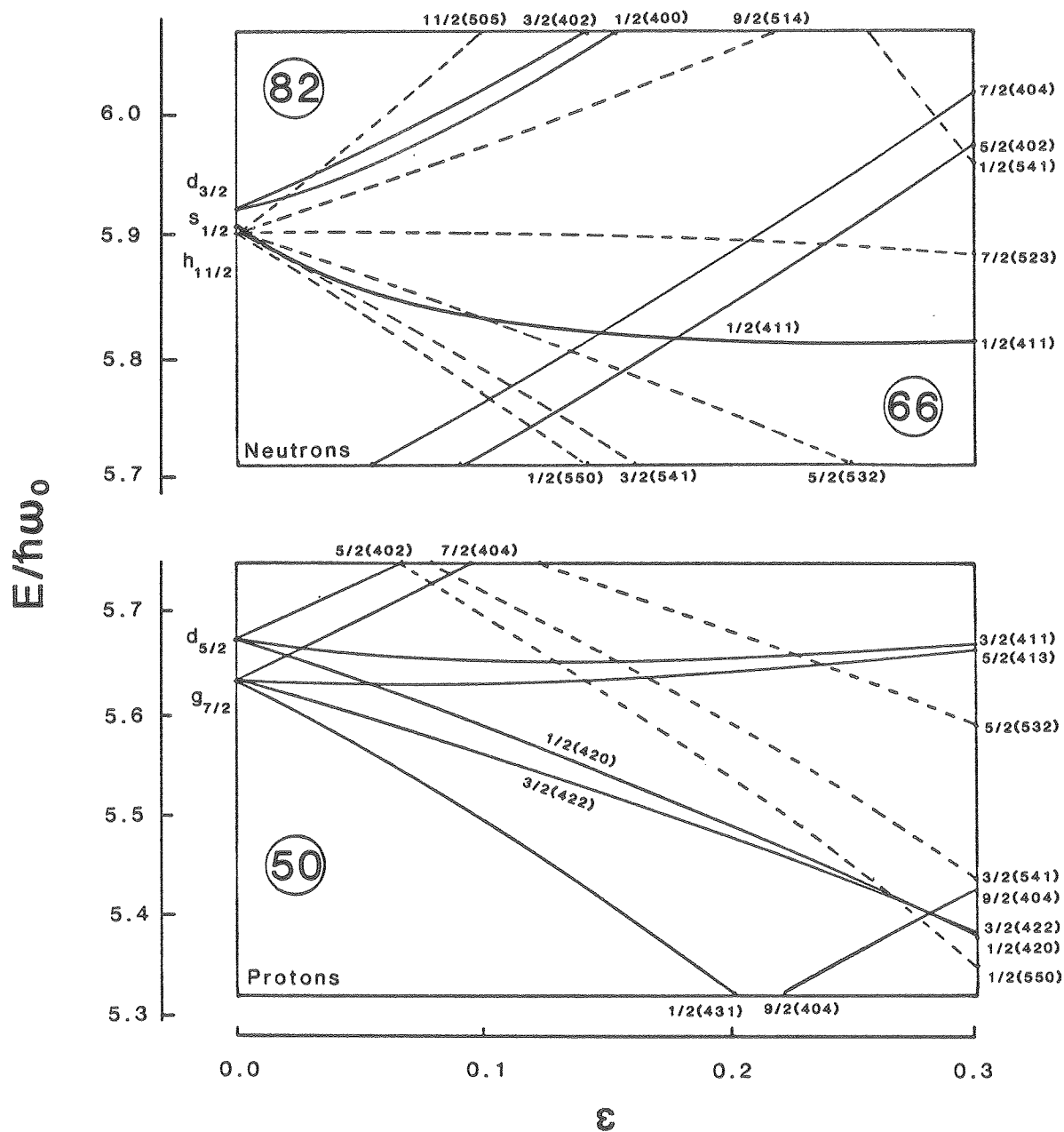
$$\omega_0 (1 - 4/3\epsilon^2 - 16/17\epsilon^3)^{1/6} = \text{const} = \omega_{00}.$$

Calculation of the single-particle energy levels using

this model (referred to as a Nilsson diagram) has been done for the pertinent shell parameters for the cesium isotopes by Ekström et al. (EKS77) and results in the diagrams shown in figure 1 for both neutrons and protons. The shell-model states $g_{7/2}$, $d_{5/2}$, $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ are available as odd-proton and odd-neutron states in the region $50 \leq N, Z \leq 82$.

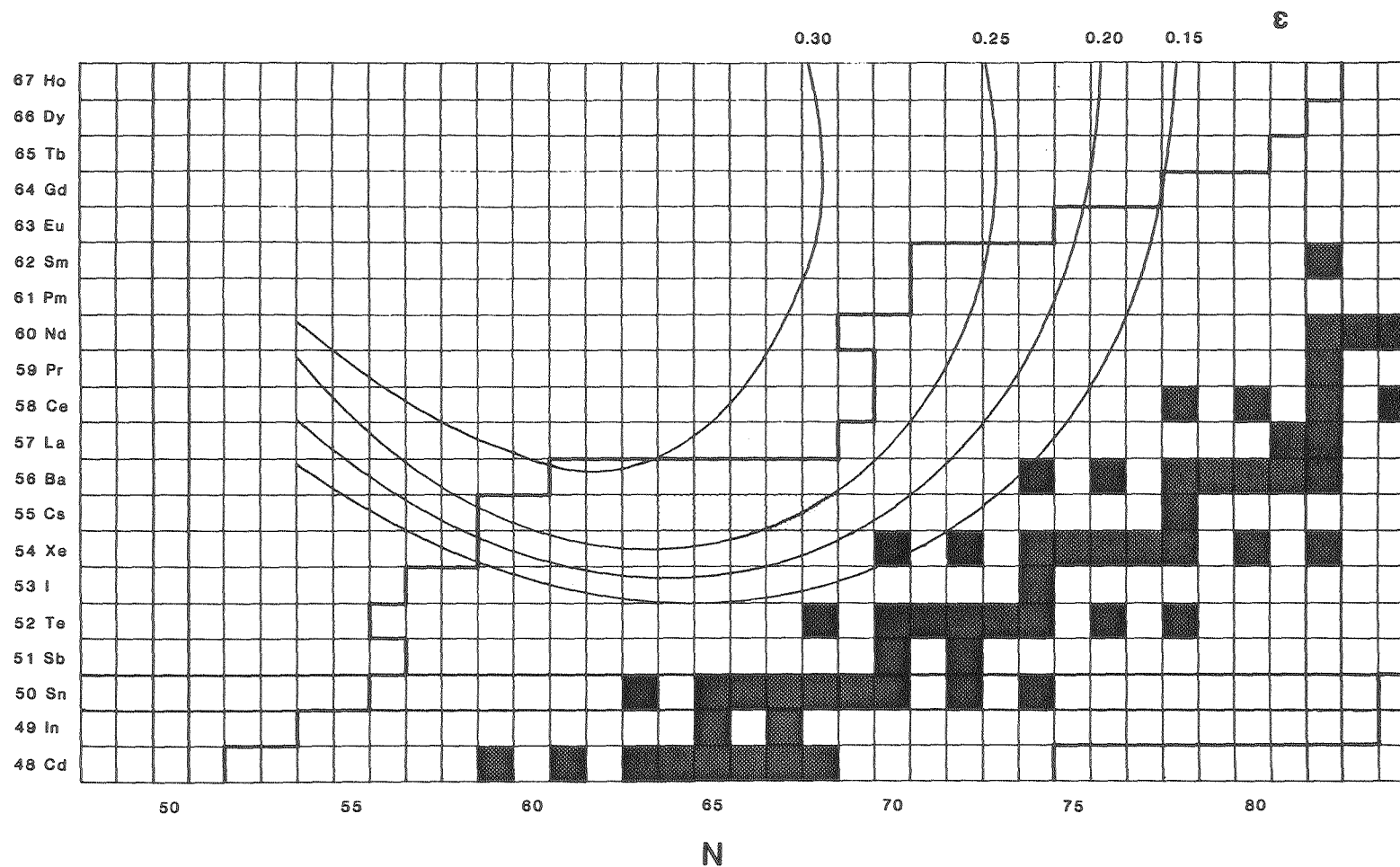
Arseniev et al. (ARS69) have calculated deformation values for prolate shapes in the region of the light cesium and xenon isotopes (figure 2). Typical deformations from these calculations for the isotopes $^{119-123}\text{Cs}$ yield $\epsilon \leq 0.25$ with an increase in deformation with decreasing A. Application of this value of deformation to figure 1 indicates that there are three even-parity orbitals available as odd-proton ground states, $1/2(420)$, $3/2(422)$, and $9/2(404)$. These correspond to deformed orbitals from $d_{5/2}$, $g_{7/2}$, and $g_{9/2}$ shell-model states. The odd-N, even-A cesium isotopes, ^{120}Cs and ^{122}Cs , have three even-parity orbitals available for the odd-neutron configuration, $5/2(413)$, $3/2(411)$, and $1/2(411)$. These correspond to deformed levels from $g_{7/2}$, $d_{5/2}$, and $s_{1/2}$ shell-model states. The isomeric levels in the light cesiums become apparent due to the accessibility of the $9/2(404)$ proton and the $7/2(523)$ neutron orbitals to first excited states.

The deformed single-particle configurations for the light cesium isotopes have been proposed by Ekström and



XBL 831-7906

Figure 1. Nilsson diagrams for odd-proton and odd-neutron levels. ϵ is the quadrupole deformation parameter. Solid lines represent the even parity and dashed lines the odd parity states [from Ekström et.al. (EKS77)].



XBL 831-7929

Figure 2. Portion of the nuclear chart showing stable (darkened squares) and known radionuclides (bound by heavy lines). The cesium isotopes investigated in this work are shown by cross-hatched squares. The isodeformation curves for prolate deformations were obtained from Nilsson-model calculations of Arseniev et al. (ARS69).

Nucleus	I^π	$\Omega [N, n_z, \Lambda]$	
		Odd proton	Odd neutron
^{123}Cs	$1/2^+$	$1/2 [420]$	-
$^{122\text{m}}\text{Cs}$	8^-	$9/2 [404]$	$7/2 [523]$
$^{122\text{g}}\text{Cs}$	1^+	$3/2 [422]$	$1/2 [411]$
$^{121\text{m}}\text{Cs}$	$9/2^+$	$9/2 [404]$	-
$^{121\text{g}}\text{Cs}$	$3/2^+$	$3/2 [422]$	-
^{120}Cs	2^+	$9/2 [404]$	$5/2 [413]$
$^{119\text{m}}\text{Cs}$	$3/2^+$	$3/2 [422]$	-
$^{119\text{g}}\text{Cs}$	$9/2^+$	$9/2 [404]$	-

Table 1. Deformed single particle configurations for selected neutron deficient cesium isotopes. From Ekström et al. (EKS77, EKS78).

are listed in table 1. The ground state spin sequence $I^\pi = 1/2^+ (^{123}\text{Cs})$, $3/2^+ (^{121}\text{Cs})$, and $9/2^+ (^{119}\text{Cs})$ supports the observation of increasing deformation with decreasing mass number.

B. Beta decay

1. Allowed transitions

The energy distribution of electrons (or positrons) in an allowed beta decay is determined by the statistical sharing of the decay energy with the antineutrinos (or neutrinos). Additional factors that contribute to the distribution are the Coulomb distortion of the emitted electron (positron) by the nuclear charge and the screening effect of the atomic electrons. Aside from these Coulomb effects, the lepton interaction (both electron and antineutrino) is separate from the nuclear interaction. This is evident in allowed decays where the leptons carry away no component of nuclear orbital angular momentum L and the parity between the initial and final states of the nuclei involved follow as $\pi_i \pi_f = +1$.

The electron-antineutrino pair ejected in the transition must carry off the angular momentum in the form $J = L + S$ where $L = \ell_e + \ell_\nu$ is the total orbital angular momentum and $S = s_e + s_\nu$ is the sum of the intrinsic spins of the emitted leptons. For the leptons to be independent

of the nuclear interaction, the L component of the total angular momentum must equal zero. For allowed transitions, the selection rules then naturally follow from the characterization of the components of the lepton spins which can be set antiparallel ($S = 0$) and parallel ($S = 1$). The two transitions correspond to $J = S$ or

$$\Delta J = | J_f - J_i | = 0 ,$$

the Fermi selection rule, and $J = S = 1$, $J_i = J_f + 1$ or

$$\Delta J = | J_f - J_i | = 0, \pm 1,$$

the parallel or Gamow-Teller selection rules. The latter selection rule omits $0^+ \rightarrow 0^+$ transitions because of the conservation of angular momentum. This stipulates for total angular momentum J, where $J_i = J_f = 0$, the value of $S \neq 0$ and the necessity of antiparallel spins.

The V-A (Vector - Axial-vector) form of the beta decay interaction Hamiltonian (SCH66) details the matrix elements between two nuclear states $|\Psi_i\rangle$ and $|\Psi_f\rangle$ for allowed decays which are of the form

$$\langle 1 \rangle \equiv \langle \Psi_f | \sum_n \tau_{\pm}(n) | \Psi_i \rangle$$

for the vector (Fermi) interaction and

$$\langle \sigma \rangle \equiv \langle \Psi_f | \sum_n \sigma(n) \tau_{\pm}(n) | \Psi_i \rangle$$

for the axial-vector (Gamow-Teller) interaction. σ is the Pauli spin operator (BAY77) and $\tau_{\pm}$ is the particle raising and lowering operator that transforms neutrons to protons in negatron decay and protons to neutrons in positron decay, respectively. The $\tau_{\pm}$ operator acts only on the nuclear components.

These matrix elements for the allowed transitions obey the previously detailed selection rules. It is easily seen that $\langle l \rangle = 0$ unless $\Delta J = 0$, and $\langle \sigma \rangle = 0$ unless $\Delta J = 0$, or 1 and both vanish identically if $\Delta \pi = \text{yes}$.

The expression for the transition probability follows from first order time dependent perturbation theory and a statistical treatment of the distribution of energy between the electron and neutrino (BAY77, SEG77). It is expressed as

$$P(p_e) = (g^2/2\pi^3) \xi^2 F(\pm Z, W) S(Z, W \mp V_0) p_e W (W_0 - W)^2 e^{\mp} \text{II.1}$$

where p_e is the electron momentum, W is the total decay energy of the electron ($E_{\text{kinetic}} + E_{\text{rest}}$), W_0 the maximum decay energy (or endpoint energy), F is the Coulomb distortion term, S the atomic electron screening term, V_0 the change in potential energy at the nuclear surface due to screening, and ξ the nuclear interaction

$$\xi^2 = C_V^2 \langle 1 \rangle^2 + C_A^2 \langle \sigma \rangle^2 \quad \text{II.2}$$

(C_V and C_A are the effective vector and axial-vector coupling constants). The expressions for F and S are (KON66)

$$F(\pm Z, W) = 4(2p_e^2 R)^{-2(1-\delta_1)} e^{\pi y} \frac{|\Gamma(\delta_1 + iy)|^2}{|\Gamma(2\delta_1 + 1)|^2}$$

$$S(Z, W \mp V_O) = \left[\frac{(W \mp V_O)^{2-1}}{W^2 - 1} \right]^{1/2} \left[\frac{W \mp V_O}{W} \right] e^{\mp}$$

$$\delta_1 = (1 - \alpha^2 Z^2)^{1/2} \quad y = \pm \alpha Z W / p_e \quad \alpha = e^2 / \hbar c = 1/137$$

$$V_O = 1.13 \alpha^2 Z^{4/3}$$

The transition probability can be rewritten in the form

$$K = \left[\frac{N(W)}{S(W, W \mp V_O) F(\pm Z, W) p_e W} \right]^{1/2} = \text{const} \cdot (W_O - W)$$

This expression is commonly used to determine the maximum decay energy, W_O . One plots the experimentally determined electron energy distribution according to this equation

generating a function which is linear and whose intercept determines the maximum decay energy, W_0 . The manipulation is historically known as a Fermi-Kurie plot.

2. Forbidden Transitions

The occurrence of a $J^\pi=8^-$ ^{122m}Cs isomeric level beta decay to a $J^\pi=8^+$ level in the daughter, ^{122}Xe , necessitates a discussion of parity, or first forbidden, transitions. The first forbidden beta decay selection rules are summarized as

$$\Delta J = | J_f - J_i | = 0, \pm 1, \pm 2$$

$$\Delta \pi = \text{yes.}$$

Problems with the experimental determination of the maximum decay energy, W_0 ($E_{0,\text{kinetic}} + E_{\text{rest}}$), can arise since there is a possibility that the experimental shape of the beta decay spectrum will deviate significantly from that of allowed shape. The effect manifests itself when the emitted leptons carry away nuclear orbital angular momentum and thus can no longer be separable from the nuclear matrix elements. This could necessitate corrections to the form of the transition probability to account for these deviations. With the occurrence of a parity change in the decay, the allowed matrix elements

$\langle l \rangle$ and $\langle \sigma \rangle$ will go to zero as mentioned earlier and second order terms in the matrix elements will take effect. There are, however, several second order effects that are energy independent and will produce an energy spectrum with allowed shape.

The matrix elements occurring in the first forbidden transition can be classified according to their origin. The group due to source velocity effects (defined below) will give elements of the form $\langle \alpha \rangle$ and $\langle \gamma_5 \rangle$ (KON65). These elements occur in allowed decay formalization but were neglected on the basis that their effects were of the order of nucleonic velocities within the nucleus and therefore only a few percent of the total magnitude of the allowed transition. $\langle \gamma_5 \rangle$ acts as a scalar and $\langle \alpha \rangle$ acts as a vector surviving only if parity changes in the transition. α is a "polar" vector operator as opposed to the axial-vector operator σ , where α changes sign in reflections through the origin and σ does not. $\langle \gamma_5 \rangle$ is a pseudoscalar and changes sign in reflections through the origin, i.e., $\mathbf{r} \rightarrow -\mathbf{r}$ gives $\gamma_5 \rightarrow -\gamma_5$ (note that σ can be expressed as $-\gamma_5 \alpha$). Other terms arise as retardation effects

$$\langle \mathbf{r} \rangle, \langle \sigma \cdot \mathbf{r} \rangle, \text{ and } \langle \sigma \times \mathbf{r} \rangle$$

where $\mathbf{r}$ is the radial vector.

The first forbidden matrix elements are typically

incorporated into the transition probability through a shape factor (SCH66), S_n (n specifies the order of the transition), where the first forbidden shape is characterized as

$$S_1 = S_1^{(0)} + S_1^{(1)} + S_1^{(2)} .$$

The parity forbidden transition is then composed of a sum of two lepton energy independent factors, $S_1^{(0)}$ and $S_1^{(1)}$, given as (UHL41,SMI51)

$$S_1^{(0)} = C_A^2 \{ \langle \gamma_5 \rangle \pm 1/2 \alpha Z \langle \sigma \cdot r \rangle \}^2$$

$$S_1^{(1)} = (C_V \langle \alpha \rangle \pm 1/2 \alpha Z (C_A \langle \sigma \times r \rangle \mp C_V \langle r \rangle))^2$$

which do not alter the allowed shape of the beta spectrum, and an energy dependent unique shape factor

$$S_1^{(2)} \propto \langle |p+q|^2 \rangle = p^2 + q^2$$

where p and q represent the electron and neutrino momentum, which is primarily responsible for deviations in first forbidden shape. The equation for the transition probability (eq. II.1) now takes the form

$$P(p_e) = (g^2/2\pi^3) S_n p_e W(W_0 - W)^2 F_0(\pm Z, W)$$

where F_0 includes the screening factor. It should be noted that for allowed decays $S_n = S_0 \equiv \xi^2$ (eq. II.2).

Wu (Wu65) points out that the energy dependent term $S_1^{(2)}$ is usually much smaller than the Coulomb shape terms $S_1^{(0)}$ and $S_1^{(1)}$, which are proportional to $Ze^2/2R$. This leads to the expectation of allowed shapes in most parity or first forbidden spectra.

Determination of a distorted shape in first forbidden beta decay can be accomplished as in the allowed case by creating a Fermi-Kurie plot and noting any major deviation from linearity. If the $S_1^{(0)} + S_1^{(1)}$ terms dominate, the spectrum will appear linear. If not, corrections must be applied to the transition probability to linearize the Fermi-Kurie plot. Another method of deducing the endpoint energy, W_0 , was suggested by Wapstra (WAP58). Analysis proceeds by plotting

$$[(N/p_e W F_0)^{1/2} / W_0 - W]$$

as a function of electron energy. By varying W_0 , the best straight line is obtained and thus the value for the maximum decay energy.

3. Log ft

The lifetime of the nucleus is expressed as the inverse of the probability of decay per unit time. The

decay constant for beta decay is expressed as (KON65)

$$\lambda = \int_1^{W_0} N(W) dW = g^2/2\pi^3 \int_1^{W_0} p_e W (W_0 - W)^2 F_0(\pm Z, W) S_n dW$$

Defining a new variable f , the decay constant can be expressed as

$$\lambda = (g^2/2\pi^3) fC$$

$$f = \int_1^{W_0} p_e W (W_0 - W)^2 F_0(\pm Z, W) dW$$

where C represents the nuclear part of the interaction.

Substitution for the form of $t_{1/2}$ gives

$$ft = f(\ln 2)/\lambda .$$

Since f , in an allowed decay, is determined by the statistical distribution of the energy of the electron and neutrino and the Coulomb effects, the determination of the half-life provides information about the allowed nuclear matrix elements. However, since f changes by 5 powers of 10 for W_0 between 1 and 5 MeV, the half-life will essentially be determined by f and not the nuclear matrix element. Because the spread of the ft values is quite large, it is more convenient to express the results in terms of $\log(ft)$. Comparison of various decays with correspondingly different interaction Hamiltonians can

then be accomplished by examining their $\log(ft)$ values.

4. Electron capture

The nuclei being studied in this investigation also have a finite probability for decay by electron capture in competition with positron emission. To describe the electron capture process, one needs only to substitute the wavefunctions of the atomic orbitals of the electrons involved for the wavefunction of the emitted electron in the ordinary beta decay process. Since atomic electrons are in finite energy states, the decay probability does not contain the statistical factors, i.e., $p_e W$. Consequently, the neutrinos are emitted at the maximum decay energy W_0 .

For the Cs isotopes, the ratios $\lambda_{EC}/\lambda_{\beta+}$ range from 6% to 11%. This will not affect the measurement of the positron decay energies, but does contribute to the $\log(ft)$ value since the total transition probability is now $\lambda_{EC} + \lambda_{\beta+}$.

5. Effects of deformation on beta decay

Since the cesium isotopes studied in this investigation exhibit deformed, prolate shapes, the effects of the collective nuclear motion on the beta decay process become important. The occurrence of the

asymptotic quantum numbers and selection rules for collective wave functions impose further restrictions on the decay. The selection rule of major consequence concerns the angular momentum component K ($= \Omega$) along the symmetry axis.

Nonvanishing matrix elements for spherical tensor operators of rank n occur for states characterized by J and K only if $\Delta J \leq n \leq J_i + J_f$ and $\Delta K \leq n$ (PRE62). The allowed beta decay matrix elements $\langle l \rangle$ and $\langle \sigma \rangle$ are composed of tensors of rank 0 and 1, therefore transitions of $\Delta K \geq 2$ are "K forbidden". Other selection rules pertain to the asymptotic quantum numbers N , n_z and Λ . Allowed transitions have

$$(\Delta N, \Delta n_z, \Delta \Lambda) = (0, 0, 0)$$

and for first forbidden decays

$$(\Delta N, \Delta n_z, \Delta \Lambda) = (1, 0, 1) \quad \text{or} \quad (\pm 1, \pm 1, 0).$$

The effects of these selection rules are on the transition rate rather than on the actual shape of the decay energy spectrum. The effect of violating one of these rules translates to an increase in $\log(ft)$ or a hindrance in the rate. Even though the asymptotic quantum numbers are not directly applicable except in the limit of strongly deformed shapes, they can however affect the

overall rates of the experimentally determined beta decays.

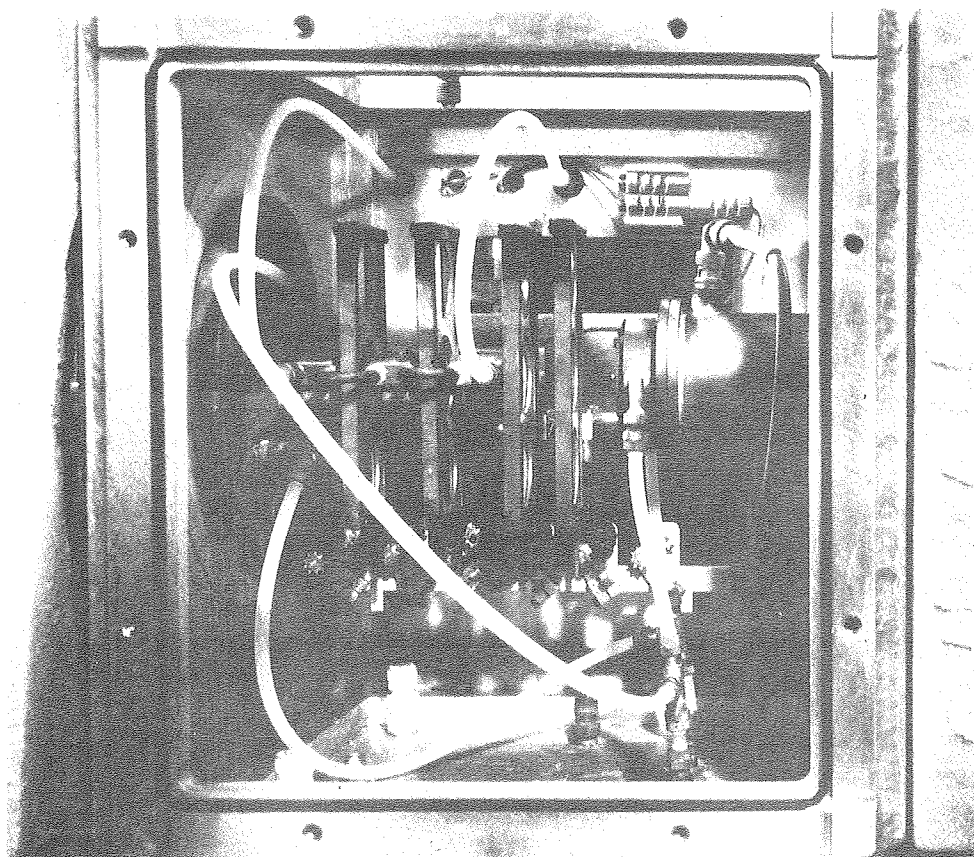
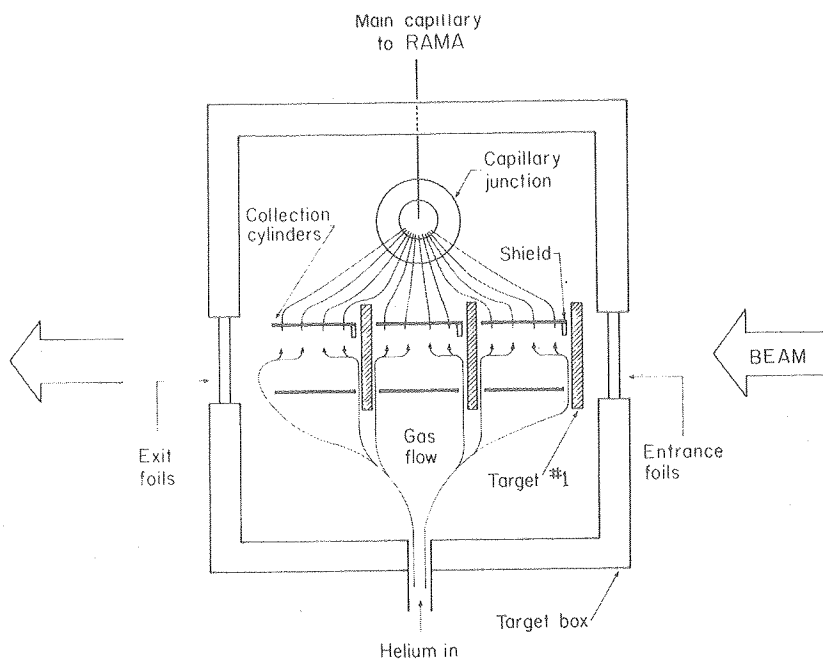
III. Experimental

The experimental study of the neutron deficient cesium isotopes is presented in this section in a series of four parts: 1) production of the cesium isotopes, 2) mass separation of the isotopes of interest using RAMA, 3) collection and transport of separated activity to the detection station, and 4) beta-gamma coincident detection of the radioactive decay. An additional section is included which describes a recent improvement to the experimental apparatus, the installation of a process control computer to RAMA.

A. Isotope production

The cesium isotopes were produced using a 140 MeV $^{14}\text{N}^{+4}$ beam supplied by the Lawrence Berkeley Laboratory 88-inch cyclotron (KEL62), directed on $^{\text{nat}}\text{CdS}$ targets of $\sim 2 \text{ mg/cm}^2$ thickness. Overall production can be summarized as $^{\text{nat}}\text{Cd}(^{14}\text{N}, \text{xn})^{123-119}\text{Cs}$ where various natural isotopes of $^{\text{nat}}\text{Cd}$ contributed to the total cross section for any one product nuclide. The average beam intensity varied between 2 and 4 μA .

The target chamber for the mass separator, RAMA, is located in the cave 2 beam line (shown schematically in figure 3). The chamber was isolated from the main beam



XBB 803-3383A

Figure 3. RAMA target chamber. (Top) Schematic view showing helium gas flow, copper cylinders, and multiple capillaries. (Bottom) Side view showing nitrogen gas cooling lines, target/degrader ladders, and copper collection cylinders.

line vacuum by two sets of two foils and pressurized with ~6 psig helium gas. Cold N₂ gas continuously flowed across the havar¹ isolation foil surfaces providing thermal conduction of heat generated by the incident beam to prevent foil breakage. The entire chamber could be temperature controlled using a refrigeration system allowing the experimenter to vary the thermal environment. This flexibility was needed when aerosols such as ethylene glycol were added for recoil adhesion to improve transport efficiency (temperature regulation in the target chamber was found not to be required when NaCl was used as the transport aerosol).

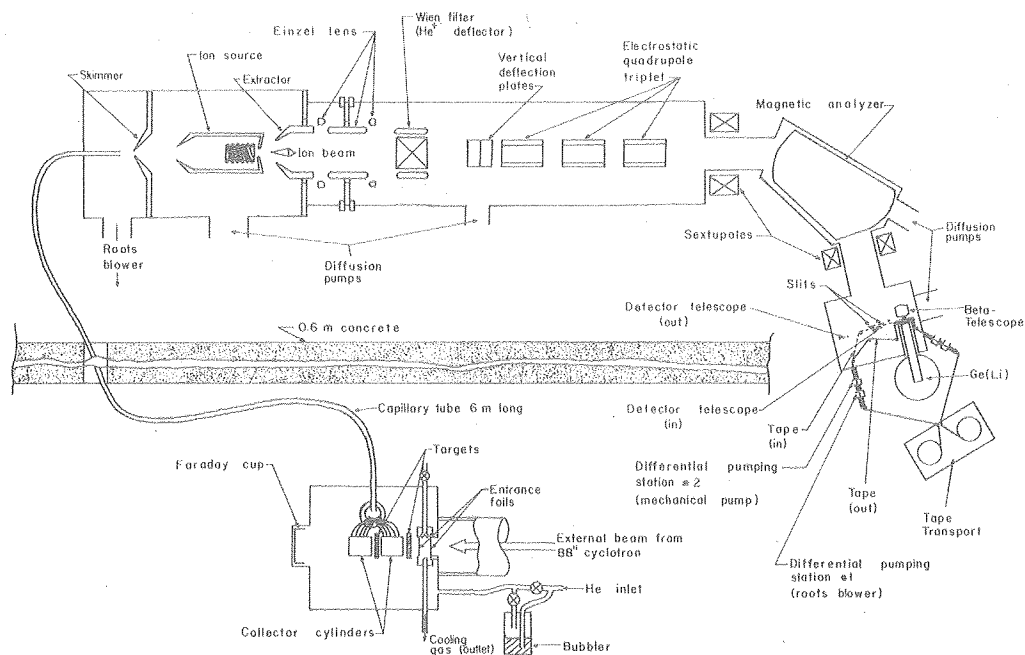
The target chamber had incorporated in it the flexibility of multiple target and beam energy degrader configurations in a variety of geometries. The target/degrader configuration used for the cesium isotopes was the two-target multiple capillary system.

The cyclotron beam entered the target chamber through the first set of cooled isolation foils, passed through the copper cylinders striking the targets, and then exited through the second cooled isolation foils to the Faraday cup. Targets and degraders were both selected from the ladder arrangement seen in figure 3. The copper cylinders defined the sweep-out volume of reaction recoils for the He-jet. The recoils were thermalized in the helium environment and swept out of the cylinders by evenly spaced 1.0 mm i.d. capillaries spread over the maximum

recoil range of the ejected nuclides. The multiple capillaries were fed to a junction in the form of a cylindrical chamber where final sweep-out was accomplished.

B. Mass separation - RAMA

RAMA, shown schematically and pictorially in figure 4, was used to provide isotopic mass separation for the study of the neutron deficient cesium isotopes. Activity from the target chamber was swept up a 6 meter 1.27mm i.d. stainless steel capillary to the separator with a typical transport time between 200 to 250 ms. The output of the capillary was introduced into an early Sidenius (SID69) type hollow cathode ion source after the helium had been skimmed away by a series of two skimming surfaces differentially pumped by a large roots blower vacuum pump system (6000 l/s of He at .1 torr) and a 30 cm oil diffusion pump (see figure 5). Singly charged ions extracted at 18 kV were then introduced into a set of focusing elements to match the admittance of the dipole analyzing magnet. Ion source support gas (He^+) was deflected away by a crude velocity separator consisting of crossed electric and magnetic fields (known as a Wien filter). After mass analysis, the nuclides of interest were studied by various detector configurations in the multiple use focal plane detector chamber. The



RAMA - 88 SCHEMATIC

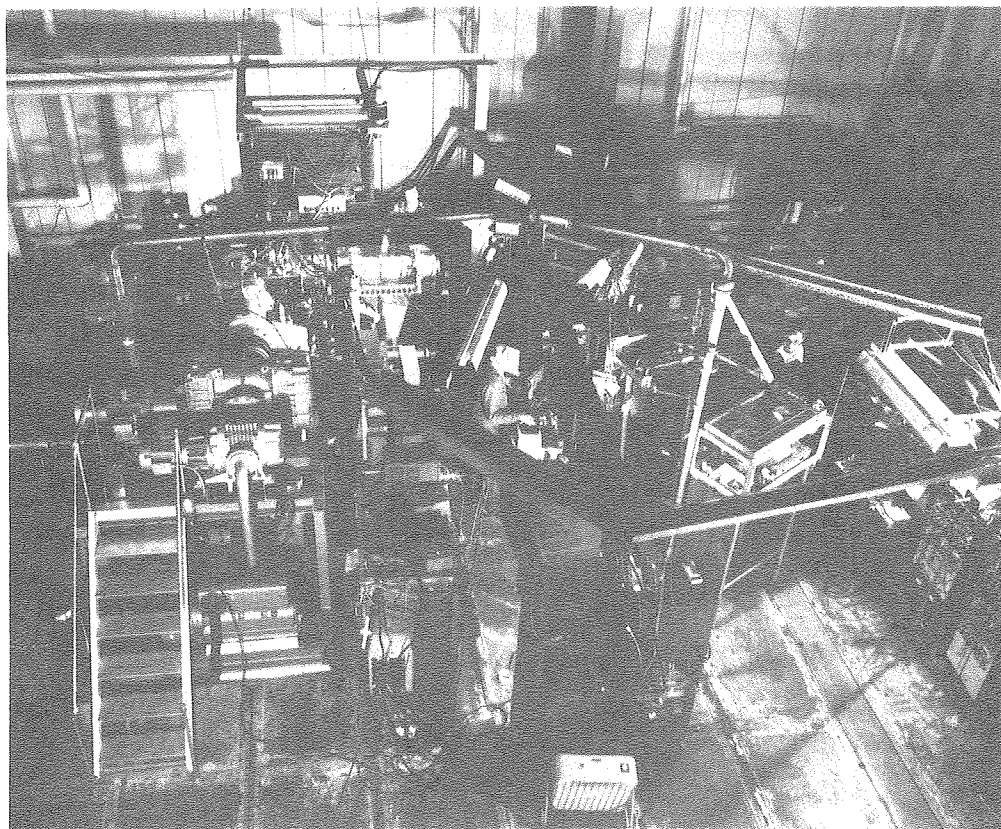
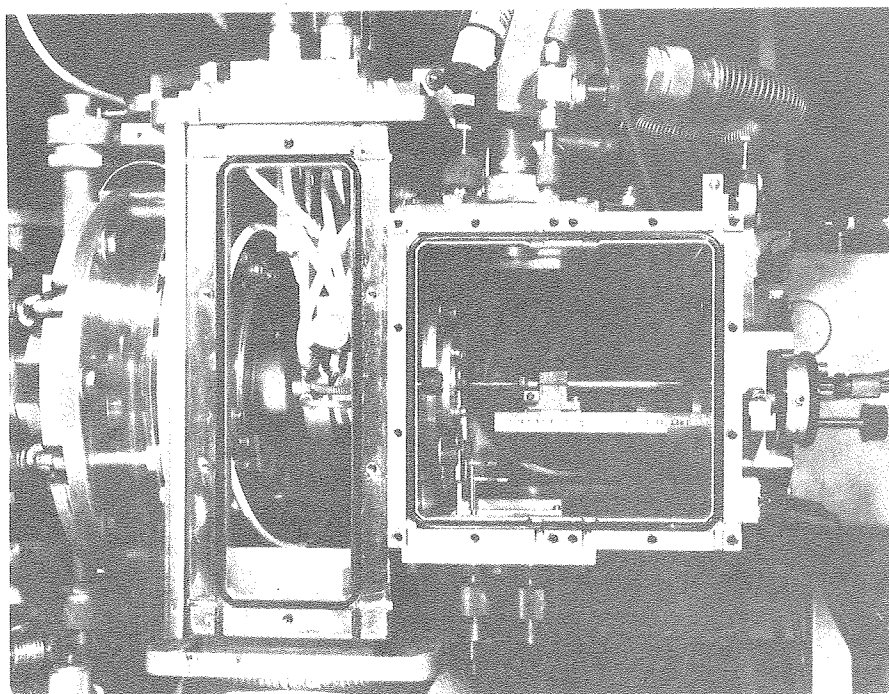
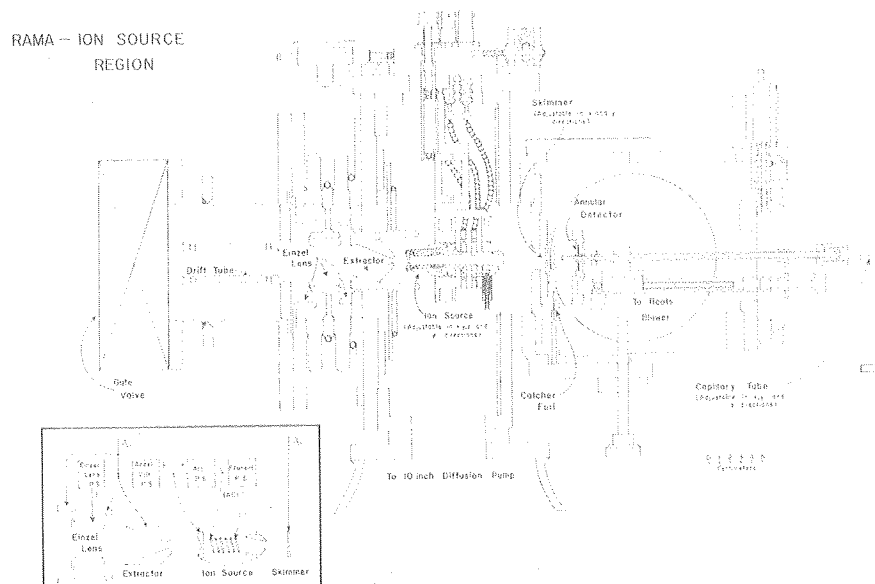


Figure 4. RAMA. (Top) Schematic view which includes the target chamber located in the cave. (Bottom) Overhead view of the apparatus. Roots blower pumps are seen on the left, detection chamber and tape transport to the right.

XBB 810-11239A



XBB 810-11247A

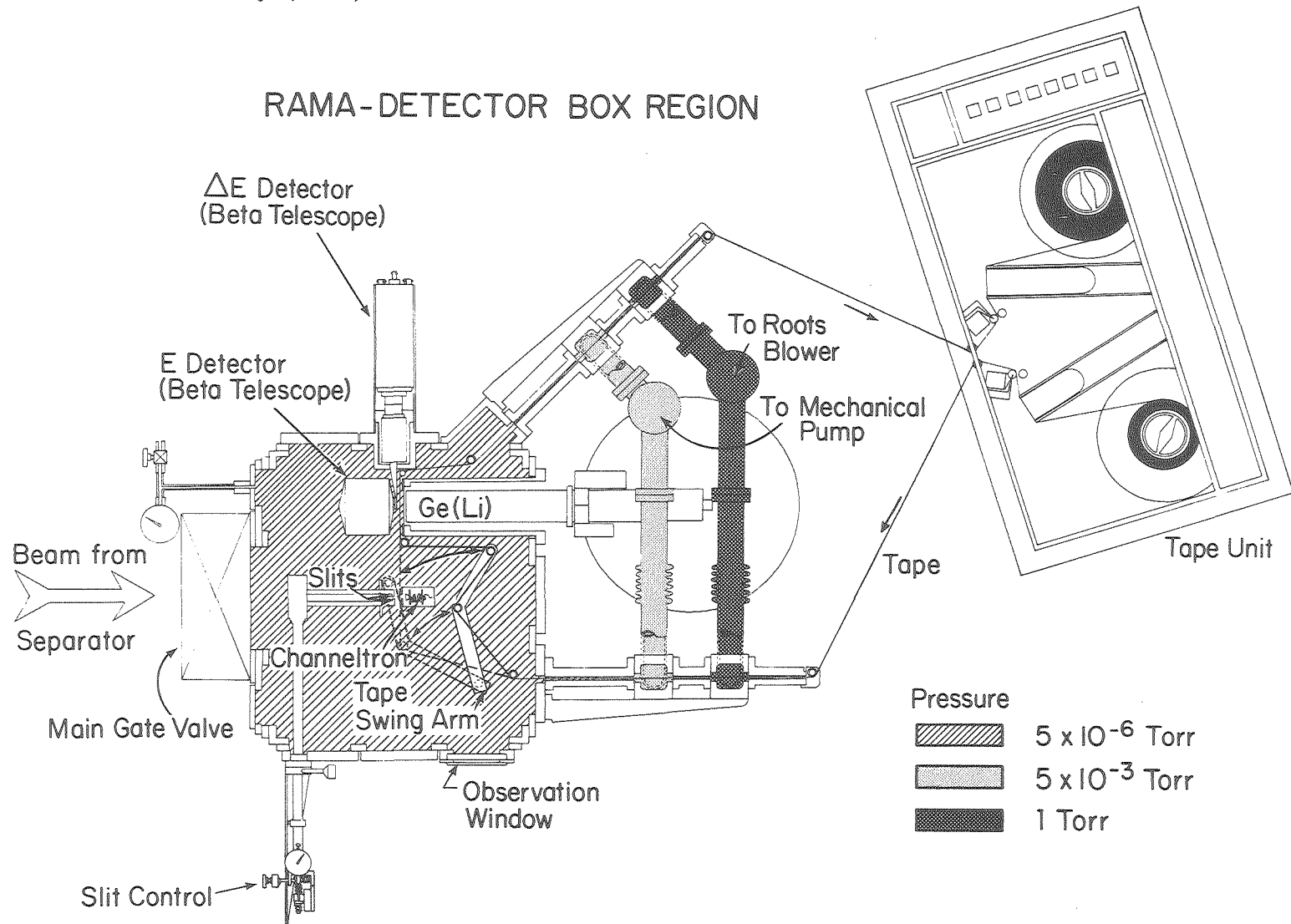
Figure 5. Ion source and differentially pumped helium skimming chambers. (Top) Enlarged schematic view of the ion source and skimmer regions. (Bottom) Side view showing (from right to left) capillary entrance, water cooling lines, extractor, and einzel lens.

investigations of beta decay endpoints of the neutron deficient cesium isotopes used a fast, differentially pumped, moving tape system along with a high geometry beta-gamma coincidence system located in and attached to the detection chamber. All the system parameters necessary for the functioning of the RAMA apparatus were monitored by a complete stand-alone process input/output computer system.

C. Tape transport

The fast tape system, shown schematically in figure 6, incorporated a standard pinch-roller type computer tape transport (a Datamec² drive) providing the reliability, speed, and positional accuracy of commercial units. Interfacing the unit to the 5×10^{-6} torr focal plane detection chamber required a two stage differentially pumped entrance and exit narrow slit (0.002 x 0.200 cm) system. The initial section consisted of a 15 cm slitted aluminum assembly providing vacuum resistivity for the first stage differential pumping, 1 atm to 1000 microns. This stage pressure was maintained by a large volume roots blower pump (3000 l/s He). Between the first and second stages was a 10 cm slitted assembly backed by a mechanical pump with stage pressure of 5 microns. The final differential pumping section was a 23 cm slitted assembly providing the last resistive stage before the detection

Figure 6. Tape transport schematic (top view). Tape path is illustrated with respect to the beam from the separator, detectors, and differential pumping stations. The tape unit is oriented horizontally (flat).

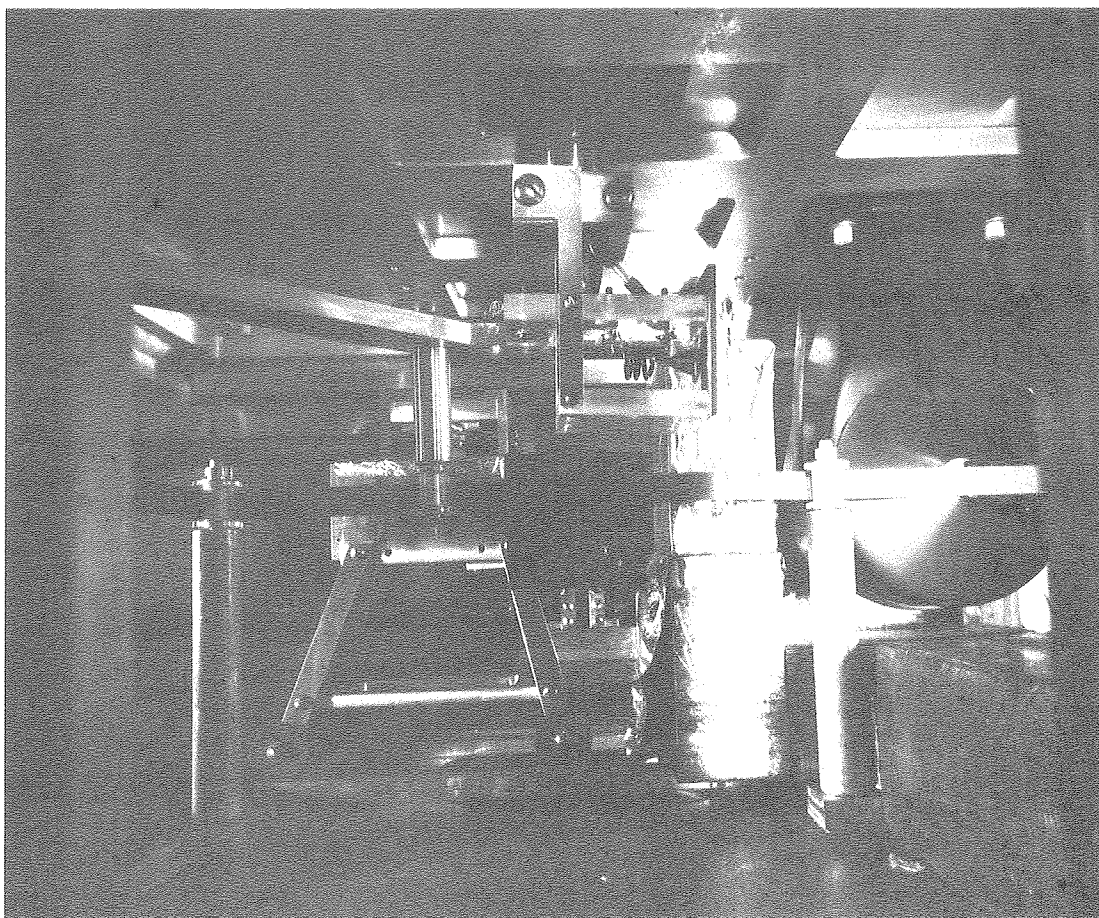


XBL 817-1034

chamber, held to 5×10^{-6} torr by a 15 cm i.d. oil diffusion pump. Each slitted aluminum piece had access panels to provide for system inspection and tape threading. Each differentially pumped arm was supported securely and each section was pinned in place. This not only provided mechanical rigidity but eliminated alignment problems which could create severe tape jamming in the narrow slits (the tape used was standard ferro-magnetic mylar backed computer tape, 0.03 mm thick).

Once inside the detection chamber, the tape proceeded over several sets of rollers correctly orienting the tape geometry. A tape swing-arm was included to provide a means of moving the tape away from the magnetic focal plane. This allowed the insertion of a channeltron electron multiplier which was used for mass calibration of RAMA. These features can be seen in figure 7. Tape speed for the system was approximately 150 cm/s, effectively shuttling activity from the collection point on the focal plane to the center of the beta-gamma detector station illustrated in the figure in 120 ms. The tape intercepted about 50% of the magnetically separated ion beam due to the tall slender profile at the focal point.

Tape transport movement was accomplished by a custom controller which handled tape movement, positioning and rewind duties. Initiation of a shuttle required only a logic (5 volt) pulse to the controller. The system encountered initial problems with voltage transients from



CBB 810-11245

Figure 7. Inside detection chamber (front view). The tape path is clearly seen with respect to guide rollers, focal plane center line (defined by analyzing slits shown in the center), and beta telescope (right). The channeltron electron multiplier is shown in the storage position (spiral tubing with horn, top-center).

high voltage sparking in the ion source region. This caused false cycling. An optical link was installed to resolve the problem by providing the necessary ground isolation. The tape controller also provided status information which was used to control the tape system remotely by the process I/O computer. Pulsing was instituted by the computer and routed to the controller. Rewind requests by the controller were cleared through the computer to allow the option of on-site monitoring of the rewind sequence by the experimenter to assure system integrity.

D. Detection instrumentation

Measurement of positrons coincident with gamma rays following the beta decay of the neutron deficient cesium isotopes was accomplished by standard application of scintillators and Ge detectors. A plastic scintillation detection telescope (in vacuum) was oriented to face the deposited activity on the transport tape while a 24% intrinsic Ge detector (in atmosphere) was positioned in a re-entry port, whose terminus was made up of a thin aluminum foil for vacuum isolation, resulting in the detector looking through the tape at the deposited activity.

Both plastic scintillator and Ge detectors were extensively shielded with upstream collimators in the

focal plane to eliminate interference from adjacent masses; lead bricks were also added to reduce the resultant background. A copper shield was employed around the Ge detector to reduce X-ray and Compton background.

The plastic scintillator ΔE -E telescope was designed to measure positrons (or electrons) to approximately 15 MeV. It consisted of a 10 mm diameter and 1 mm thick NE102 plastic scintillator as a ΔE detector (for gamma ray rejection) and a large cylindrical 11.4 cm diameter and 11.4 cm long NE102 E scintillator. A beta detection geometry of 24% was achieved by placing the ΔE detector 3 mm in front of the E detector scintillator and 3 mm from the transport tape.

Plastic light-pipe was used to couple the individual scintillators to the photomultiplier (PM) tubes. Each scintillator surface was highly polished and coated with ~ 2000 Angstroms of aluminum to assure minimum loss of scintillation photons. The light-pipe was permanently affixed to each scintillator for mechanical rigidity and minimum optical loss at the junction surface. Coupling of the PM tube to the light-pipe was done using optical grease to permit PM replacement and to guarantee a good vacuum seal. A photomultiplier tube with a high gain (40) gallium phosphide first dynode was used to amplify the low level ΔE detector signal, whereas the E PM tube used a standard copper-beryllium first dynode with gain of 6, as with all the remaining 12 dynodes within both tubes. The

PM tube, light-pipe and scintillator were biased to -2300 volts to eliminate stray electric fields. Each photomultiplier was wrapped in black tape and grain oriented steel for stray light and magnetic field protection.

An ultra high purity Ge crystal (manufactured by ORTEC³) with a nominal resolution of 1.7 keV at 1 MeV was used as the gamma ray detector. It was inserted into a re-entry port in which its physical distance to the tape was 1 cm, subtended a solid geometry of approximately 30%, and was isolated from the system vacuum by a 2.5×10^{-3} cm thick Al window. Total overall solid geometry for the beta-gamma coincidence detection station was approximately 7%.

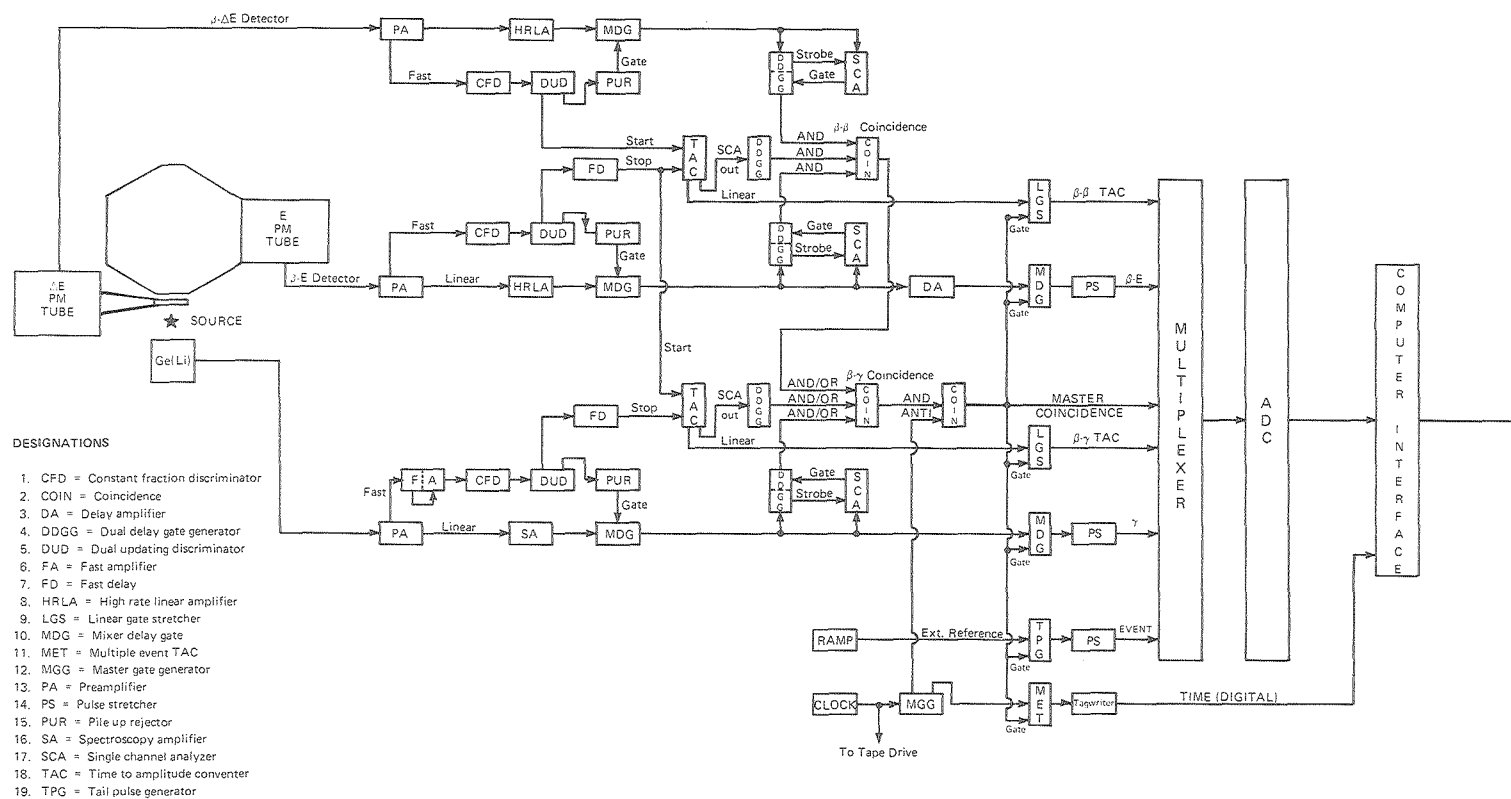
Fast-slow coincidence techniques were used for the beta-gamma telescope system. The beta ΔE and E scintillator fast signals (picked off the anodes of the respective PM tubes) and Ge preamp timing signal were used, after pile-up rejection, to determine overall beta-gamma coincidence requirements. The use of fast signals for gating reduced chance coincidences inherent in the fairly high count rate environments (~ 2000 cts/sec). Timing resolution of 5 ns was obtained between the plastic scintillators and 20 ns in the overall beta-gamma coincidence configuration.

Additional gating was applied during tape transport cycles supplied by the RAMA computer cycling program.

This gating signal also initiated a multiple event TDC (time-to-digital converter) which tagged each event with the time elapsed since the last tape cycle. This signal provided experimental information for direct determination of half-life.

To monitor overall counting rates, a separate TAC unit (event TAC) was incorporated which used an externally produced pseudo-linear ramp signal. This ramp was generated by a digital clock driven, digital-to-analog converter where clock ticks were set to 3-5 minute intervals. Every coincident event generated a TAC signal proportional to the slow pseudo-ramp and thus provided a method to monitor directly the experimental beta-gamma coincidence counting rate.

Six parameters were recorded for each coincident event: event TAC, beta energy from the E scintillator, gamma energy from the Ge detector, beta ΔE -E scintillator TAC, beta-gamma TAC, and TDC. These parameters were passed to the experimental data acquisition computer (not to be confused with the RAMA computer) and recorded on magnetic tape in an event-by-event format. This was accomplished using the ModComp IV/25 computer⁴ and a data acquisition program denoted CHAOS (MAP79). Figure 8 schematically illustrates, in a modular fashion, the electronic setup used for the detectors mentioned above.



XBL 817-1068

Figure 8. Experimental electronic configuration schematic for the plastic beta telescope and gamma detector.

E. RAMA computer system

Soon after RAMA began operation on a regular basis, it became apparent that many critical operating parameters (e.g., ion source voltages and currents) needed almost continual attention. Also, the physical location of the system (located on the roof blocks that cover the experimental caves) could, in the case of high-intensity light-ion beams, prohibit an experimenter from inspecting RAMA because of high neutron fluxes from the target area below. To resolve these problems and to increase the reliability of the experimental apparatus, a process input/output minicomputer system was installed to monitor and record standard operation parameters, alert experimenters to any RAMA deviations, and provide control over more critical parameters.

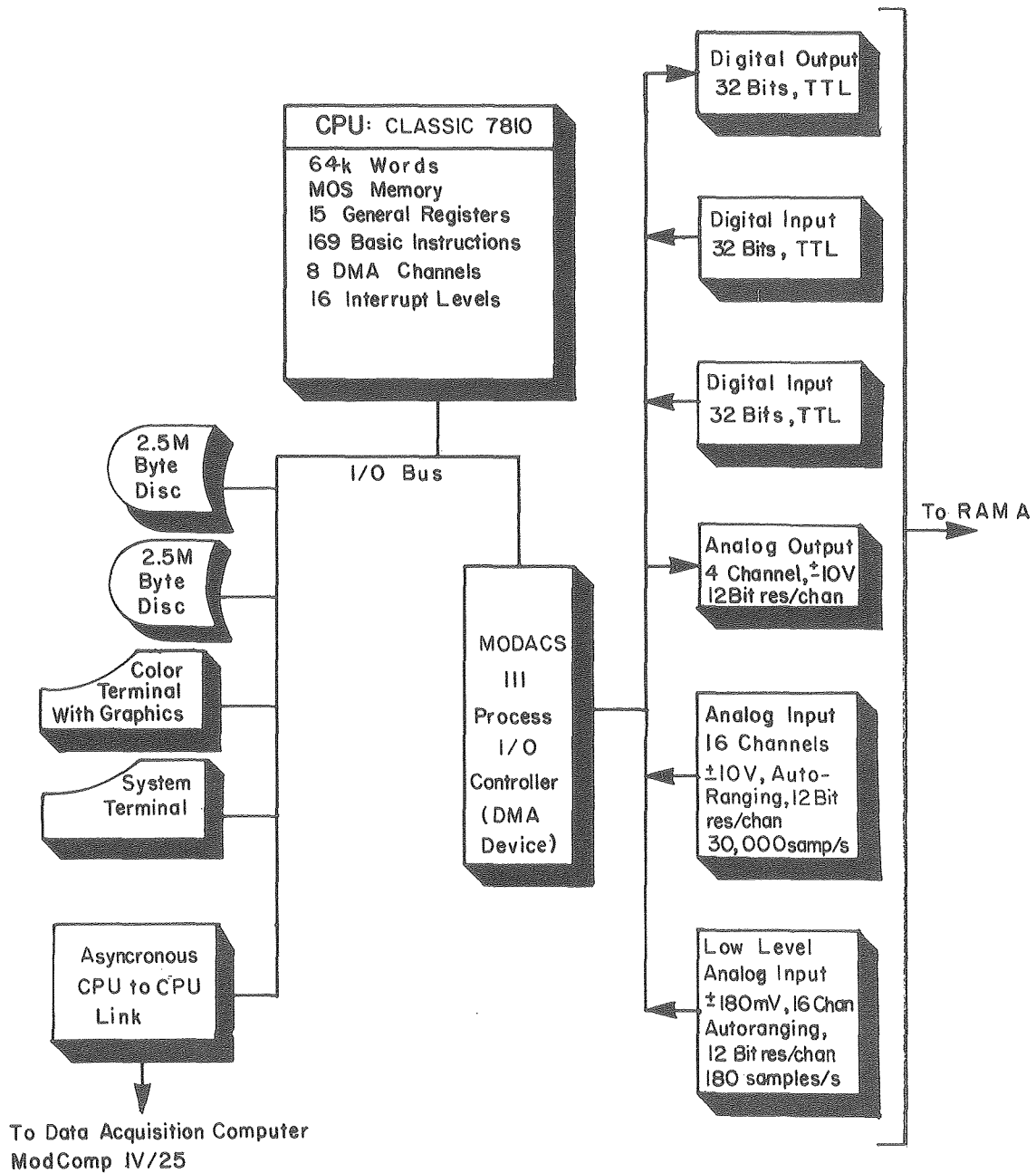
Several criteria were considered in selecting the appropriate system. Maximum compatability with the existing facility (the ModComp IV/25 acquisition computer) was desired for use in transferring RAMA system data to the main data taking computer. Also desired was software compatability to allow for program development on a larger machine. The system had to be stand-alone with a standard serial-link to a remote terminal for use with existing devices, have sufficient potential for expansion for

future monitor and control applications, and a minimum memory capacity of 32K of 16 bit words. The system also needed to handle 20-30 channels of both digital and analog information in approximately 10 ms.

The system chosen that fulfilled these requirements was a process control system known as the ModComp MODACS III. The computer system, shown schematically in figure 9, had a link for connection to the ModComp IV/25 mainframe, independent control operations, and plug in slots for a variety of analog and digital input and output electronic circuit cards. Since the IV/25 and MODACS III were hardware and software compatible, only minimal need for development was required. The present system, shown pictorially in figure 10, was supported by two 2.5M byte moving head disc drives, an eight color terminal with moderate graphics, appropriate interfaces between the computer and the devices monitored, and 64K of 16 bit memory.

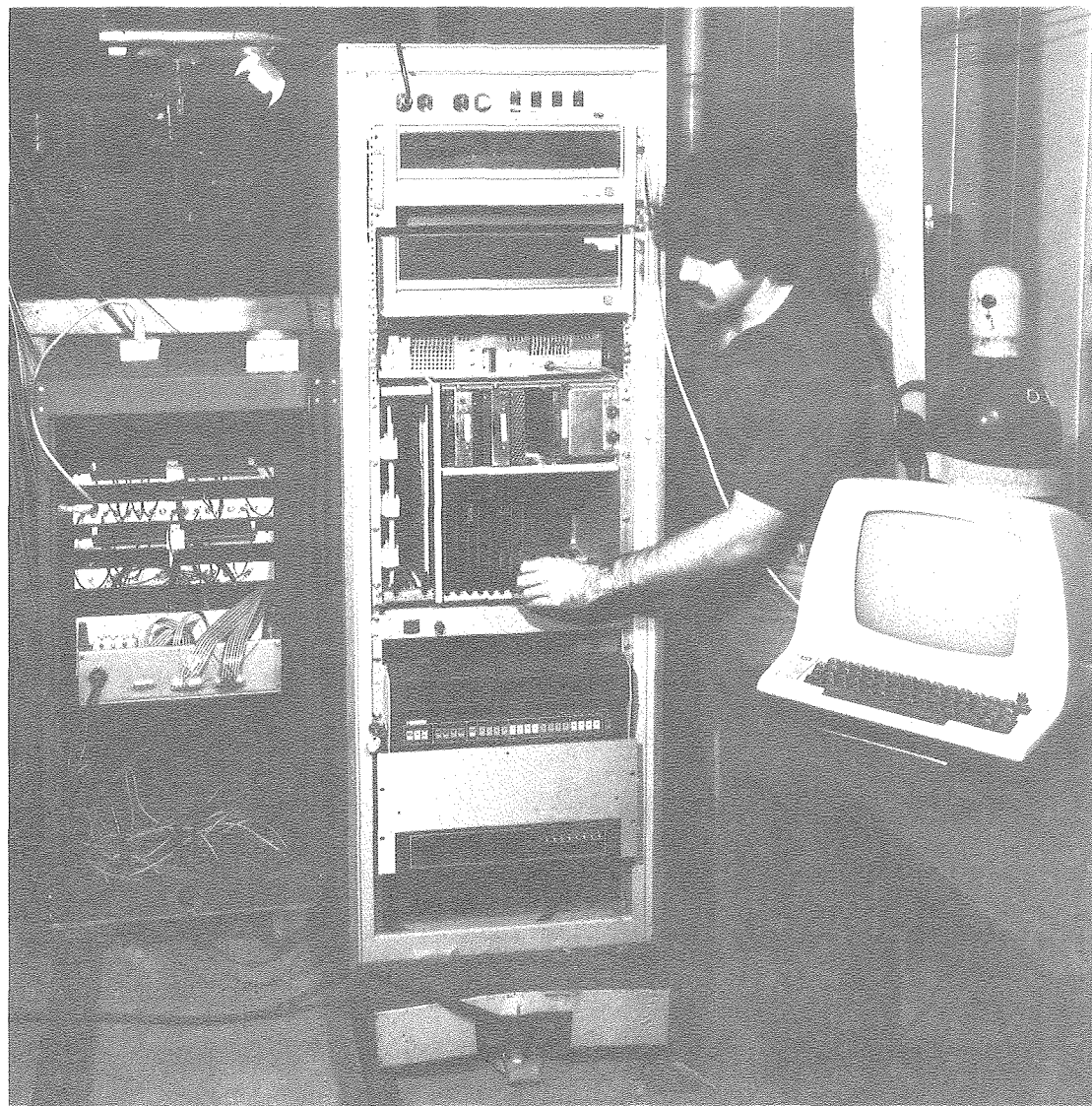
The software developed for this system took full advantage of the multitasking abilities of the MODACS III computer. Separate "tasks" or complete program units provided a unique method to simplify on-line RAMA system data acquisition and analysis software. The overall package consisted of four independent tasks.

The central data acquisition task collected RAMA parameters in forms of voltages and logic levels (open/closed valves, etc.) from analog and digital input



XBL 8210-3003

Figure 9. RAMA computer schematic.



CBB 810-9845

Figure 10. RAMA computer. The central processing unit, disk drives, and process input/output cards are located in the center rack. The cable interface is shown to the left which is the terminus for digital and analog signals from RAMA.

electronics. This process occurred in a direct memory addressing environment; there existed a separate processor in the MODACS III system which filled memory with the RAMA system data independent of the central processor unit, effectively speeding up program execution. The voltages and logic levels were then translated to their associated physical values, including target chamber temperature, magnet and ion source currents, system pressures, analyzing magnet field strength, and overall system integrity. This task provided these values to other independent tasks through a shared memory region commonly referred to as a global common area.

The second task was the tape control program. This software initiated pulsing to the tape transport controller which translated to tape movement or the shuttle of activity collected on the focal plane of the separator to the detection station. The program also controlled the rewind sequence by granting permission for the controller rewind the collection tape. The cycling time and rewind signal were also passed through the global common area for communication with other tasks.

The third task was the unit-controller program used to control the magnetic field strength of the dipole analyzing magnet. This corresponded to the current mass setting of the separator. Control was handled in a closed loop fashion in which the computer obtained the field strength by reading a NMR device, calculated from the

preset mass position the proper current for the magnet power supply, and then applied any necessary correction to the magnet (this task was only partly implemented in this experiment and only set the magnetic field strength to a user specified value).

The fourth task was the interactive display program which was used to communicate system conditions to the experimenter. The program contained the supervisory unit which initially configured the system by placing the previously mentioned tasks into memory and then interacted with the user to establish the initial RAMA parameters that would be monitored and/or controlled along with allowable tolerances. The program provided a multicolor updating scan of the RAMA system for the experimenter. An example of this display (in black and white) is shown in figure 11. Other options allowed for multicolor time histogrammed displays of any parameter in the system showing tolerance limits, the preset calibration value, and the actual measured value. A time histogram of the target chamber pressurizing with helium is shown in figure 12 (in black and white). There were also other functions available which communicated with the other system tasks, such as setting the tape cycle time and current separator mass calibration values.

```

***** ION SOURCE *****
FILAMENT VOLTAGE= W 0 0) CURRENT= A ( 0 0) POWER= W 0 0)
ARC VOLTAGE= V ( 0) CURRENT= A ( 0 0) POWER= W 0 0)
GAS FLOW= ( 0) TOTAL ION SOURCE POWER = M ( 0 0)

***** OPTICS *****
EXTRACTION VOLTAGE = 1224 (1224) EINZEL LENS VOLTAGE = V ( 0)
WIEN FILTER MAGNETIC = -33.12 MV (-33.12) ELECTRIC = 910 V ( 911)
QUADRUPOLES A = 1233 V ( 1244) B = 955 V ( 905)
SEXTUPOLES 1 = 63.9 MK 63.6) 2 = 55.3 MK 55.7) SLITS = 3.5 MM ( 3.5)
DIPOLE FIELD STRENGTH = 2784.50 GAUSS FREQ = 11.8555 MHz MASS = 98.09 ( 0.00)

***** HE-JET *****
TARGET BOX PRESSURE = 0.45 ( 0.02) X SIG CAPILLARY FLOW = ( 0 )
TEMPERATURE CYLINDER 20.43 ( 20.25) GAS = 20.49 ( 20.25)

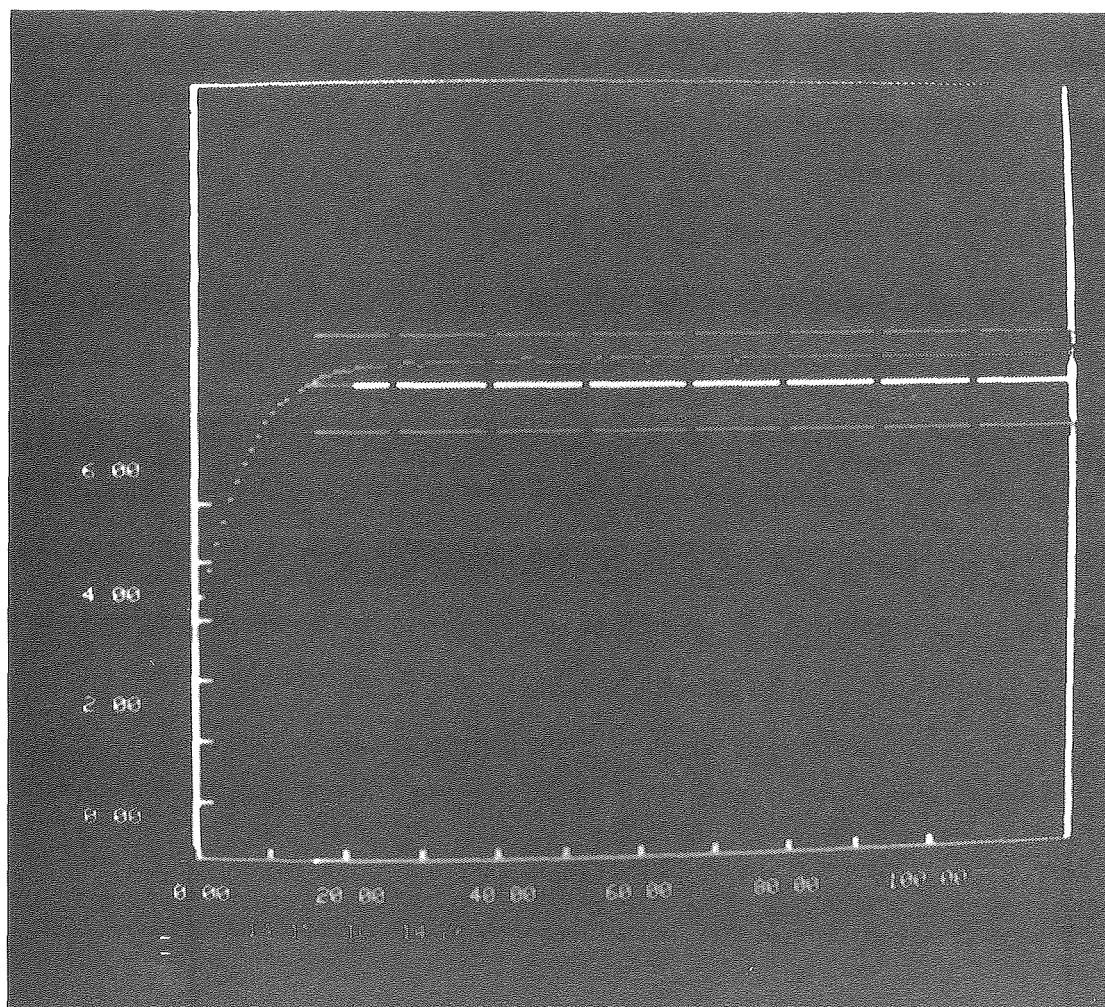
***** VACUUM STATUS *****
MERCAUS VALVE CLOSED (OPEN ) ION SOURCE ISOLATION VALVE HEU-ET (OPEN )
DETECTOR BOX ISOLATION VALVE CLOSED (OPEN ) DP2R1 ON (ON ) REFRIG ON (ON )
DP2R2 ON (ON ) LNR2 ON (ON ) DP2R3 OFF (ON ) LNR3 ON (ON )
DP2R4 ON (ON ) LNR4 ON (ON ) WATER ION SOURCE ON (ON ) F CUP ON (ON )
PRESSURES SKINNER BOX 0.1 ( 0.1) ION SOURCE BOX 3.9 ( 4.0)
(X 10-5) MAGNET REGION 0.2 ( 0.2) DETECTOR BOX 0.0 ( 0.3)

***** DETECTOR SYSTEMS *****
TAPE CYCLE TIME 60 SEC TIME LEFT UNTIL NEXT CYCLE 21 SEC
TIME OF DAY 14 24 25 DATE 10/13/81 TIME THIS SAMPLE TAKEN 14 24 21

```

CBB 810-9849

Figure 11. Color terminal display. Although shown here in black-and-white, the overall system status is clearly displayed with a breakdown of various RAMA parameters.



CBB 810-9851

Figure 12. Time histogram of the target chamber pressurization as shown on the color graphics terminal (in black-and-white). The x-axis is elapsed time (arbitrary units) and the y-axis is pressure in psig. The upper and lower lines represent tolerance limits (in red), the center line the calibration or desired value (in blue), and the curved line the actual recorded pressure (in green).

IV. Analysis of Beta Spectra

Analysis of the raw gamma-coincident beta decay spectrum proceeded in two distinct steps: 1) gamma ray coincident gating and removal of beta background and 2) stretch fit analysis (to be described below) to determine endpoint energies. The gamma ray gating and background removal was accomplished by regenerating the histogrammed spectra from the event-by-event data recorded by the acquisition program CHAOS. Coincident gating requirements were set on the $\Delta E - E$ plastic scintillator TAC (beta-beta TAC), the plastic scintillator telescope - Ge gamma detector TAC (beta-gamma TAC), and on the 511 keV annihilation peak or on the gamma energy resulting from a known transition in the daughter nucleus. Background removal was accomplished by setting identical TAC gates and a gate above the primary gated gamma energy of equal width to generate a background beta energy spectrum. This background spectrum was subtracted from the primary gated beta energy spectrum producing the final histogrammed positron spectrum which was subsequently analyzed by the stretch fitting procedure.

A shape fitting analysis procedure was used in this work which departed from the typical method of beta analysis, the Fermi-Kurie plot. To appreciate the improvements this technique provided, a short discussion of the Fermi-Kurie method is presented followed by a

description of the stretch fit analysis procedure.

A. Fermi-Kurie Analysis

The historical method of analyzing a beta decay spectrum has been to plot, vs. energy, a function of the data which should be linear with energy and intercept the energy axis at the endpoint energy, $W_0(E_{O,kinetic} + E_{rest})$. The procedure was implemented for that part of an undistorted spectrum which contained the contribution of only one beta decay component. When necessary, this decay energy would be separated from beta decays to other levels in the daughter nucleus by suitable gamma coincidence gating. The method is referred to as a Fermi-Kurie plot (ROS55).

The above method is sound with respect to the theoretical aspects of determining the maximum energy of the emitted beta particles given the availability of an undistorted beta spectrum. However, the use of currently available detection systems inherently introduce distortions in the measured beta spectrum (PAU71,BAD67,BER69). The distortion effects produce tailing and pileup in the measured spectrum which results in nonlinear Fermi-Kurie plots (ROG65). Foreknowledge of the response of the detector (a plastic scintillator in this case) to these experimental distortions was required to determine accurately the endpoint energy W_0 . Spectrum

analysis was thus limited by the distortion of the measured spectra: the greater the distortion effects the greater the difficulty in determining endpoint energies (and branch intensities of beta decays to several levels in the daughter nucleus).

In the plastic scintillator case, the major contributions to the distortion effects have been summarized (WOH72, ROG65) as: finite energy resolution due to low resolving power of the scintillator, backscattering of the beta particles out of the surface of the detector at lower energies and sidescatter out of the detector at higher energies (tailing effects), bremsstrahlung photons with sufficient energy to escape the detector (incomplete light detection), and annihilation radiation in the case of positrons where the 511 keV gamma rays could cause pileup (summing effects). The result of these effects can be summarized mathematically as

$$D(W) = \int_0^{E(\max)} T(W') R(W, W') dW' \quad \text{IV.1}$$

$$\int_0^{\infty} R(W, W') dW = 1 \quad \text{for normalization}$$

where $D(W)$ represents the measured, distorted beta spectrum, $T(W')$ the true beta spectrum, and $R(W, W')$ the overall response function of the detector that described the distortion features outlined above. Since most measurement systems have used a multichannel analyzer or

equivalent histogrammed event recording, the integral is usually replaced with the summation

$$D(W_j) = \sum_{k=1}^K T(W_k) R(W_j, W_k) \Delta W_k$$

$$\sum_{k=1}^{\infty} R(W_j, W_k) \Delta W_j = 1$$

where the index k runs over channel number and W_j represents the histogrammed energies. This summation approximation to the integral would be good providing that both $T(W_k)$ and $R(W_j, W_k)$ vary slowly over an energy region of size ΔW_k .

Application of the Fermi-Kurie method then involved the prior determination of the appropriate response function characteristics before endpoint energy determinations could be made. A typical method used to elucidate the response function involved measurement of several monoenergetic electron energy spectra and a least-squares fit of the peak shapes to an empirical gaussian function of the form (WOH72)

$$R(W, W_0) = H \exp(-x^2) \quad W_0 < W \quad \text{IV.2}$$

$$= H ((1-A) \exp(-x^2) + A) \quad W_0 - W_C < W < W_0$$

$$= H ((1-A+B(x-x_C)^N) \exp(-x_C(2x-x_C)) + A) \quad W < W_0 - W_C$$

where $x = (W_0 - W) \sigma / \sqrt{2}$ and $x_C = W_C \sigma / \sqrt{2}$. The energy W_0 is

the gaussian centroid (or peak energy), σ is the gaussian width, and H is the peak height parameter. To account for skewing due to partial light detection and summing at W_c , the gaussian was replaced by an exponential where B is the skewing parameter, while to account for the low energy tail due to backscattering and sidescatter, the term A was introduced for all energies below the peak energy W_0 . This method was convenient for studying electron emission, however, the availability of betatrons capable of producing positrons was rare and prohibitive to use conveniently. Therefore simplifications arose to accommodate this problem. If one assumed that the skewing and backscattering were minimal compared to that of the finite response of the detector, equation IV.2 would sometimes be used exclusively (BEC69) with slight degradation in the endpoint energy resolution (i.e., larger energy uncertainty).

Once a functional description for the response was determined, several methods were available for dealing with the distorted spectrum. One was to directly or numerically solve by iteration equation IV.1 for the undistorted spectrum $T(W)$. The resulting undistorted spectrum could then be linear least-squares fit to obtain endpoint values and branch intensities (OTT79). This was the historical "unfolding" technique where the distortion was removed from the spectrum prior to analysis. This method was generally quite sensitive to statistical

fluctuations in the data where the fluctuations could be magnified by iterative approaches. Smoothing could be applied to reduce these fluctuations but resulted in added distortions.

Another technique was regarded as the "folding" method (REH78). It involved generation of a theoretical spectrum and distorting it. The distorted theoretical spectrum could then be nonlinear least-squares fitted to the measured data. The theoretical undistorted spectrum would be characterized as

$$T'(W) = A F_0(\pm Z, W) p_e W (W_0 - W)^2 S_n(W) \delta \quad e^{\mp}$$

where $F_0(\pm Z, W)$ is the Fermi function with screening, A the amplitude coefficient, and W , the total energy ($E_{\text{kinetic}} + E_{\text{rest}}$) in the beta decay. The step function δ was unity for $W < W_0$ and zero for $W > W_0$ where W_0 was the endpoint of the beta spectrum. $S_n(W)$ was the shape factor mentioned earlier in beta decay theory. The distorted theoretical spectrum then became

$$D(W_j) = \sum_{k=1}^K R(W_j, W_k) \Delta W_k F_0(\pm Z, W_k) p_{e,k} A (W_0 - W_k)^2 S_n(W_k) \delta$$

again where the index k represents channel number.

The distorted theoretical spectrum could also be compared to the undistorted theoretical spectrum generating a correction factor $K'(W)$ of the form (SCH75)

$$K'(W) = D'(W) / T'(W)$$

where the primed values denote the theoretical spectrum. The correction factor could be applied to the distorted real data to obtain an undistorted spectrum. This technique represented a combination of "folding" and "unfolding" methods.

With several known beta spectra, one then produced an energy vs. histogram bin (or channel number) calibration curve to be used for the unknown analysis. The technique was entirely iterative in deducing a final linear calibration curve. The endpoint of the unknown spectrum was first estimated, followed by the calculation of the response function and undistorted spectrum, application of the correction, and then generation of a Fermi-Kurie plot. The process would be repeated until a least-squares fit with a minimum in χ^2 was obtained. Although the method converged in most cases, determination of the minimum in chi-squared would not always be unique due to statistical fluctuations in the data being magnified by the iterative process, and the approximation of the form of distortions in the response function $R(W, W')$ would not always be complete.

The "folding" and/or "unfolding" process results were thus characterized by a strong dependence on an accurate description of the response correction and minimal effects associated with statistical fluctuations in the data. In

most experimental situations, the response function cannot always be described as completely as was desired. There were always other sources of distortions arising from finite source thickness, background, electronic pile-up, as well as numerous other problems due to the detector environment and electronic detection techniques that enter into the actual measured beta spectrum.

B. Stretch fitting

Instead of trying to incorporate all the above features into a response function and using a Fermi-Kurie technique, a good approximation to the experimental shape of a beta spectrum can be calculated numerically by interpolating between the shapes of calibrated spectra, a method known as "stretch fitting" (G0073). A smooth curve is fit through a standard positron (or electron) spectrum numerically generating a standard experimental shape. Utilizing this standard shape, additional calibration beta spectra can be normalized in intensity and nonlinear least-squared fit to the standard shape generating linear "stretch factors" that are proportional to the endpoint of the parent (standard shape) spectrum.

This "stretch fit" method has the advantage of incorporating all the distortion features arising in an experiment via direct fit; there is no massaging of the data by a correction factor nor are there numerical

iterations to "unfold" the undistorted beta spectrum.

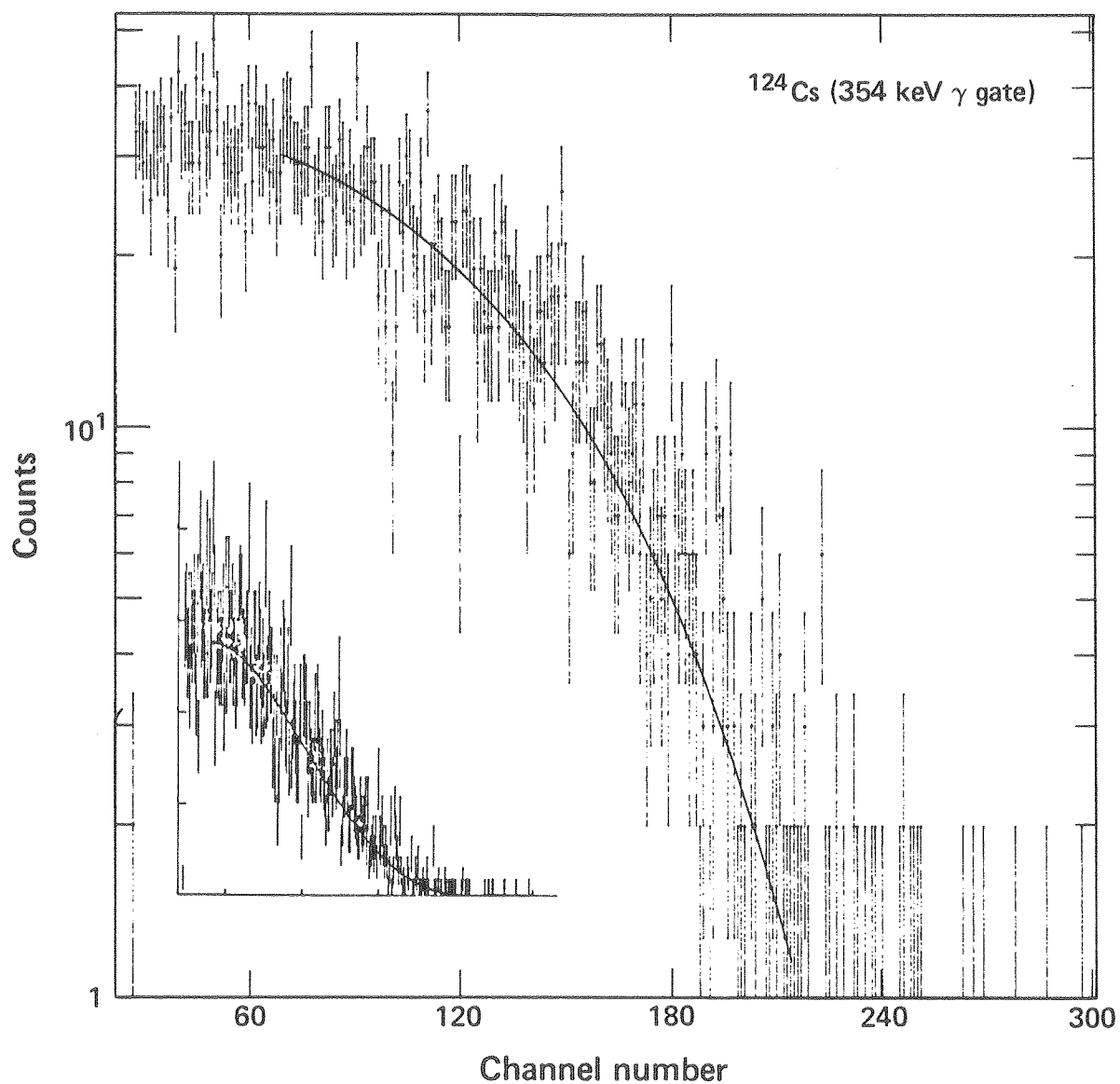
This method provides a direct measurement technique for the determination of endpoint energies. It does however have drawbacks: multiple branches can not be extracted directly as with stripping a Fermi-Kurie plot; the beta decays have to be of the allowed type or allowed shape; and the highest decay energy branch to the daughter nucleus has to be fairly well separated from other branches. The difficulty with multiple branches can be addressed in principle by suitable gamma ray coincidence gating to select the desired branch for measurement.

Davids et al. (DAV79) have successfully obtained a four parameter expression which approximates the positron shape quite accurately for plastic scintillators made with NE102 material. It is

$$N_0 S(x) = N_0 (a + bx + x^2) (x - x_0)^2 \quad \text{IV.3}$$

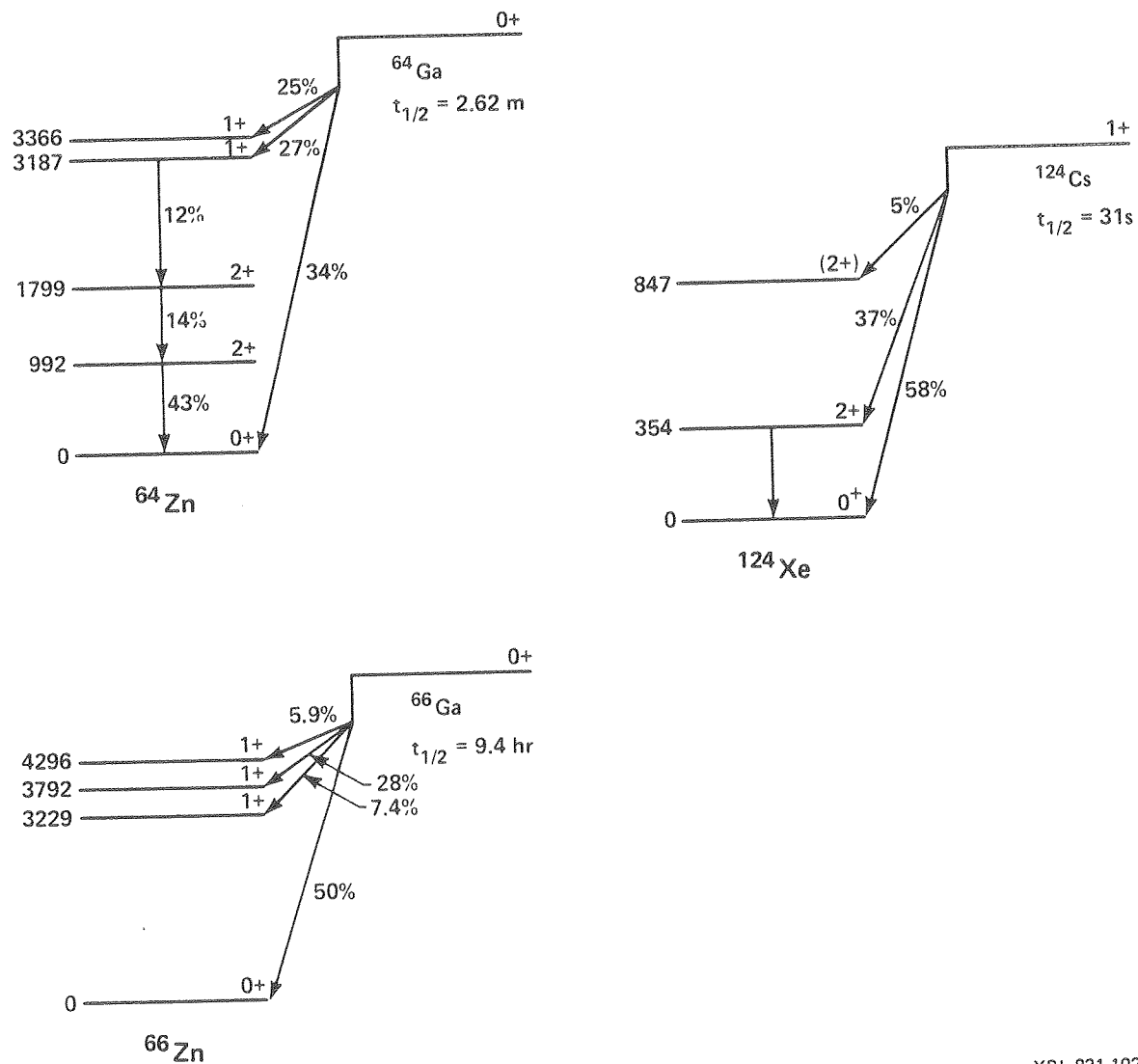
where N_0 is the overall normalization, x is the channel number in the histogrammed data, and a, b , and x_0 are unknown parameters of the shape function $S(x)$. Once N_0, a, b , and x_0 are determined from the standard spectrum by a nonlinear least-squares method, they are fixed for all subsequent fits. This constitutes the standard shape function to be used in the fit to the remaining calibration and unknown spectra.

Figure 13 illustrates the nonlinear least-squares



XBL 831-1045A

Figure 13. ^{124}Cs beta spectrum with stretch fit. The spectrum was generated by coincidence gating on the 354 keV gamma ray (with background subtraction). The insert shows the linear representation of the stretch fit. Error bars shown for the data are the respective statistical, $1/\sqrt{N}$, values.

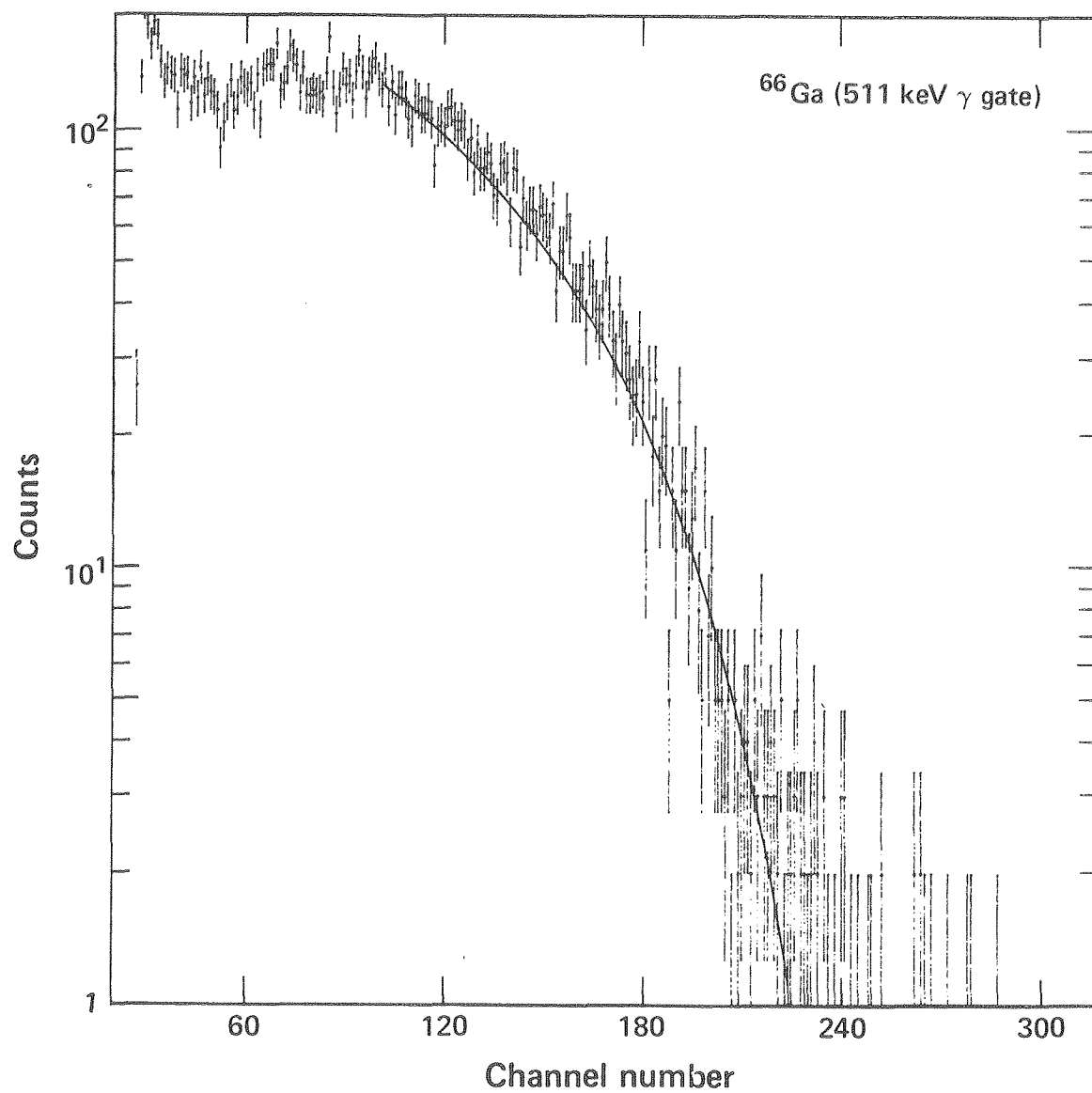


XBL 831-1029

Figure 14. Partial decay schemes for the nuclei used in the stretch fit calibration.

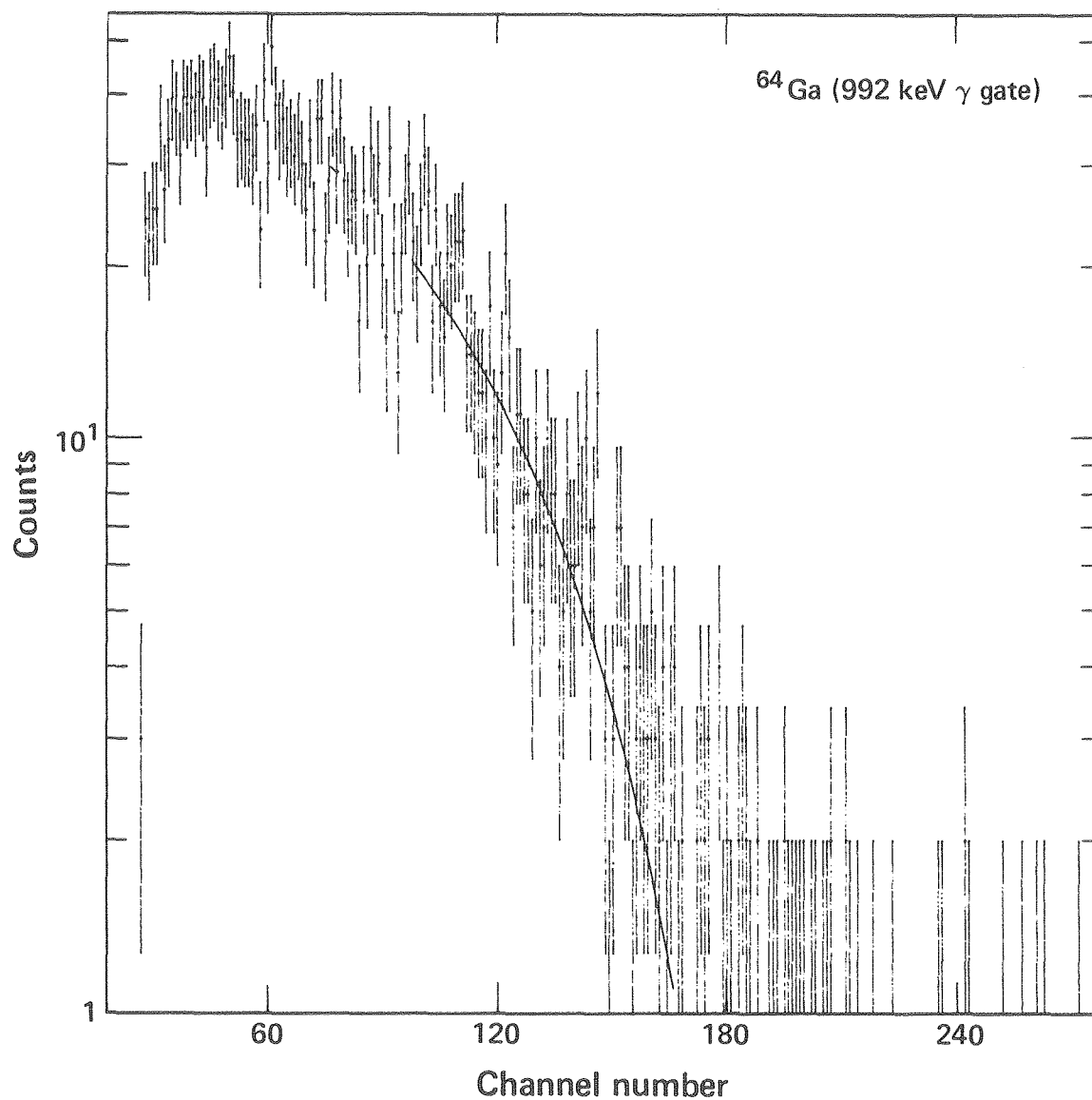
application of equation IV.3 to our experimental standard spectrum, ^{124}Cs . The beta spectrum was generated by gamma coincidence gating on the 354 keV gamma transition in ^{124}Xe (see fig. 14). This represented the 1^+ ^{124}Cs ground state decay to the first excited 2^+ state in ^{124}Xe ($Q_\beta = 4.397 \pm 0.142$ MeV). The resultant shape fit, shown in the semi-logarithmic plot (figure 13), included all the data at higher energies as did subsequent shape fits to other calibration and unknown beta decay spectra. The shape fit cutoff shown at higher channel number was an artifact of the semi-logarithmic presentation. A linear plot (shown as an insert) illustrates the entire fit which included the data at higher channel numbers. The chi-squared from the shape fit procedure ($\chi^2 = 1.12$) indicated that equation IV.3 well describes the experimental shape.

The calibration process then continued by fitting beta spectra of nuclei with known endpoint energies. These spectra were nonlinear least-squares fit to the standard shape using a two parameter function $N_i S(\alpha x)$, where N_i is an overall normalization, α is a stretching or compression factor which takes into account differing decay energies, and S is equation IV.3 with fixed values of N_0 , a , b , and x_0 . Figures 15, 16, and 17 illustrate fits to decays from the additional calibration nuclei used in this work, ^{66}Ga and ^{64}Ga , with their respective partial decay schemes shown in figure 14. Stretch factors of 1.06, 1.28, and 0.76 result for the 511 keV gamma ray gated beta spectrum



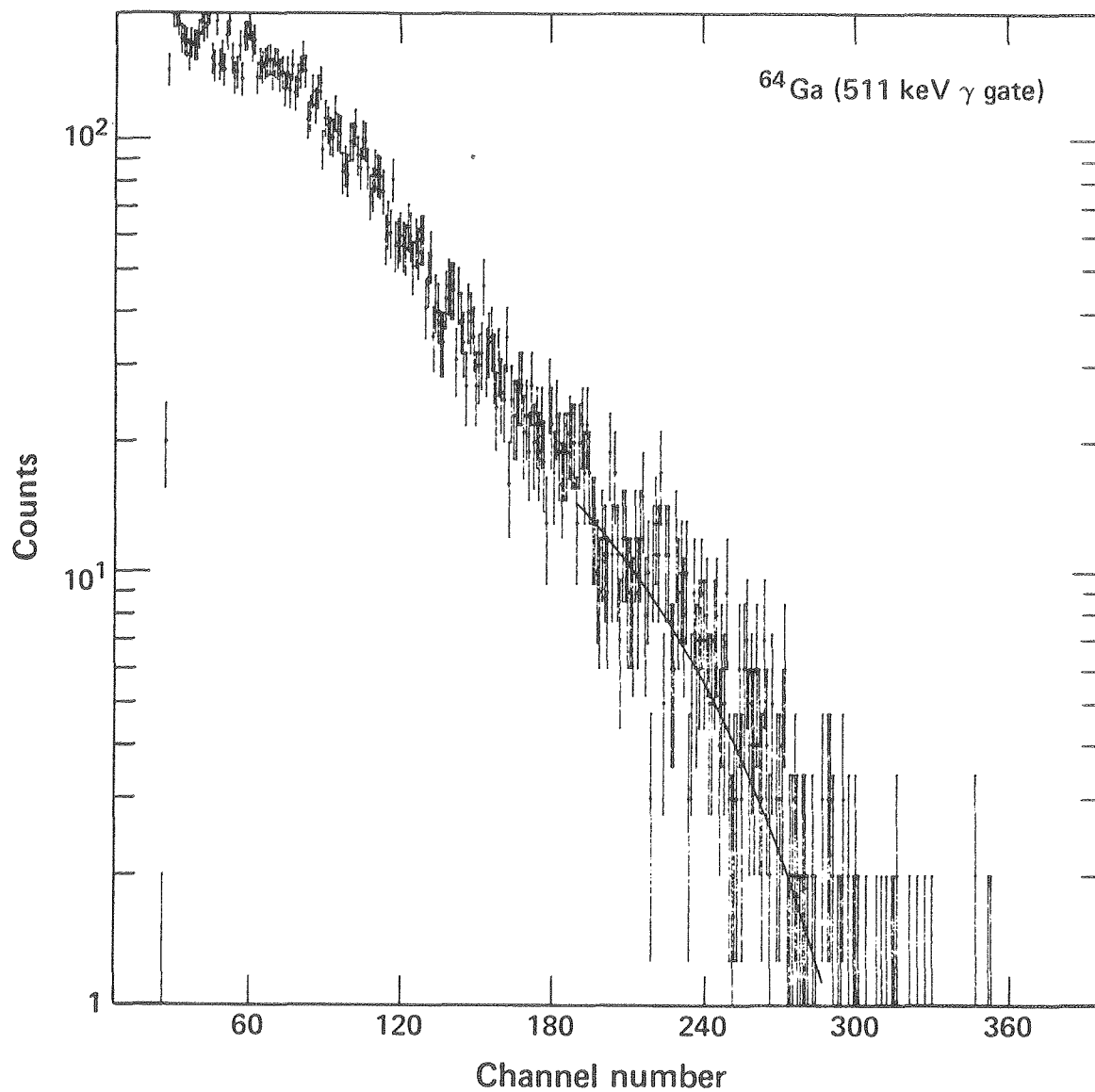
XBL 831-1043

Figure 15. ^{66}Ga beta spectrum with stretch fit. The spectrum was generated by coincidence gating on the 511 keV annihilation gamma ray energy (with background subtraction).



XBL 831-1044

Figure 16. ^{64}Ga beta spectrum with fit. This spectrum was generated by coincidence gating on the 992 keV gamma ray (with background subtraction). This spectrum is the low energy beta transition.

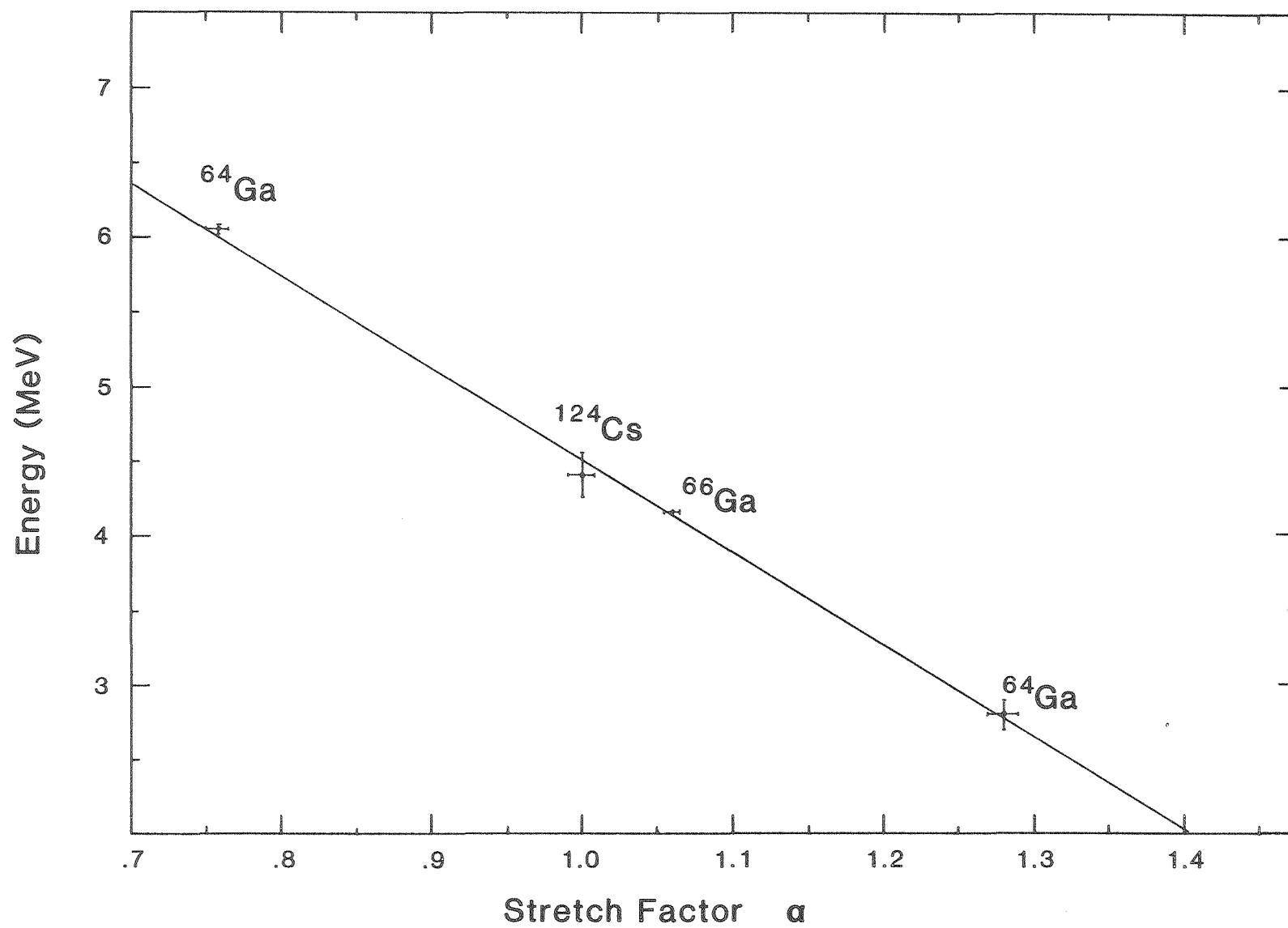


XBL 831-1042

Figure 17. ^{64}Ga beta spectrum with fit. This spectrum was generated by coincidence gating on the 511 keV annihilation gamma ray energy (with background subtraction). This spectrum is the high energy beta transition.

of the $0^+ {}^{66}\text{Ga}$ ground state decay to the 0^+ ground state in ${}^{66}\text{Zn}$ ($Q_\beta = 4.153 \pm 0.004$ MeV), the 992 keV gamma ray gated beta spectrum of the $0^+ {}^{64}\text{Ga}$ ground state decay to the 3186.8 keV 1^+ level in ${}^{64}\text{Zn}$ ($Q_\beta = 2.79 \pm 0.08$ MeV), and the 511 keV gated 0^+ ground state ${}^{64}\text{Ga}$ decay to the 0^+ ground state of ${}^{64}\text{Zn}$ ($Q_\beta = 6.05 \pm 0.03$ MeV), respectively. The resultant calibration curve which related the stretch factors (α 's) to their respective Q_β values is illustrated in figure 18.

Determination of unknown beta endpoints proceeded by fitting to the standard shape, calculating the stretch factor, α , and using the calibration curve to arrive at the endpoint energy. The basic assumption used was that alpha was linear over moderate energy ranges, which was verified by the linearity of the fit to the experimental calibration nuclei.



XBL 831-7907

Figure 18. Experimental calibration curve for decay energy versus stretch factor, α .

V. Results

Presented here are the experimental results of Q_β and deduced Q_{EC} values from the decays of the neutron deficient isotopes ^{123}Cs to ^{119}Cs . Along with decay Q -value measurements, beta-coincident gamma ray relative intensities will be listed. The relative intensities for the 511 keV annihilation quanta have only been corrected for the energy dependent efficiency of the intrinsic Ge detector, but not for positron range effects. The listed annihilation intensities are therefore only approximate. In reviewing prior literature results, their proposed level schemes for $^{121,119}\text{Cs}$ have failed to incorporate some of the experimentally observed gamma rays. Using the intensities from this work and the literature decay scheme information, additions to these schemes will also be presented.

A. ^{123}Cs

The beta decay of 5.6 min ^{123}Cs was studied previously by several investigators (DAU66,WES75,SOF81). The most recent decay study, by Sofia et al. (SOF81), presented the decay scheme shown in figure 19. Our experimental beta-coincident gamma ray intensities, listed in table 2, in most cases compare well to the literature

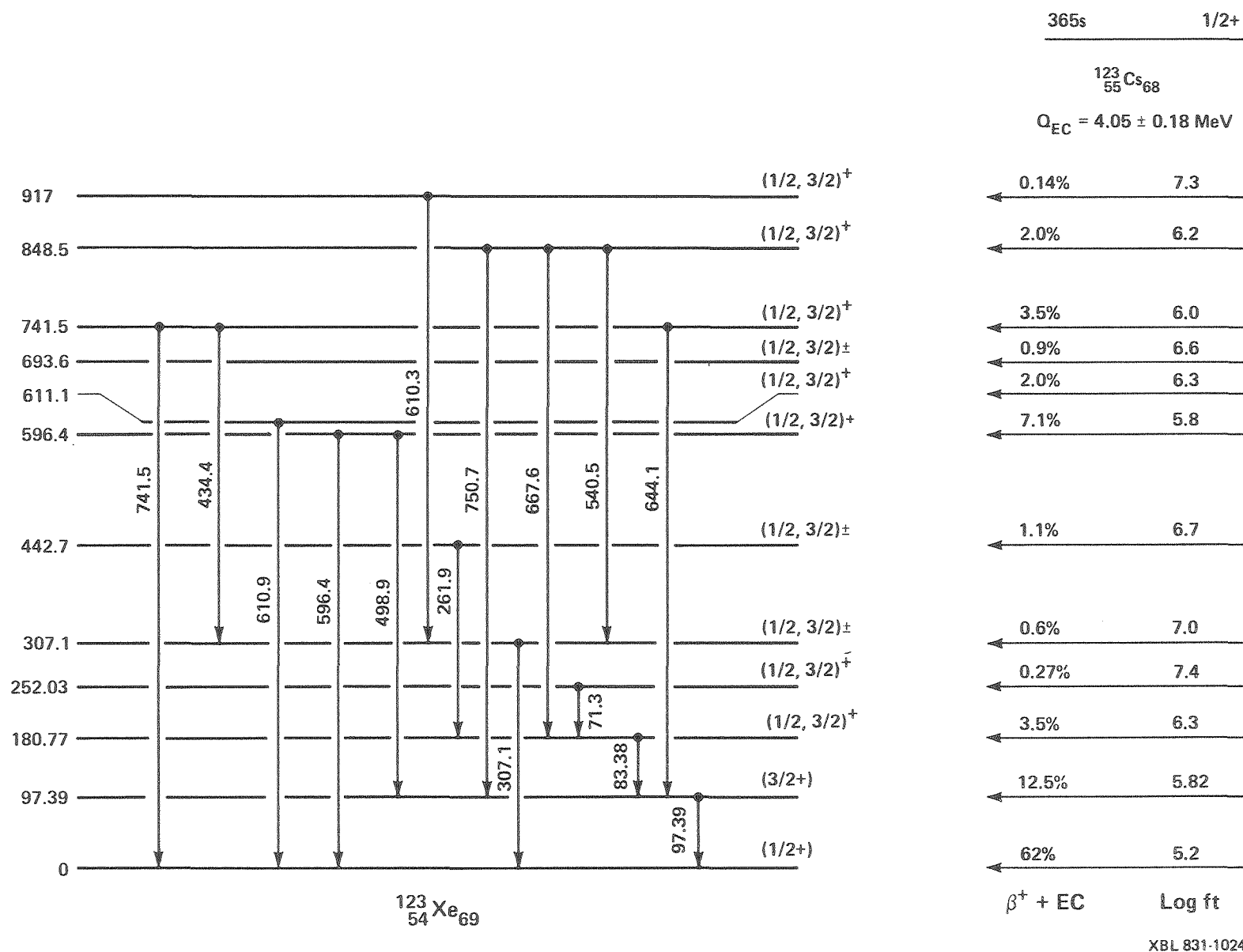


Figure 19. Decay scheme for ^{123}Cs [from Sofia et al. (SOF81)]. The decay Q -value is from our work.

E_{γ} (keV)	$I_{\gamma}\%$		
	This work	Westgaard et al. ¹	Sofia et al. ²
71.3	4 $\pm$ 2		1.2 $\pm$ 0.1
83.38	8 $\pm$ 3		21 $\pm$ 1
97.39	100	100	100
261.9	3 $\pm$ 2		13 $\pm$ 1
307.1	8 $\pm$ 5	21 $\pm$ 10	21 $\pm$ 1
434.3	2 $\pm$ 1		4.7 $\pm$ 0.7
498.9	10 $\pm$ 3		6 $\pm$ 2
511	1130 $\pm$ 260	3010 $\pm$ 410	1300 $\pm$ 200
540.5	14 $\pm$ 2		4 $\pm$ 1
596.4	64 $\pm$ 4	103 $\pm$ 18	57 $\pm$ 3
610.9	29 $\pm$ 3	41 $\pm$ 9	16.7 $\pm$ 1.9
644.1	12 $\pm$ 2	17 $\pm$ 5	15 $\pm$ 2
667.6	4 $\pm$ 1		7 $\pm$ 1
741.5	14 $\pm$ 2	15 $\pm$ 5	17 $\pm$ 2
750.7	2 $\pm$ 1		4.8 $\pm$ 0.7

Table 2. ^{123}Cs beta-coincident gamma ray intensities. Literature values included for comparison.

¹Ref. (WES75)

²Ref. (SOF81)

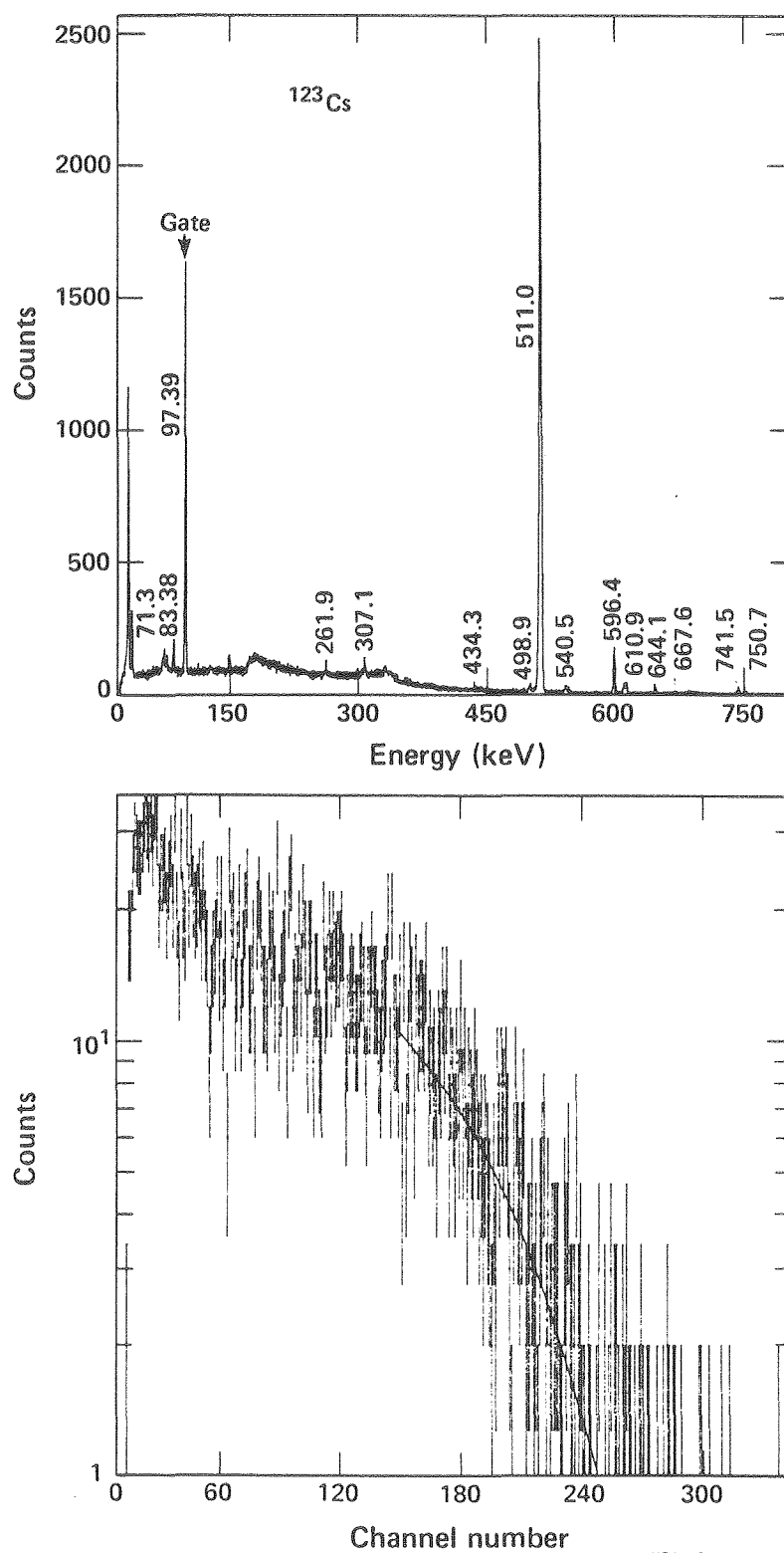


Figure 20. Beta-coincident gamma ray and beta decay spectra of ^{123}Cs . The beta spectrum was generated via the 97.39 keV gamma ray gate with background subtracted. Error bars are statistical, $1/\sqrt{N}$.

XBL 832-7800

values of Westgaard et al. (WES75) and Sofia et al. The slight deviation in intensities was possibly due to differences in the overall beta-gamma coincident detection efficiencies.

The observed gamma spectrum and beta decay spectrum with stretch fit are presented in figure 20. The beta decay energy, Q_β , for ^{123}Cs was determined by measuring positrons in coincidence with the 97.39 keV gamma ray, the decay of the $1/2^+$ ^{123}Cs ground state to the 97.39 keV $3/2^+$ first excited state in ^{123}Xe (see fig. 19). Stretch fit analysis of this gated spectrum yielded a $Q_\beta = 2.93 \pm 0.18$ MeV which resulted in a total decay energy, $Q_{\text{EC}} = 4.05 \pm 0.18$ MeV, consistent with Sofia et al. ($Q_{\text{EC}} = 4.0 \pm 0.1$ MeV).

B. $^{122\text{m,g}}\text{Cs}$

The decay of 21 s $^{122\text{g}}\text{Cs}$ and 4.2 min $^{122\text{m}}\text{Cs}$ have been studied previously (WES75,DAU76,GEN77) yielding both ^{122}Xe level scheme information (figure 21) and a value for Q_{EC} for the ground state decay, $^{122\text{g}}\text{Cs}$, with approximately 0.5 MeV uncertainty. The spin of the ground state and isomer have also been determined (EKS77) as 2^+ for $^{122\text{g}}\text{Cs}$ and 8^- for $^{122\text{m}}\text{Cs}$.

The experimental beta-coincident gamma spectrum and intensities for $^{122\text{g}}\text{Cs}$ are shown in figure 22 and table 3, respectively. Assuming that 80% of the 2^+ $^{122\text{g}}\text{Cs}$ ground state decays to the 331.1 keV 2^+ first excited state in

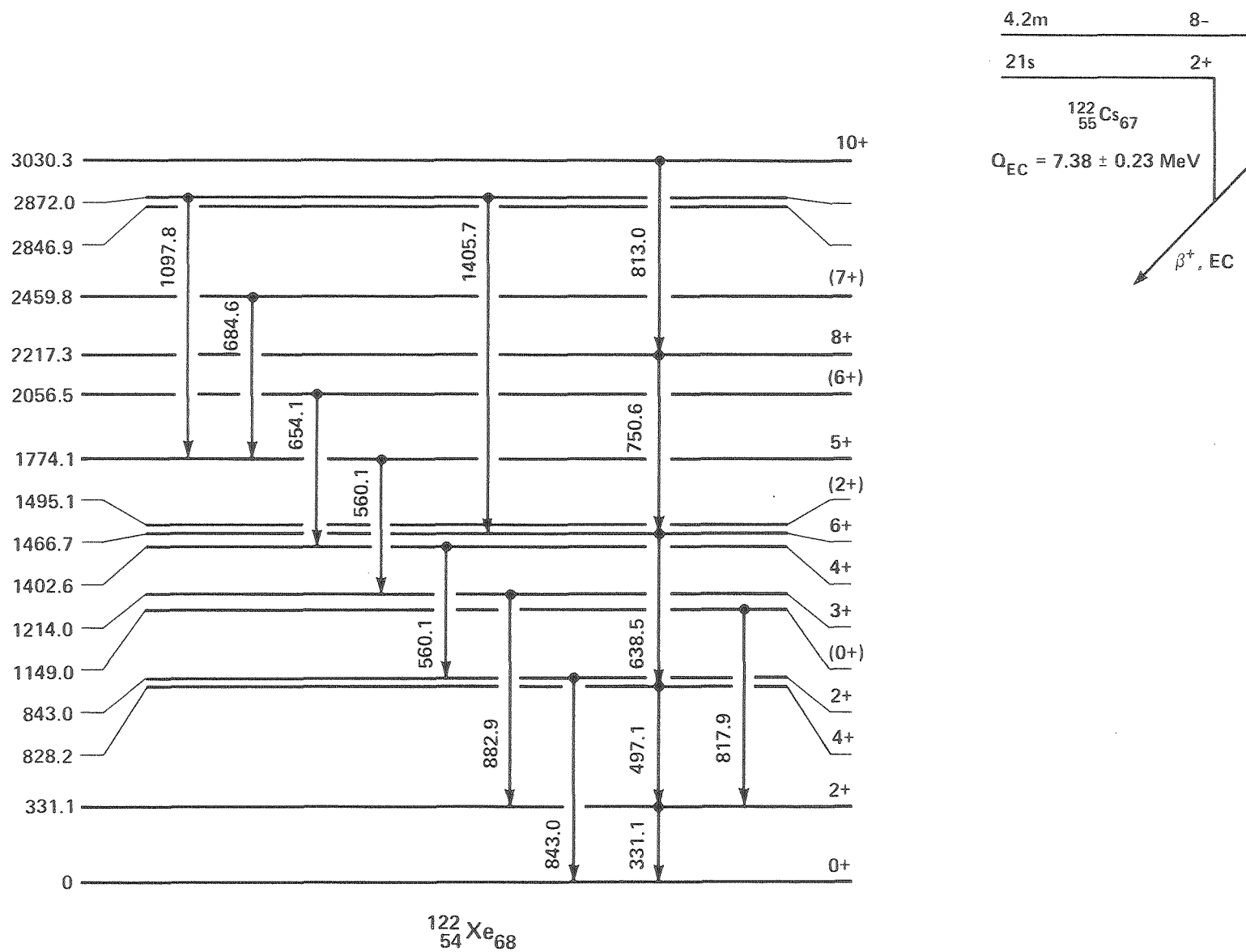
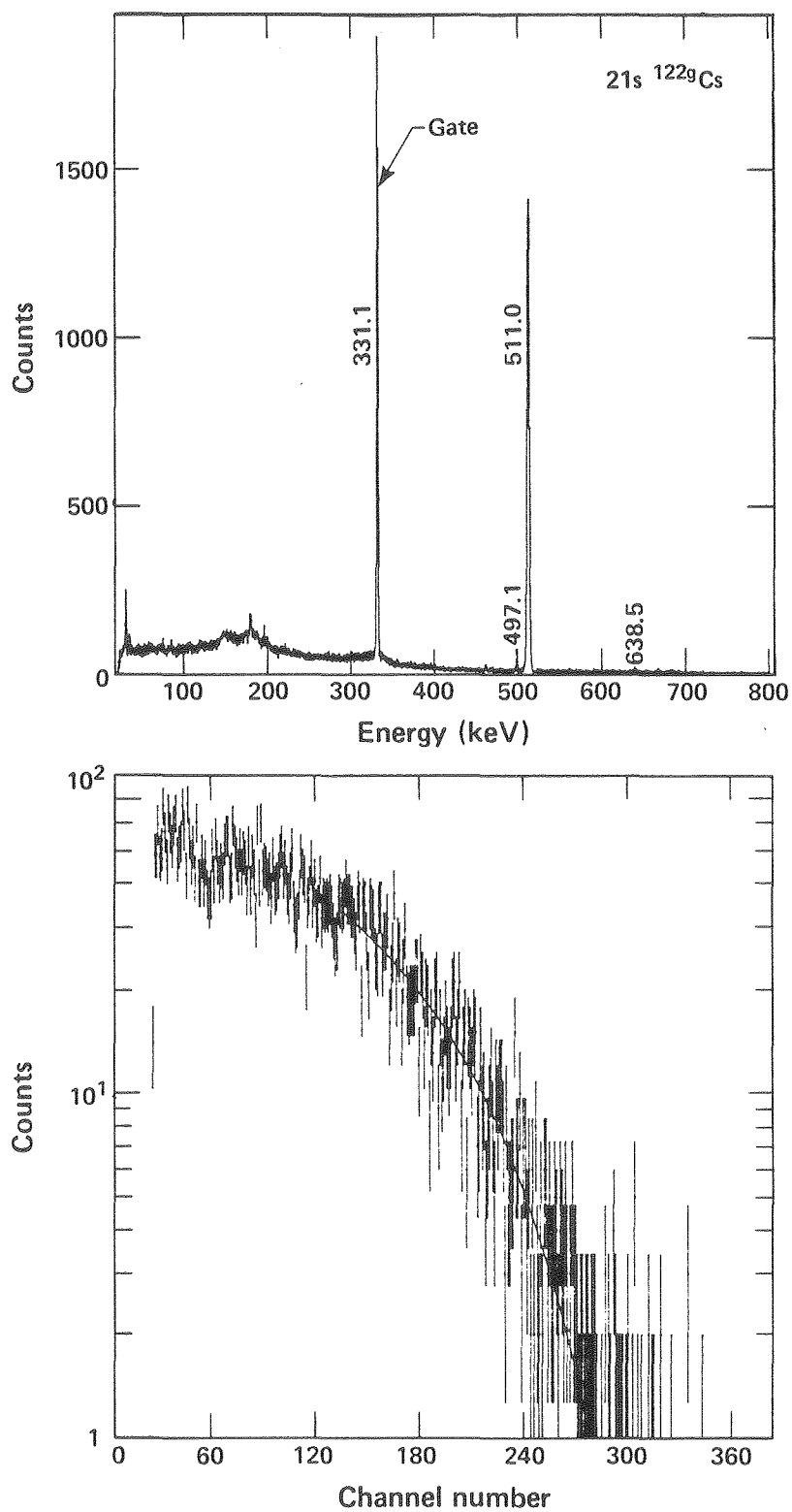


Figure 21. Level scheme for ^{122}Xe [from Genevey-Rivier et al. (GEN77)]. The decay Q -value is from our work.

XBL 831-1023



XBL 831-1033

Figure 22. Beta-coincident gamma ray and beta decay spectra of ^{122g}Cs . The beta spectrum was generated using the 331.1 keV gamma ray gate with background subtracted. Error bars are statistical.

E_{γ} (keV)	$I_{\gamma}\%$	
	This work	Westgaard et al. ¹
331.1	100	100
497.1	3 $\pm$ 1	≤ 7.5
511	193 $\pm$ 47	402 $\pm$ 53
817.9	5 $\pm$ 1	7.0 $\pm$ 2.1
843.0	7 $\pm$ 1	11.2 $\pm$ 2.8

a. ^{122g}Cs beta-coincident gamma ray intensities.

E_{γ} (keV)	$I_{\gamma}\%$
	This work
331.1	100
497.1	79 $\pm$ 4
511	288 $\pm$ 52
560.1	35 $\pm$ 3
638.5	119 $\pm$ 8
654.1	17 $\pm$ 3
750.6	35 $\pm$ 2

b. ^{122m}Cs beta-coincident gamma ray intensities.

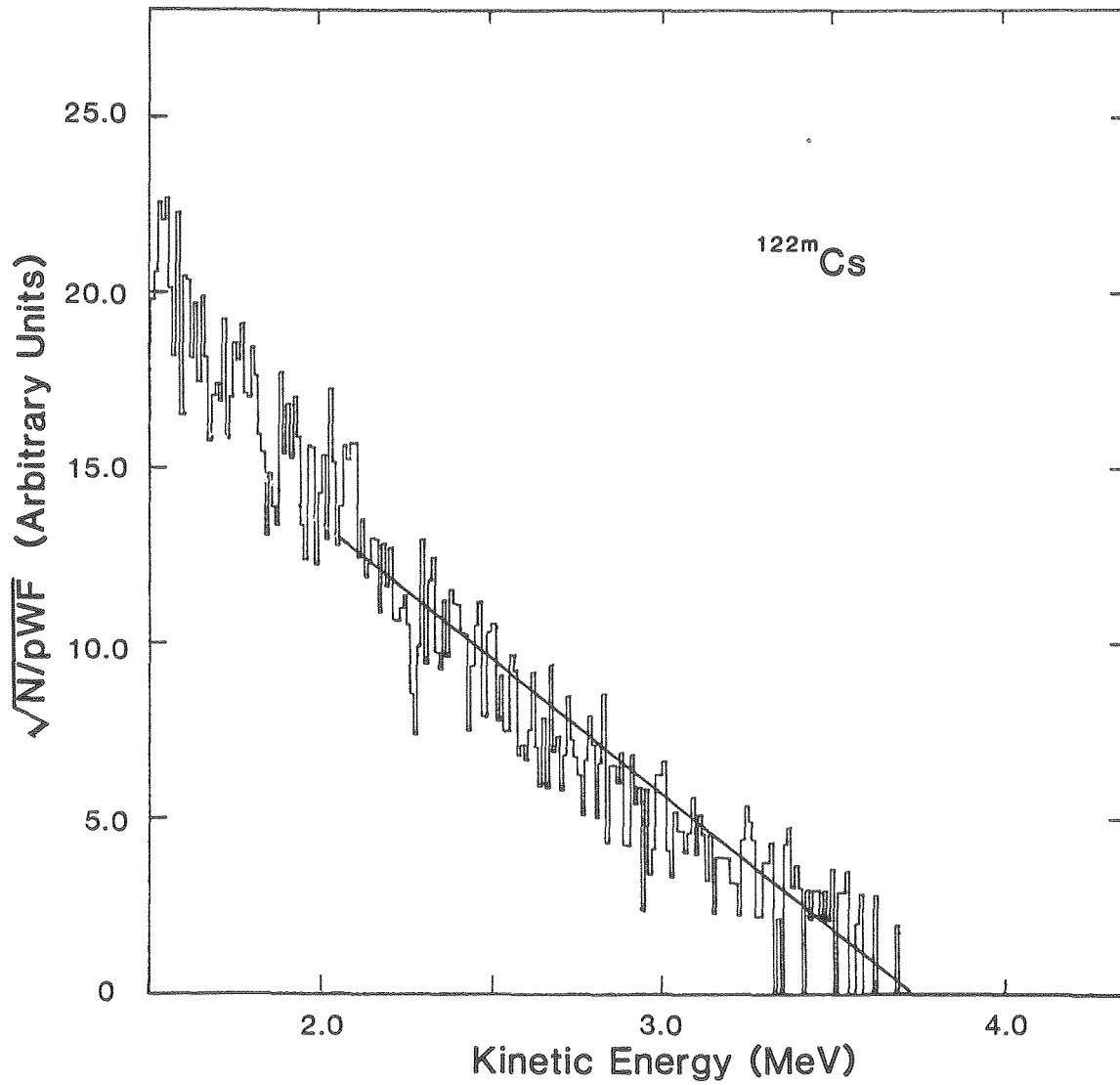
Table 3. ^{122}Cs beta-coincident gamma ray intensities. Literature values included for comparison.

¹Ref. (WES75)

the ground rotational band of ^{122}Xe (WES75), the stretch fit analysis (shown in figure 22) results in $Q_{\beta} = 5.69 \pm 0.18$ MeV or the value of $Q_{\text{EC}} = 7.05 \pm 0.18$ MeV. This value agrees well with the literature value (DAU76), $Q_{\text{EC}} = 7.05 \pm 0.5$ MeV.

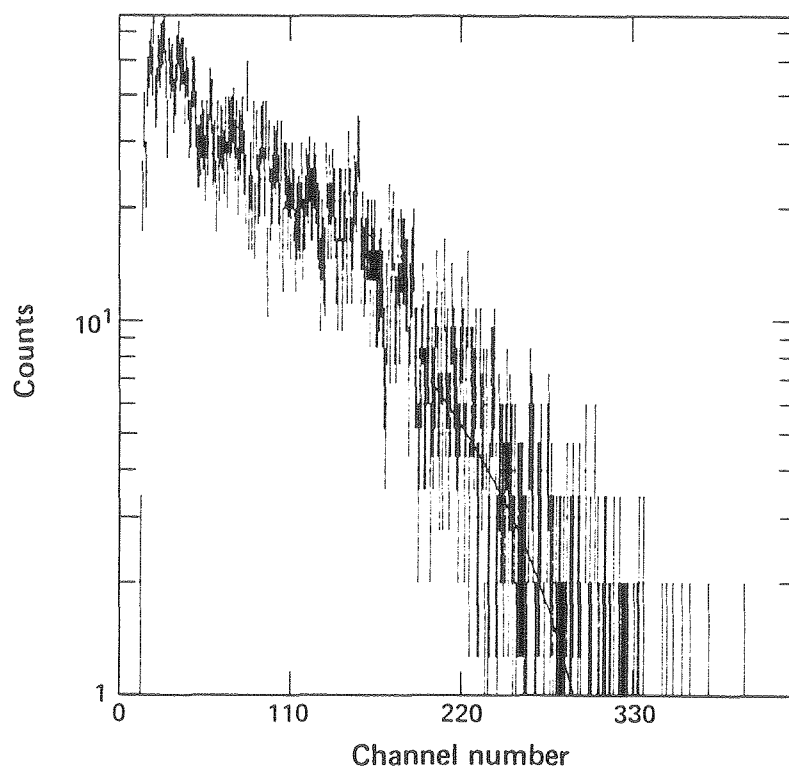
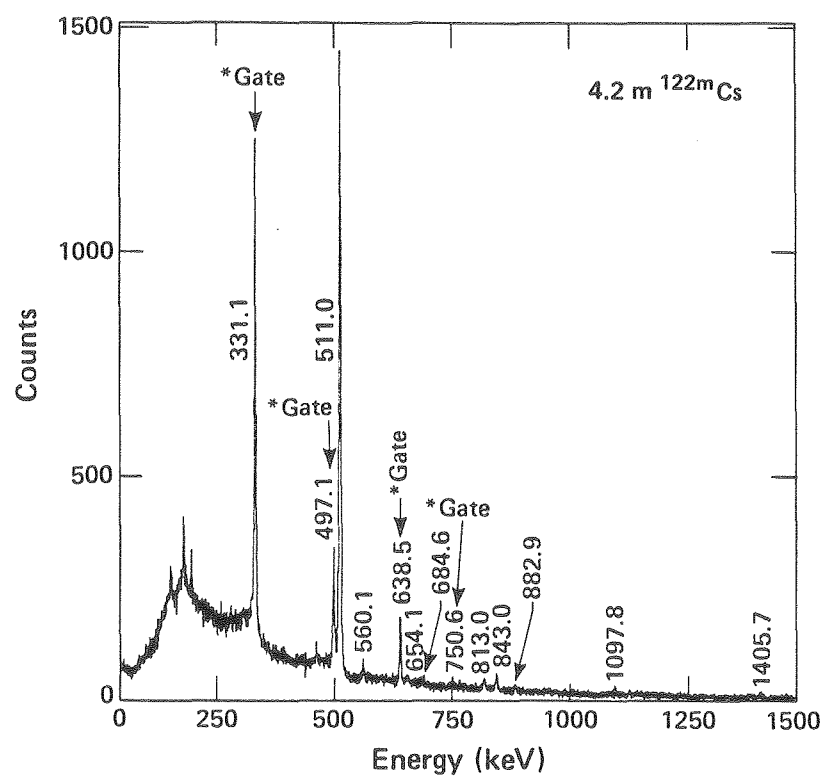
The Q_{β} value for the 4.2 min isomeric state had not been previously determined. Our experimental beta-coincident gamma intensities listed in table 3 indicated, as did the gamma-gamma coincident studies of Genevey-Rivier et al. (GEN77), that the isomeric decay was from the low lying 8^{-} isomeric state in ^{122}Cs to the 2217.3 keV 8^{+} level in the ground state rotational band of ^{122}Xe . The coincidence gating conditions for the 4.2 min $^{122\text{m}}\text{Cs}$ decay therefore used all the gamma rays in the $8^{+} \rightarrow 6^{+} \rightarrow 4^{+} \rightarrow 2^{+} \rightarrow 0^{+}$ cascade. The $2^{+} \rightarrow 0^{+}$ 331.1 keV gamma-coincident positrons were gated so that only those events recorded 2 minutes after the shuttle to the detection station were included in the beta spectrum. This reduced significantly any contribution from the 21 s $^{122\text{g}}\text{Cs}$ decay.

The $8^{-} \rightarrow 8^{+}$ isomeric beta decay was a parity forbidden transition and necessitated additional investigation regarding the suitability of shape analysis. To determine if the spectrum was of allowed shape (necessary for stretch fitting), a response corrected Fermi-Kurie plot was generated using the combined "folding" and "unfolding" technique. The plot that resulted is shown in figure 23. No attempt was made to deduce an endpoint energy from this



XBL 831-7932

Figure 23. Fermi-Kurie plot of $^{122\text{m}}\text{Cs}$ beta spectrum.



XBL 831-1040

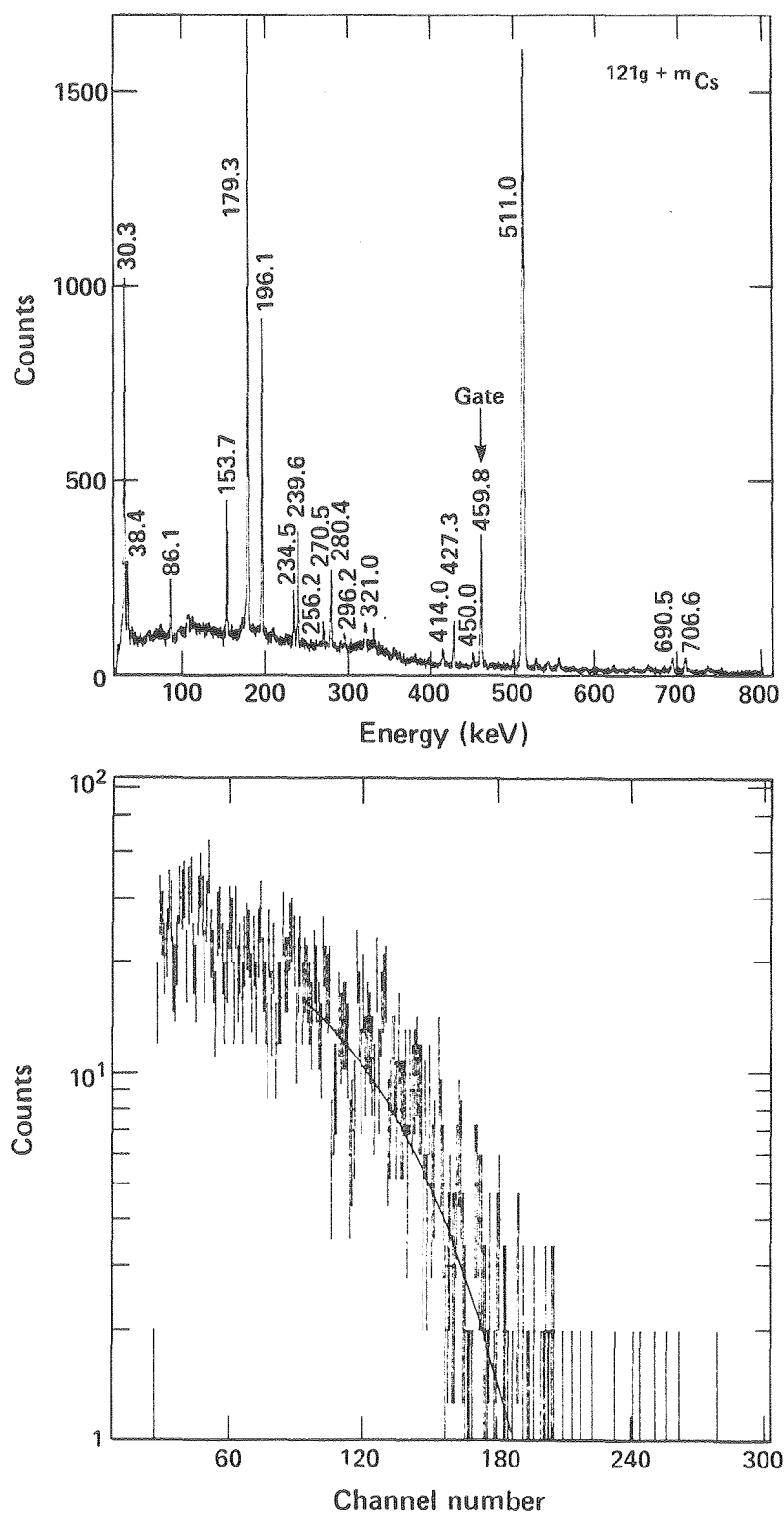
Figure 24. Beta-coincident gamma ray and beta decay spectrum of ^{122m}Cs .

plot, only to note that the analysis clearly indicated a linear result. Application of the stretch fitting technique (figure 24) also indicated the shape of the spectrum was not noticeably skewed from that of an allowed shape. This was also evident in the value of χ^2 ($= 1.12$) for the fit.

The stretch fit result, $Q_\beta = 3.71 \pm 0.25$ MeV, translated to the value of $Q_{EC} = 6.95 \pm 0.25$ MeV. This maximum decay Q-value implied that the isomer was fairly close to the ground state, as was also observed by Epherre et al. (EPH79) in their direct mass measurements of the cesium isotopes. Unfortunately, the relative level spacing of the ground state and the isomer could not be deduced from the decay Q-values due to the large uncertainties involved.

C. ^{121}Cs

Level schemes for the beta decay daughter, ^{121}Xe , have been proposed by several investigators from in-beam gamma-gamma coincident xenon (GAR79, CHO81, BAR82) and beta-gamma coincident (SOF81) cesium decay studies. The most recent in-beam gamma-gamma coincidence study of ^{121}Xe by Barci et al. (BAR82) did not include several gamma rays that were observed from the decay of ^{121}Cs by Sofia et al. and this work. Our experimental beta-coincident gamma ray spectrum and intensities are shown in figure 25 and



XBL 831-1034

Figure 25. Beta-coincident gamma ray and beta decay spectra of $^{121}\text{m} + \text{g}^{137}\text{Cs}$.

E_{γ} (keV)	$I_{\gamma}\%$
30.3	65 ± 4
34.8	13 ± 2
86.1	7.1 ± 1.8
153.7	19 ± 2
179.3	100
196.1	51 ± 3
234.5	12 ± 1
239.6	27 ± 3
256.2	3.6 ± 1.5
270.5	4.6 ± 1.1
280.4	24 ± 3
296.2	4.9 ± 1.0
321.0	13 ± 1
414.0	9.0 ± 1.1
427.3	$2.4 \pm .8$
450.0	8.7 ± 1
459.8	82 ± 7
690.5	13 ± 1
706.6	18 ± 1

Table 4. ^{121m}gCs beta-coincident gamma ray intensities.

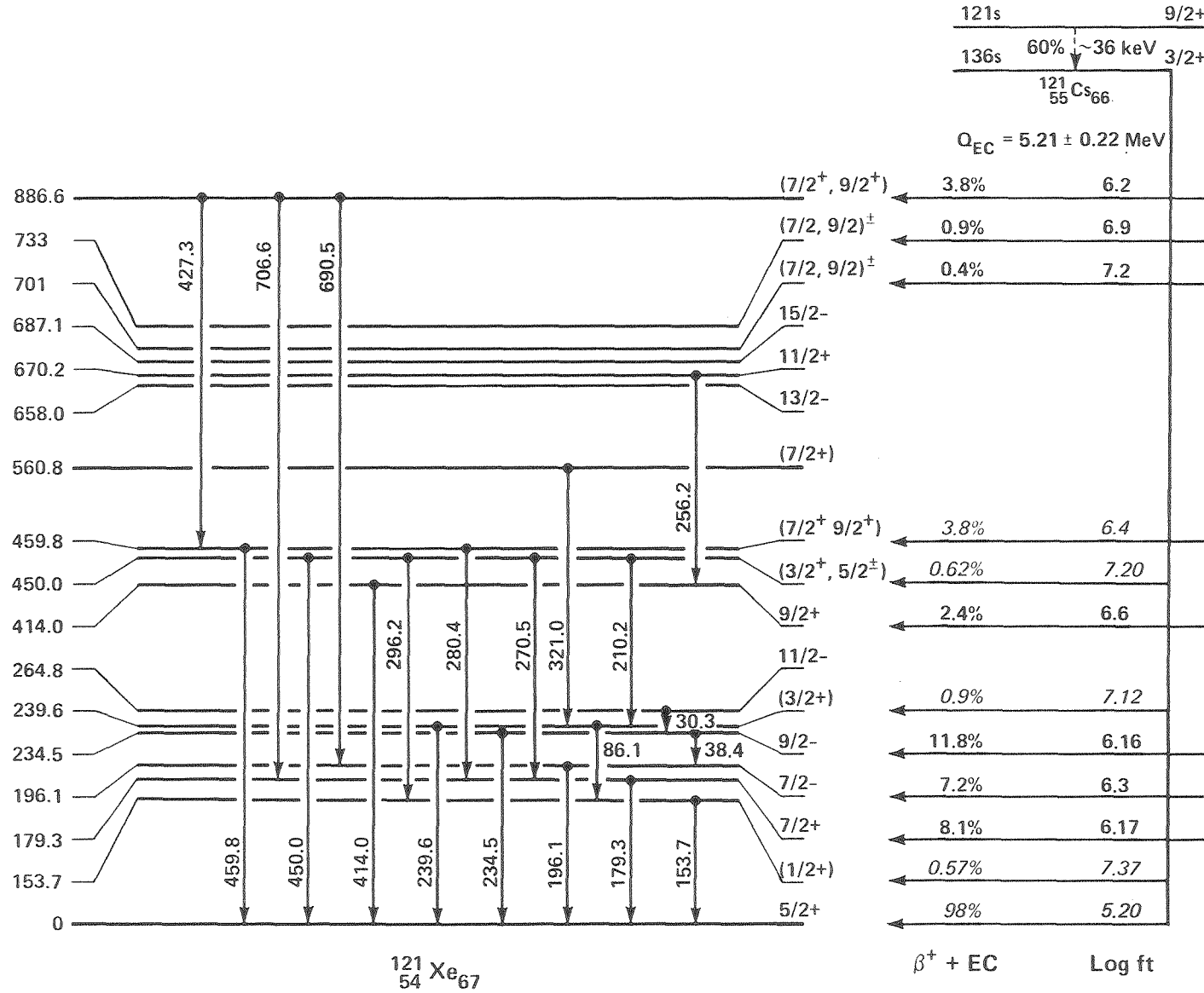


Figure 26. Proposed level scheme for ^{121}Xe based on the gamma-gamma coincidence studies of Barci et al. (BAR82) and the beta-coincident gamma ray investigations of Sofia et al. (SOF81) and this work. ^{121}Cs decay Q -value from our work.

XBL 831-1026

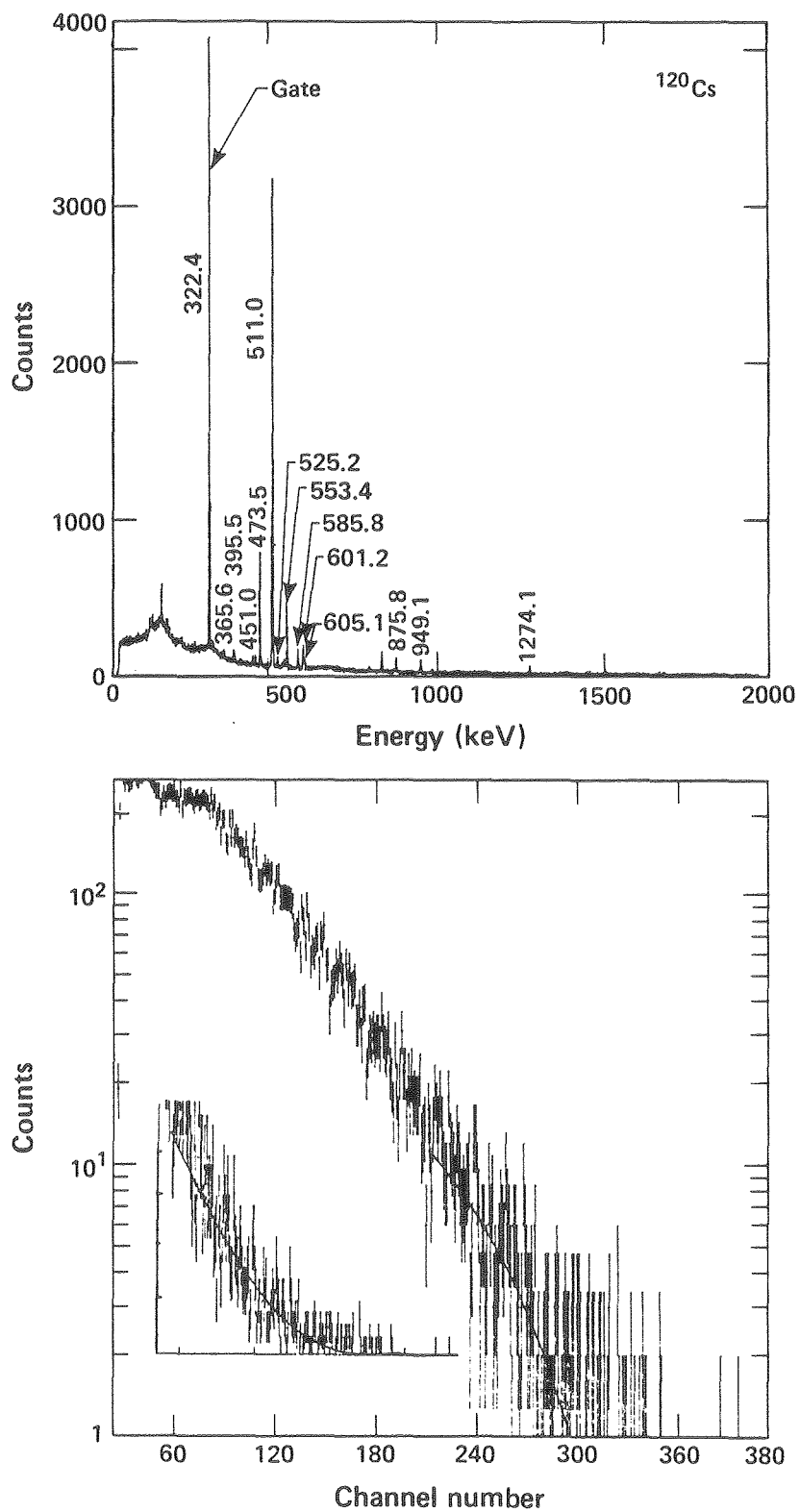
table 4, respectively.

A proposed decay scheme is shown in figure 26 that was based on both the in-beam gamma-gamma and beta-gamma coincident information. Placement of the $9/2^-$ 234.5 keV and $7/2^-$ 196.1 keV levels were taken from the in-beam work and the addition of the $(7/2, 9/2)^+$ 886.6 keV and 459.8 keV levels from the beta decay measurements of Sofia and this work (proposed spin and parities from Sofia et al.). Addition of these two levels accounted for five beta-coincident gamma ray energies (see fig. 26): 706.6, 690.5, 459.8, 427.3, and 280.4 keV.

Based on this decay scheme, the 459.8 keV gamma ray was selected for coincidence gating of the beta spectrum, shown in figure 25. The stretch fit analysis generated a value $Q_\beta = 3.73 \pm 0.22$ MeV which translated to an experimental value for $Q_{EC} = 5.21 \pm 0.22$ MeV. This compared well with the previous value of Sofia et al. (SOF81) $Q_{EC} = 5.40 \pm 0.02$ MeV. It should be noted however that the uncertainty expressed in their value was inappropriately precise given the Fermi-Kurie analysis method and the data they presented.

D. ^{120}Cs

The beta-coincident gamma spectrum and gated beta spectrum (with stretch fit) are shown in figure 27. The gamma ray intensities and decay scheme (GEN77) are shown

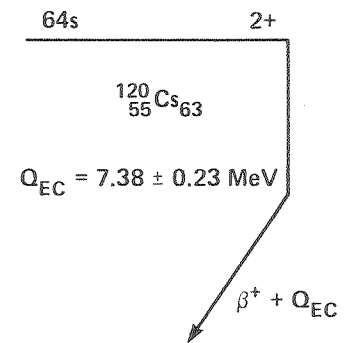
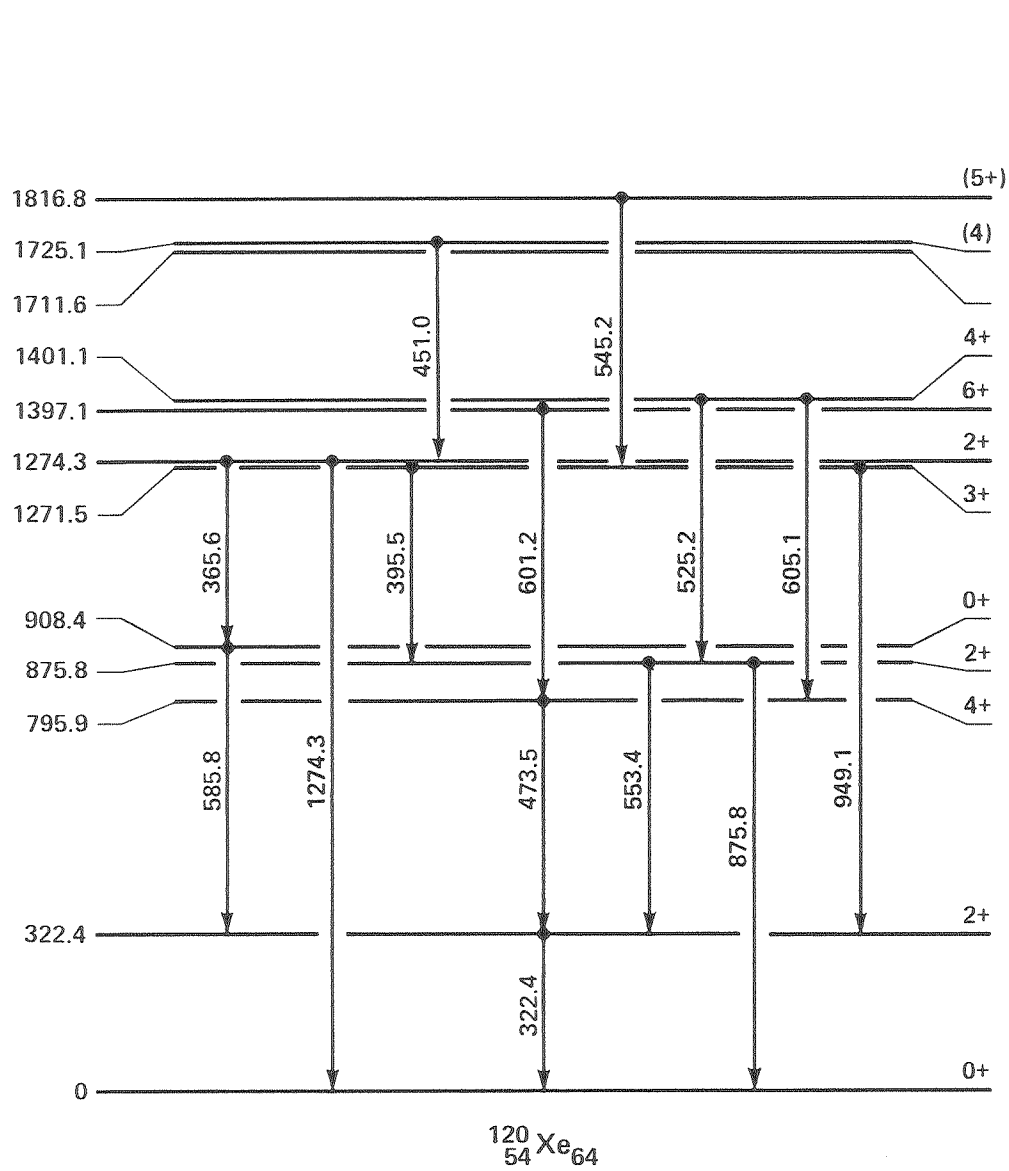


XBL 831-1035A

Figure 27. Beta-coincident gamma ray and beta decay spectra of ^{120}Cs . The insert shows the linear representation of the stretch fit for the beta spectrum. Note that the fit extends over the higher channel data.

E_{γ} (keV)	$I_{\gamma}\%$
322.4	100
365.6	1.7 ± 1.0
451.0	2.9 ± 1.1
473.5	28 ± 5
525.2	3 ± 1
545.2	$1.0 \pm .6$
553.4	20 ± 2
585.8	9 ± 1
601.2	9 ± 1
605.1	3.8 ± 1.3
875.8	9 ± 1
949.1	10 ± 1
1274.1	7.4 ± 1.4

Table 5. ^{120}Cs beta-coincident gamma ray intensities.



XBL 831-1028

Figure 28. Level scheme for ^{120}Xe [from Genevey-Rivier et al. (GEN77)]. The decay Q -value was from our work.

in table 5 and figure 28, respectively. The value for $Q_{\beta} = 6.04 \pm 0.23$ MeV, from the beta decay spectrum gated with the 322.4 keV $2^{+} \rightarrow 0^{+}$ gamma decay in ^{120}Xe , agreed well with the literature values, $Q_{\beta} = 6.5 \pm 1.0$ MeV (DAU76) and $Q_{\beta} = 6.0 \pm 0.5$ MeV (BAT76), but with reduced uncertainty.

An additional beta decay component was observed at a lower endpoint energy coincident with the measured $2^{+} \rightarrow 2^{+}$ decay. A beta spectrum generated by gating with 473.5 keV gamma rays was found to have only the lower energy component present and an endpoint energy of $Q_{\beta} = 3.97 \pm 0.21$ MeV. This low energy component agreed well with that observed by Batsch et al. (BAT76), $Q_{\beta} = 4.1 \pm 0.3$ MeV. The decay energy could be accounted for by a decay to a higher lying level in ^{120}Xe . However, there were no assigned, approximately 2400 keV, energy levels found in the literature decay scheme.

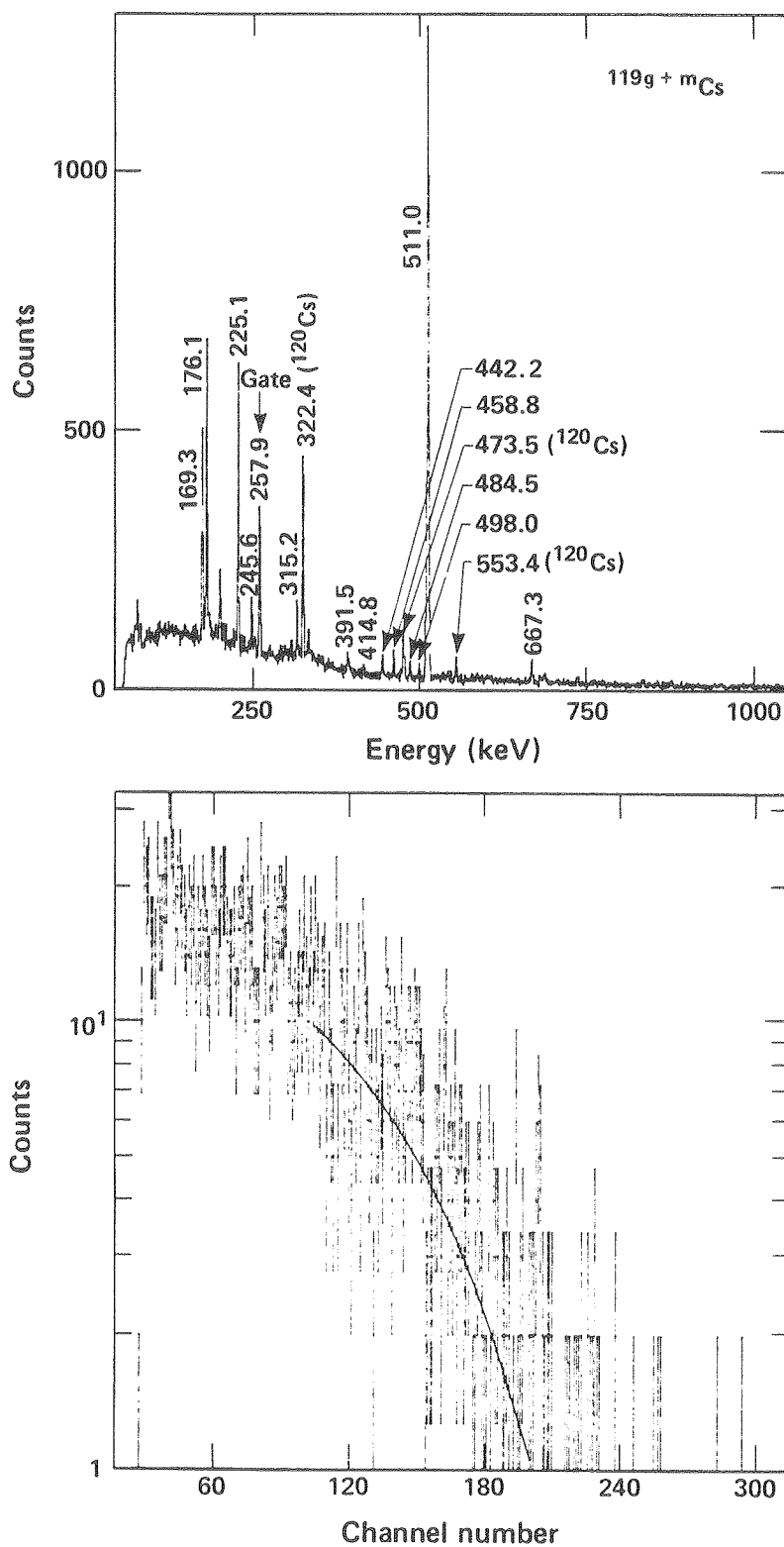
Assuming the coincident gamma from the $2^{+} \rightarrow 2^{+}$ (322.4 keV) decay defined the highest energy decay component (well separated from the observed lower energy branch), the value for the maximum beta decay energy results in $Q_{\text{EC}} = 7.38 \pm 0.23$ MeV.

E. ^{119}Cs

The beta decay for this isotope had not been previously characterized. A level scheme for the daughter, ^{119}Xe , was proposed by Barci et al. (BAR76) from

in-beam gamma-gamma coincidence measurements of ^{119}Xe . The in-beam work did not observe several beta-coincident gamma rays seen in this work from the decay of ^{119}Cs . The beta-coincident gamma ray spectrum and intensities are shown in figure 29 and table 6. A proposed decay scheme is presented in figure 30. This scheme includes three additional levels to that proposed by Barci et al. : 667.3, 458.8, and 414.8 keV. These levels accounted for six experimentally observed beta-coincident gamma ray energies (see fig. 29): 667.3, 498.0, 458.8, 442.2, 414.8, and 245.6 keV.

Assuming that the $9/2^+$ ground state ^{119}Cs decays to the $9/2^+$ level in ^{119}Xe , the 258.8 keV gamma ray was chosen as the coincident gate for the beta spectrum (figure 30). The stretch fit analysis yielded a $Q_\beta = 4.98 \pm 0.29$ MeV which translated to a value for $Q_{\text{EC}} = 6.26 \pm 0.29$ MeV.



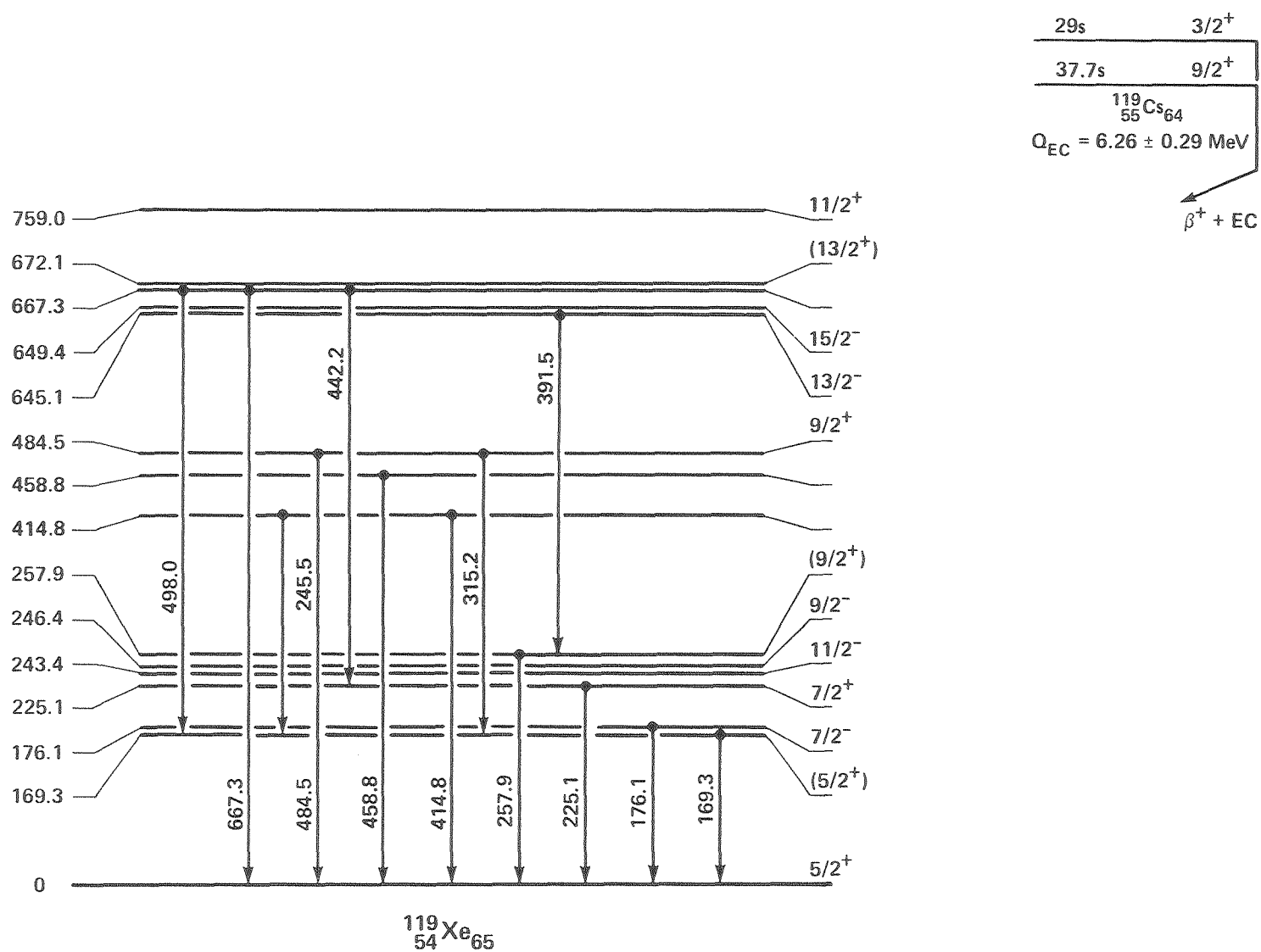
XBL 831-1046

Figure 29. Beta-coincident gamma ray and beta decay spectra of $^{119\text{m}+g}\text{Cs}$.

E_{γ} (keV)	I_{γ} %	
	This work	Westgaard et al. ¹
169.3	51±7	~67
176.1	77±9	~81
225.1	100	100
245.5	15±3	34±9
257.9	82±11	57±12
315.2	26±6	38±11
391.5	13±3	16±7
414.8	14±3	
442.2	13±4	
458.8	21±6	
484.5	21±6	
498.0	11±2	
667.3	32±7	17±8

Table 6. $^{119\text{m}+\text{g}}\text{Cs}$ beta-coincident gamma intensities.

¹Ref. (WES75)



XBL 831-1025

Figure 30. Proposed level scheme for ^{119}Xe based on the gamma-gamma coincidence studies of Barci et al. (BAR82) and this work. ^{119}Cs decay Q -value was from our work.

VI. Discussion

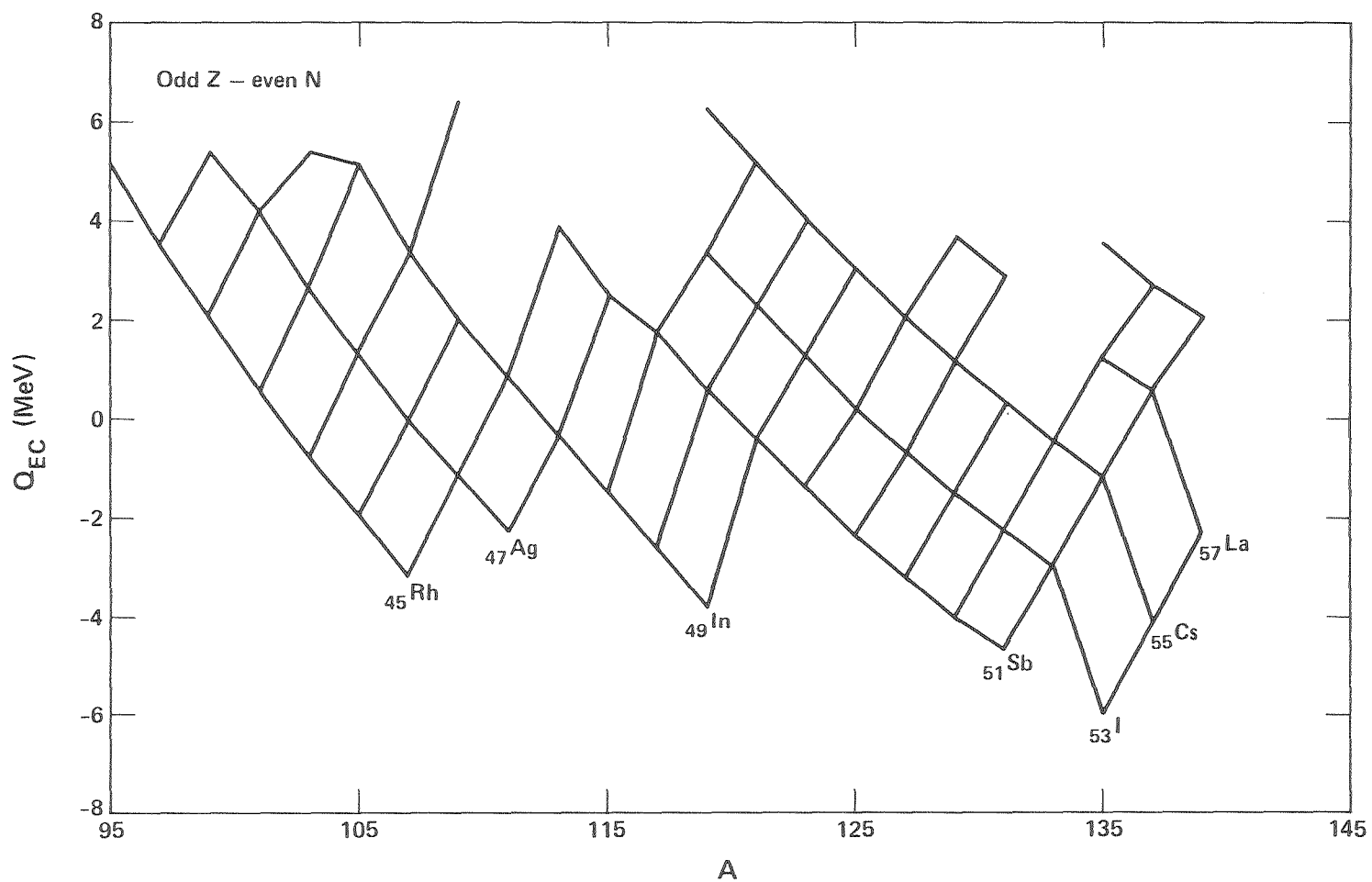
Analysis of the decay measurements of the neutron deficient cesium isotopes and investigation of the associated mass surface proceeds here in both model-independent and model-dependent fashion. A comparison of measured Q_{EC} values and neutron binding energies with neighboring nuclei highlights any deviation from the systematics of the region. Conversion of the experimentally measured Q_{EC} values to cesium mass excesses using the xenon mass excess literature values provides a vehicle for comparisons to the theoretical predicted and direct measured cesium mass excesses.

A comparison of experimental Q_{EC} values with the systematics of the heavier cesium and related odd-Z neutron deficient nuclei was done using the modified Way-Wood diagrams (WAY54) shown in figures 31 (odd-Z, even-N nuclei) and 32 (odd-Z, odd-N nuclei). Q_{EC} systematics presented in this manner show approximate linear characteristics between nuclei of the form (Z,N) to $(Z+2,N-2)$ in both constant N and Z contours. Separate plots are necessary for odd and even A nuclei because differences in Q_{EC} arise due to the neutron pairing energy. This effect is seen by comparing figure 31 (even-N) to figure 32 (odd-N). Higher values of Q_{EC} are evident for the odd-N nuclei due to the pairing of an odd-proton

and removal of a odd-neutron. The Way-Wood diagram also illustrates the $Z=50$ shell closure (seen between the nuclei $_{49}\text{In}$ and $_{51}\text{Sb}$) and the $N=82$ shell closure (seen as the recognizable gap in the lower right of both figures 31 and 32). In summary, changes in the even-odd differences of neutron and proton binding energies show up as deviations from linearity in the line separation pattern.

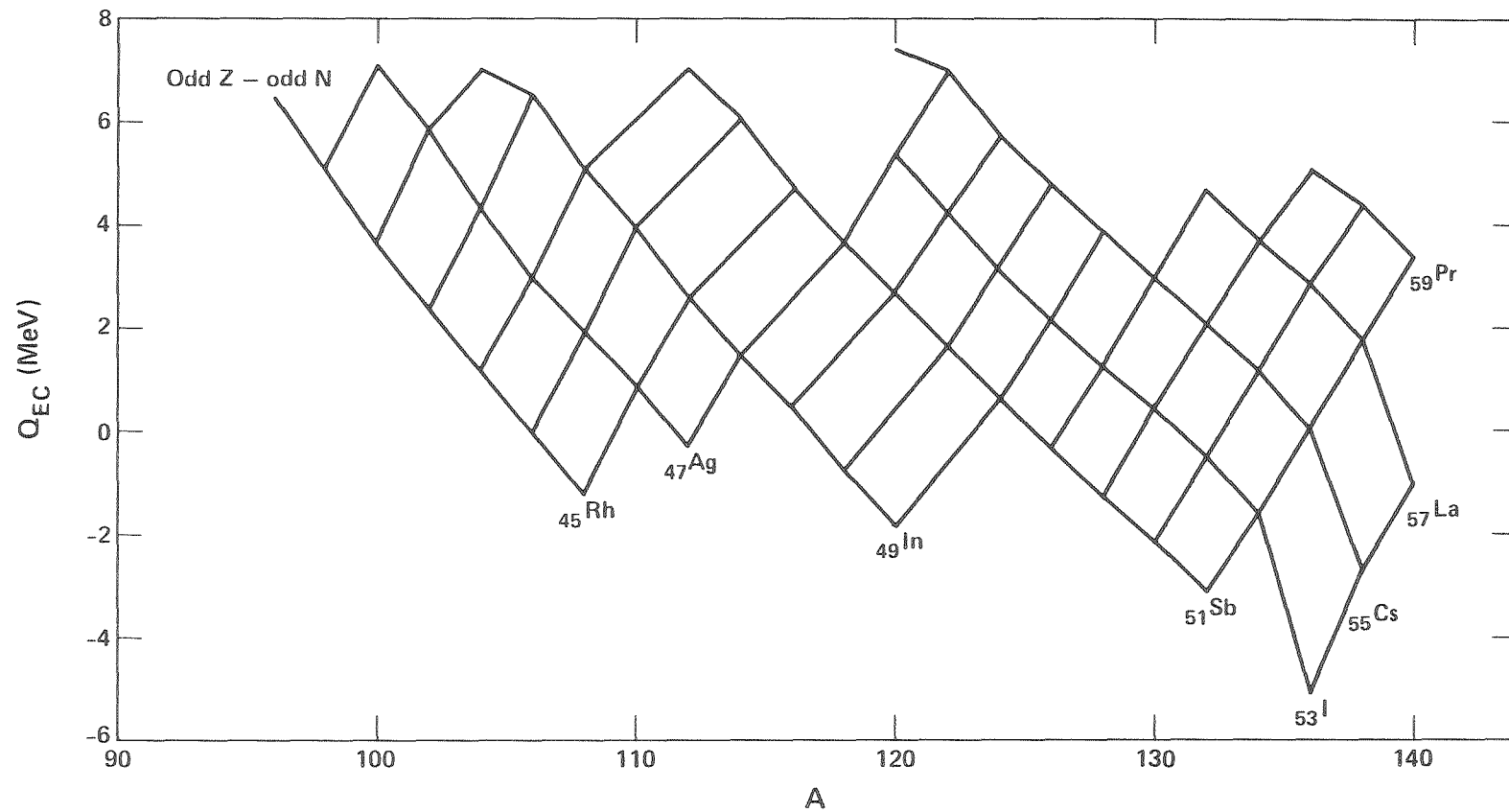
The Q_{EC} values for the odd-A cesium isotopes ^{119}Cs , ^{121}Cs , and ^{123}Cs plotted in figure 31 showed no particular deviations from the systematics of neutron and proton binding energies. The Q_{EC} value for the even-A (figure 32) cesium isotope, ^{122}Cs , also showed little deviation from the systematics of even-A cesium isotopes. However, the Q_{EC} value for ^{120}Cs deviated from the $Z=55$, cesium contour. The plotted decay energy appears approximately 500 keV lower than what was expected.

To provide a more quantitative understanding of the deviation in ^{120}Cs , a comparison of the predicted Q_{EC} values of three mass models -- the semi-empirical shell model calculation of Liran and Zeldes (LIR76), the Janecke modified empirical mass relations of Garvey-Kelson (JAN76), and the liquid drop model including Strutinsky-normalized shell and deformation corrections of Seeger-Howard (SEE76) -- with the experimental cesium Q_{EC} values was made and is shown in table 7. Agreement with all three of the theoretical mass models was quite good for all the experimentally measured cesium isotopes with



XBL 831-1027

Figure 31. Modified Way-Wood diagram (WAY54) showing total decay energies of odd Z - even N nuclei in the region of the neutron deficient cesium isotopes.



XBL 831-1031

Figure 32. Modified Way-Wood diagram (WAY54) showing total decay energies of odd Z - odd N nuclei in the region of the neutron deficient cesium isotopes.

Nucleus	I^π	$t_{1/2}$	Gating transition (keV)	Experimental Q_{EC} (MeV)	Literature Q_{EC} (MeV)	Prediction from mass formulae: Q_{EC} (MeV)		
						Liran ¹ Zeldes	Janecke ² Garvey Kelson	Seeger ³ Howard
¹¹⁹ Cs	9/2 ⁺	38 s	258.8	6.26±0.29	—	6.49	6.27	6.0
¹²⁰ Cs	2 ⁺	64 s	322.4	7.38±0.23	7.3±0.5 ⁴	8.25	7.98	7.8
¹²¹ Cs	3/2 ⁺	2.6 m	459.8	5.21±0.22	5.40±0.2 ⁵	5.24	5.01	5.0
^{122g} Cs	1 ⁺	21 s	331.1	7.05±0.18	7.05±0.40 ⁶	7.01	6.95	6.7
^{122m} Cs	8 ⁻	4.2 m	331.1 +497.1 +638.5 +750.6	6.95±0.25	—	—	—	—
¹²³ Cs	1/2 ⁺	5.9 m	98.1	4.05±0.18	4.0±0.1 ⁵	4.08	3.92	4.1

Table 7. Q_{EC} comparisons for the neutron deficient cesium isotopes.

¹Ref. (LIR76)

²Ref. (JAN76)

³Ref. (SEE76)

⁴Ref. (BAT76)

⁵Ref. (SOF81)

⁶Ref. (DAV76)

the exception of ^{120}Cs . The deviation for this nuclide averaged approximately 650 keV from the formulae presented. As a result, both the model-independent Way-Wood diagram and the model-dependent Q_{EC} values exhibited a deviation for ^{120}Cs . We shall note that the previous experimental Q_{EC} measurements of ^{120}Cs (DAU76,BAT76) supported our experimental value but had significantly larger uncertainties.

Cesium mass excesses were deduced from our experimental Q_{EC} values using the literature xenon mass excesses (WAP81) and are listed in table 8. Included in the table are literature cesium mass excesses taken from Wapstra (WAP81) and the direct mass measurement values of Audi et al. (AUD82). Generally good agreement was found (within the uncertainties) between the experimental and Wapstra-tabulated cesium mass excesses with the exception of ^{120}Cs , which differed by at least 850 keV. The comparison of our experimental mass excesses to the direct mass excess values of Audi (from mass triplet measurements) showed average deviations of approximately 500 keV for all but ^{120}Cs , which differed by 1300 keV. The two direct cesium mass excesses adjusted with other nuclear data (see table), ^{121}Cs and ^{123}Cs , however showed good agreement.

The direct mass measurements indicated the cesium isotopes to be poorer bound (with the exception of the adjusted values) than the mass excesses reported by

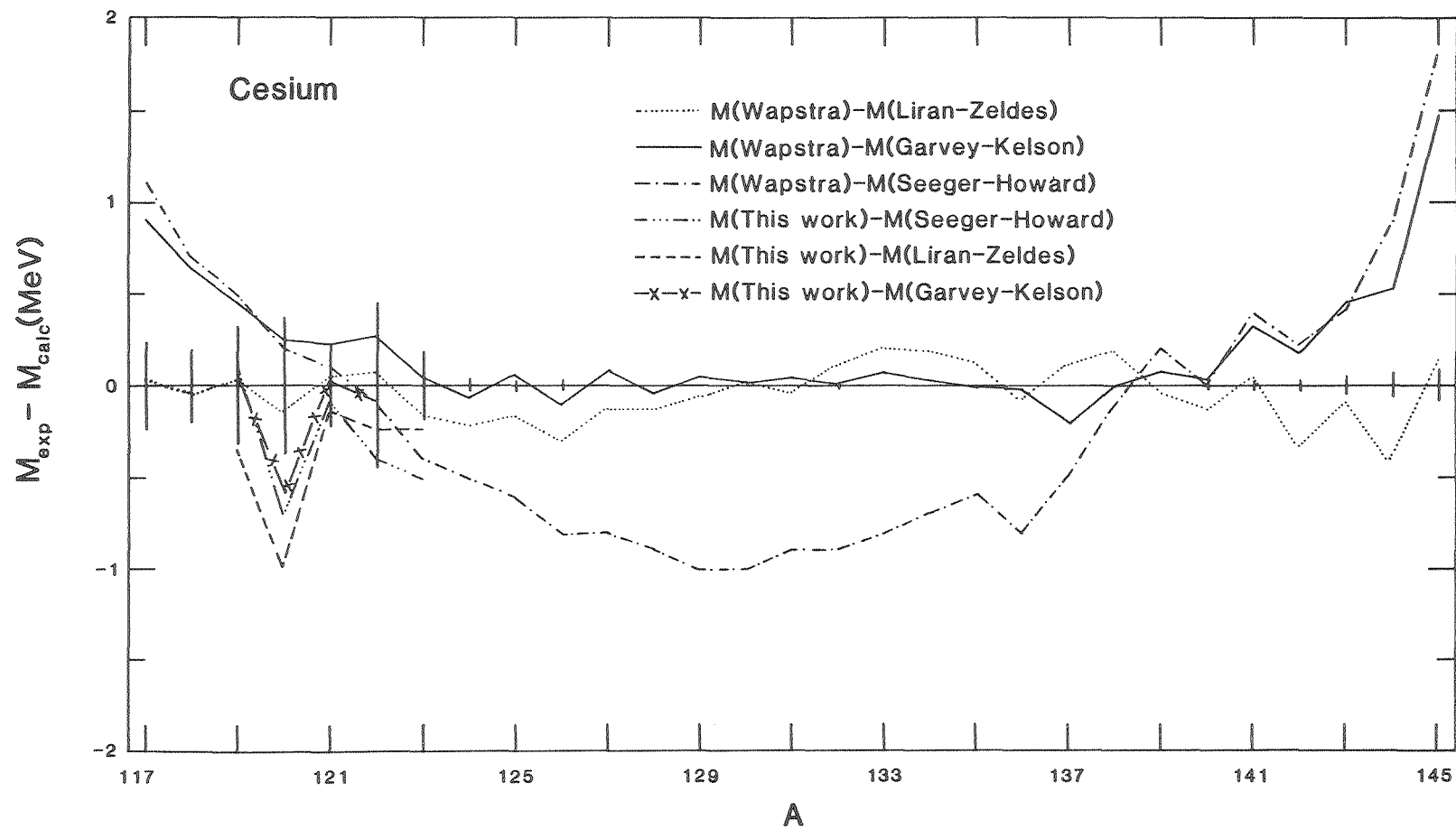
Nucleus	Cesium Mass Excesses (MeV)			
	This Work	Wapstra ¹	Audi et al. ²	
			I	II
¹¹⁹ Cs	-72.56±0.33	-72.187±0.143	-71.700±0.160	
¹²⁰ Cs	-74.65±0.37	-73.806±0.115	-73.360±0.130	
¹²¹ Cs	-77.25±0.23	-77.058±0.076	-76.760±0.120	-77.080±0.100
¹²² Cs	-78.30±0.45	-77.963±0.081	-77.750±0.080	
¹²³ Cs	-81.21±0.18	-81.137±0.060	-80.810±0.070	-81.250±0.100

Table 8. Comparison of experimental cesium mass excess values to the literature values of Wapstra [¹Ref. (WAP81)] and direct mass measured values of Audi et al. [²Ref. (AUD82)]. Values in column I from mass triplet measurements; column II are adjusted from other available nuclear data.

Wapstra and this work. No attempt was made to explain the differences between the direct and Wapstra values other than to note that the direct mass measurement value also indicated an anomaly at ^{120}Cs . The results from both comparisons showed ^{120}Cs to be better bound than the direct mass measurement and Wapstra cesium mass excess values.

A comparison of our experimental and the literature (Wapstra) mass excesses of the cesium isotopes with the aforementioned mass predictions is shown in figure 33. The semi-empirical shell model calculations of Liran and Zeldes seemed to best fit the mass surface using both experimental (with the exception of ^{120}Cs) and Wapstra mass excesses. The independent-particle relations of Garvey and Kelson did well in the middle of the mass surface but showed increasing deviation as one approached both neutron deficient and neutron excess isotopes. The modified liquid drop calculations of Seeger and Howard were found to poorly fit the cesium surface. Taken together, the mass predictions highlighted well the discontinuity of the experimental ^{120}Cs data.

A plot of single neutron separation energies, S_n , versus neutron number for the cesium isotopes (shown in figure 34) provided yet another model-independent comparison of our experimental mass excesses. A deviation at ^{120}Cs was clearly evident and indicated an increased binding energy in cesium of approximately 750 keV.



XBL 831-7931

Figure 33. Comparison of experimental and literature cesium mass excesses to theory.

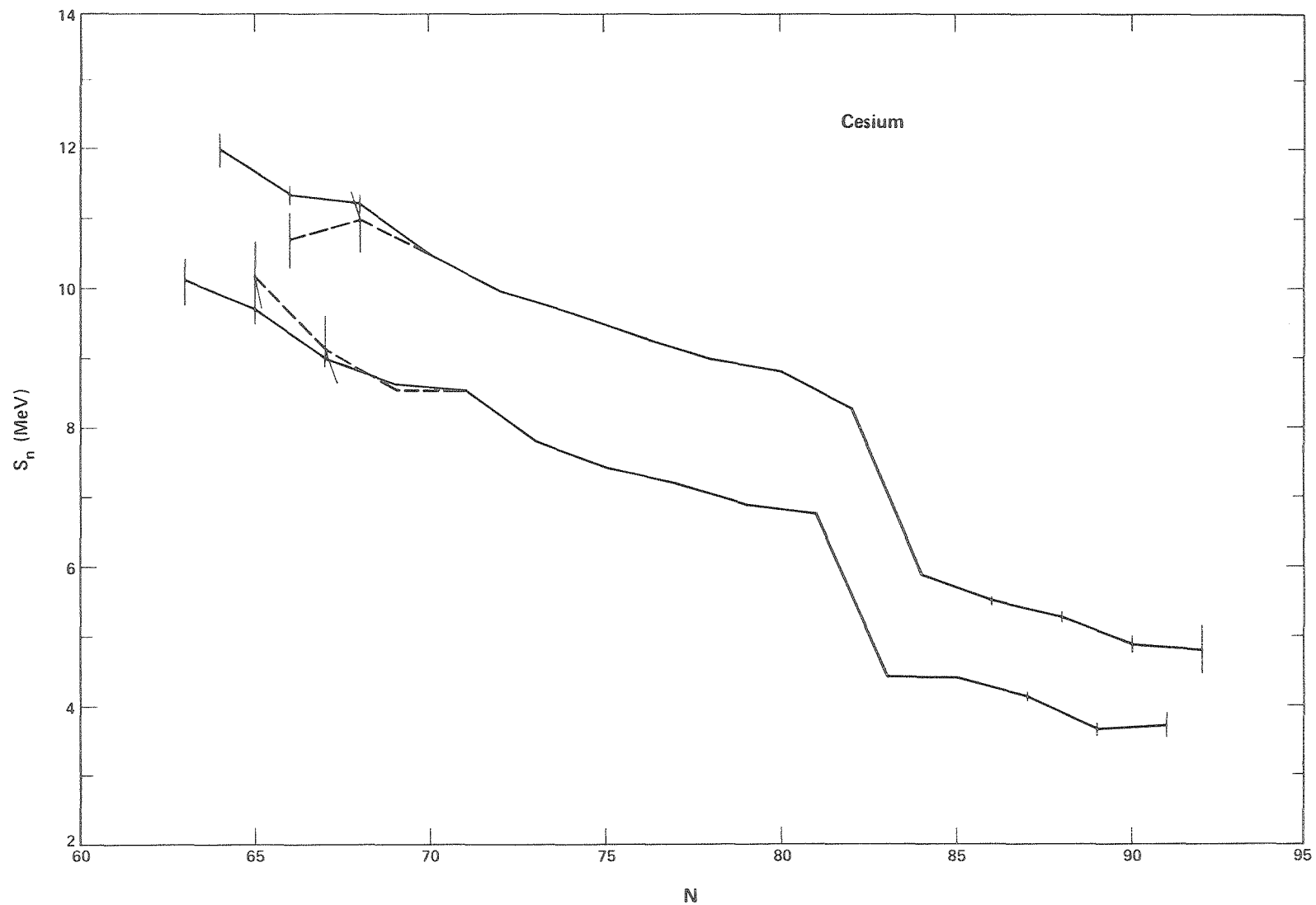


Figure 34.. Single neutron separation energies for cesium. Solid lines represent S_n taken from literature (Wapstra) mass excess values; the dashed lines, from our experimental values.

Comparisons of Q_{EC} -deduced mass excesses and neutron separation energies to the literature all highlight an irregularity for ^{120}Cs while providing systematic and experimental support for the ^{119}Cs and $^{121-123}\text{Cs}$ results.

An obvious explanation for the deviation in ^{120}Cs would seem to lie in an incorrect assignment of the level in ^{120}Xe that was being fed by beta decay. All the previous comparisons suggest that a level 400 to 800 keV higher than the 322.4 keV 2^+ state used for beta-coincidence gating in ^{120}Xe was being fed by the 2^+ ground state ^{120}Cs decay. Our experimental evidence, however, did not support this conclusion. A beta endpoint energy measurement of the decay to the 2^+ level at 875.8 keV in ^{120}Xe (refer to figure 28) was found to be approximately 400 keV less in energy. The experimental beta statistics for allowed decays to the remaining 3^+ , 2^+ , and 1^+ levels in ^{120}Xe were insufficient to determine endpoint values.

An alternative explanation for the mass excess deviation could be that the mass excess value of ^{120}Cs expressed by Wapstra (and also by Audi) was incorrect or had a much larger than reported uncertainty associated with it. The differences observed in the two tabulations were significant enough to cast suspicion on either set of values. Such an explanation, however, does not account for the systematic inconsistency of the ^{120}Cs Q_{EC} value nor for the observed deviation for ^{120}Cs data in the single neutron separation energy.

A more plausible explanation arises from a closer examination of the collective features observed in the cesium isotopes. The deformed single-particle levels illustrated earlier in figure 1 showed the crossing of the $9/2(404)$, $1/2(420)$, and $3/2(422)$ proton orbitals at the deformation value $\epsilon \approx 0.27$. It was also observed that the deformation in the cesium isotopes increased as A decreased (EKS78). A deformed single-particle configuration which would account for the added stability would be the coupling of the $9/2(404)$ proton orbital to the $5/2(413)$ neutron orbital. Another possible configuration could be an admixture of the three proton orbitals mentioned above coupled again to the $5/2(413)$ neutron orbital, resulting in a spin and parity of 2^+ . In either case, the inclusion of the $9/2(404)$ proton orbital was clearly supported by the ^{120}Cs magnetic moment measurement of Ekström et al. (EKS78). The net effect of using the $9/2(404)$ proton orbital would be a substantial increase in deformation and a resultant increase in binding energy (GAR78, CHO78, CUN82). This sudden increase in deformation was observed in the hyperfine structure and isotope shift studies of Thibault et al. (THI81). Figure 35 illustrates this point explicitly. A large increase in deformation was observed ($\epsilon=0.27$ to 0.32) going from ^{121}Cs to ^{120}Cs . This effect could clearly add to an explanation of the increased binding energy found in ^{120}Cs .

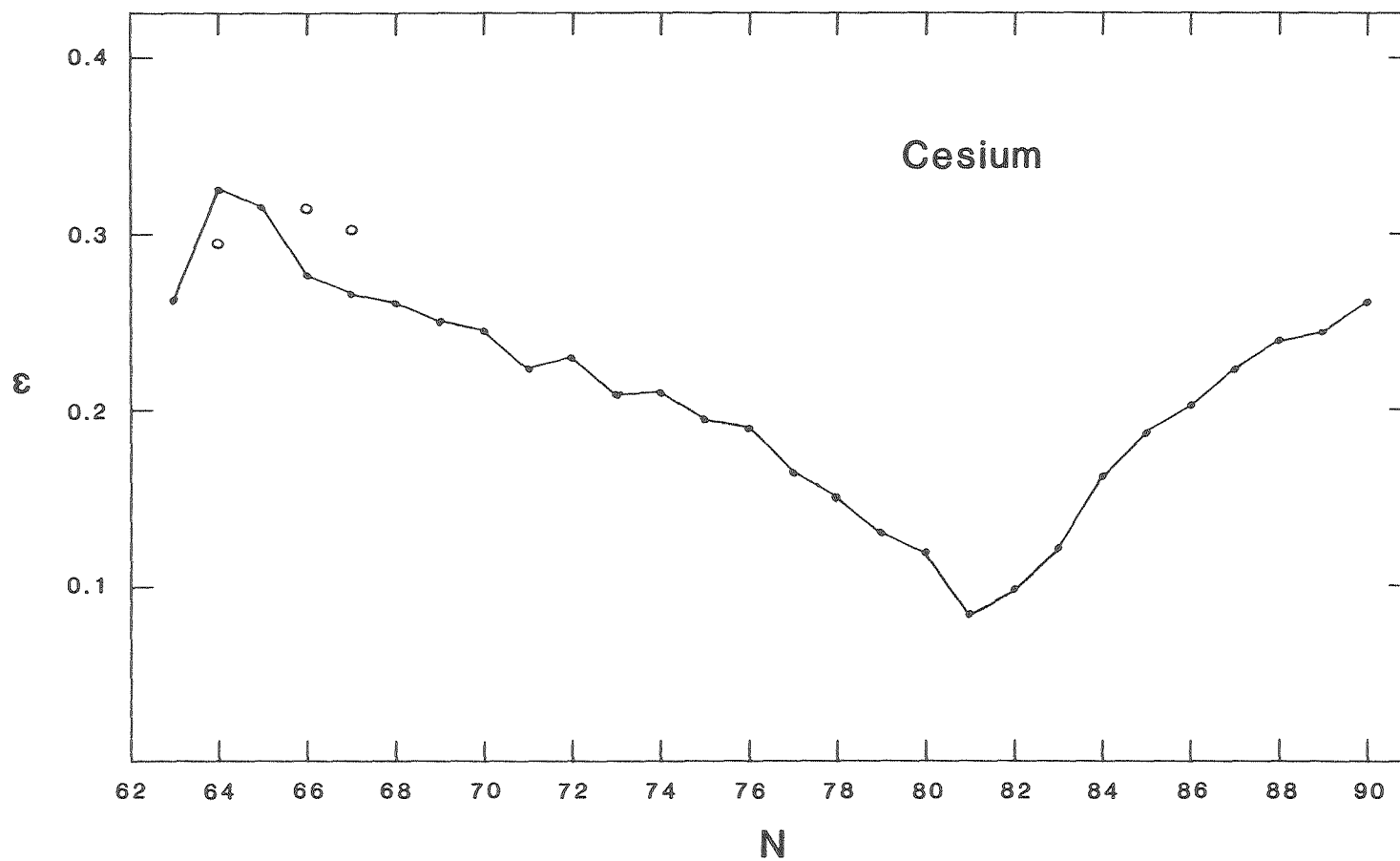


Figure 35. Quadrupole deformation values of the cesium isotopes [from Thibault et al. (THI81)]. Open circles represent isomeric states.

XBL 831-7905

Attributing the increased binding energy solely to the increase in deformation would be premature. Until the absolute beta decay branch intensities for the decay of ^{120}Cs into levels in ^{120}Xe are known and the larger than expected deviations between the direct mass excess measurements of Audi and those tabulated by Wapstra are resolved, an accurate understanding of the deviation in the experimental mass excess for ^{120}Cs will not be available.

VII. Summary and conclusions

The incorporation of a differentially pumped tape transport system, a large volume plastic scintillator beta telescope, and an intrinsic Ge gamma detector into RAMA provided a method to determine positron endpoint energies for several neutron deficient cesium nuclides. Additionally, the utilization of a process control computer provided a completely centralized experimental apparatus for the experimenter, resulting in a reliable and effective instrument for studying exotic nuclei.

A stretch fitting method was used to analyze the experimental beta energy spectra of these cesium isotopes. This technique provided an unique way to avoid functionally removing the distortion effects in the plastic scintillator through a complicated process of iteration and unfolding. The stretch fitting procedure basically provides a direct fit to the data, eliminating the need for smoothing and therefore minimizing the effect of statistical fluctuations in the data which typically hinder the Fermi-Kurie analysis process.

These measurements have led to beta endpoint energy determinations of the neutron deficient $^{119-123}\text{Cs}$ isotopes. The total decay energies of $^{122\text{m}}\text{Cs}$ ($Q_{\text{EC}} = 6.95 \pm 0.25 \text{ MeV}$) and ^{119}Cs ($Q_{\text{EC}} = 6.26 \pm 0.29 \text{ MeV}$) were new measurements. The total decay energies of ^{123}Cs ($Q_{\text{EC}} =$

$4.05 \pm 0.18 \text{ MeV}$), ^{122}gCs ($Q_{\text{EC}} = 7.05 \pm 0.18 \text{ MeV}$), ^{121}Cs
 ($Q_{\text{EC}} = 5.21 \pm 0.22 \text{ MeV}$), and ^{120}Cs ($Q_{\text{EC}} = 7.38 \pm 0.23$
 MeV) were measurements with significantly improved
 uncertainties as compared to the literature. Furthermore,
 an analysis combining the energy levels derived from
 literature gamma-gamma coincident measurements and our
 experimental beta-coincident gamma ray decay energies has
 provided an improved level scheme for ^{121}Xe and three
 proposed new energy levels in ^{119}Xe .

Comparison of the deduced cesium mass excesses
 (determined with our experimental Q_{EC} values and known
 xenon mass excesses) with both literature (Wapstra
 tabulated) and theoretical cesium mass excess values were
 generally in agreement; however, a marked deviation was
 observed in all cases for ^{120}Cs of $\sim 800 \text{ keV}$. Comparison
 of the ^{120}Cs experimental mass excess with the direct mass
 measurement of Audi et al. (AUD82) resulted in an even
 greater deviation of $\sim 1300 \text{ keV}$. It was additionally
 observed that all the direct mass measurement values
 (except those corrected with other available nuclear data)
 deviated to some degree from both the experimentally-
 determined and Wapstra-tabulated cesium mass excesses.

Model-independent analysis based on the systematic
 behavior of the Q_{EC} values and single neutron separation
 energies further revealed that the mass of ^{120}Cs was ~ 650
 keV lower than would have been expected from the
 systematics in this mass region. Attributing this

observed discrepancy to a possible sudden increase in deformation will require further investigations into the beta decay branch intensities of ^{120}Cs and a resolution of the deviations between the direct mass measured excess values and data available in the literature from other sources.

The logical extension of this work would be to continue beta endpoint measurements into the even more neutron deficient isotopes, $^{116-118}\text{Cs}$. This would complement the beta-delayed alpha and proton measurements of Hornshøj et al. (HOR75) and Płochocki et al. (PLO81) in this region. However, the level schemes of the corresponding xenon nuclei are not yet known. Therefore, endpoint measurements would need to be preceded by gamma-gamma coincident measurements to deduce levels, spins, and parities. Experimental determination of the mass excesses of these light cesium isotopes would also require an investigation into previously unknown xenon mass excess values by either direct mass measurement or decay Q-value studies of the neutron deficient xenon isotopes, $^{116-118}\text{Xe}$.

Experimentally, extension of these studies to lighter cesium isotopes would require separated ^{106}Cd targets for increased production cross sections and improvements to the ion source to increase the overall RAMA efficiency.

Acknowledgements

In the course of my graduate career, many people contributed to the experimental effort who deserve recognition and my sincere appreciation.

To Professor Joseph Cerny, my research director, for his unending support and inspiration in spite of my inexperience and diverse projects.

To all the postdoctoral fellows and visiting professors who assisted in my endeavors and furthered my nuclear physics knowledge, Dr. Juha Äystö, Dr. Ralph von Dincklage, Dr. Hugh Evans, Dr. Jorma Honkanen, Dr. Peter Haustein, and Dr. Hubert Thierens.

To my fellow graduate students, both present and past, for their experimental assistance and with whom to share the blame, Alden Bice, Mike Cable, Dennis Moltz, David Vieira, and Jan Wouters.

To all the 88" cyclotron crew for the dogged pursuit of high quality beams and their persistence and ability to face the utmost challenge in cyclotron operation, dealing with the experimenters. I wish to also thank Roy Burton, Ron Burger, Matt Renkas, Don Lundgren, Larry Brusse, and all the shop personnel for their assistance and guidance in all my construction pursuits, be it electrical or mechanical, and Carol Adams for her constant moral

support.

To Dr. Creve Maples and Dan Weaver for their invaluable advice and assistance in the development of software and hardware for the RAMA computer project from which I learned a great deal.

And finally, to my wife Pam who supported me through it all enduring my odd hours, the numerous electronic projects, and my rather expensive hobbies.

This work was supported by the Director, U.S. Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics, and by Nuclear Sciences of the Basic Energy Sciences Program of the U.S. Dept. of Energy under contract number DE-ACO3-76SF00098.

Appendix A - Wapstra xenon and cesium mass excess values¹

A	Xenon mass excess (MeV)	Cesium mass excess (MeV)
117		-66.235 ± 0.265
118		-68.268 ± 0.198
119	-78.818 ± 0.156	-72.187 ± 0.143
120	-82.028 ± 0.284	-73.806 ± 0.115
121	-82.459 ± 0.076	-77.058 ± 0.076
122	-85.344 ± 0.414	-77.963 ± 0.081
123	-85.257 ± 0.016	-81.137 ± 0.060
124	-87.463 ± 0.134	-81.689 ± 0.047
125	-87.150 ± 0.032	-84.103 ± 0.034
126	-89.158 ± 0.008	-84.328 ± 0.028
127	-88.315 ± 0.006	-86.210 ± 0.010
128	-89.861 ± 0.002	-85.934 ± 0.006
129	-88.697 ± 0.002	-87.525 ± 0.014
130	-89.881 ± 0.002	-86.863 ± 0.009
131	-88.423 ± 0.004	-88.070 ± 0.007
132	-89.288 ± 0.004	-87.187 ± 0.021
133	-87.667 ± 0.007	-88.094 ± 0.006
134	-88.125 ± 0.007	-86.914 ± 0.006
135	-86.511 ± 0.011	-87.670 ± 0.008
136	-86.431 ± 0.007	-86.362 ± 0.006
137	-82.385 ± 0.007	-86.564 ± 0.006
138	-80.162 ± 0.055	-82.902 ± 0.022

139	-75.696 ± 0.060	-80.716 ± 0.007
140	-73.017 ± 0.062	-77.077 ± 0.016
141	-68.363 ± 0.093	-74.513 ± 0.025
142	-65.533 ± 0.105	-70.573 ± 0.033
143		-67.790 ± 0.050
144		-63.416 ± 0.066
145		-60.231 ± 0.086
146		-55.892 ± 0.130
147		-52.631 ± 0.336

¹Ref. (WAP81)

Footnotes

1. Havar is the trade name for a metal alloy consisting of Co(42.5%), Ni(13.0%), Cr(20.0%), and Fe(17.9%) with a density of 8.3gm/cm^3 and manufactured by: Metals division, Hamilton Watch Co., P.O. Box 1609, Columbia Ave., Lancaster, Pa. 17604
2. Datamec drive manufactured by DATAMEC, 345 Middlefield Rd., Mountain View, Ca.
3. Ortec Inc., 100 Midland Rd., Oak Ridge, TN 37830
4. ModComp computers manufactured by Modular Computer Corporation, 1650 West McNab, Ft. Lauderdale, Fl.
33310

References

- ARS69 D.A. Arseniev, A. Sobiczewski, and V.G. Soloviev,
Nucl. Phys. A139, (1969) 269
- AUD82 G. Audi, M. Ephreffe, C. Thibault, A.H. Wapstra,
and K. Bos, Nucl. Phys. A378, (1982) 443
- AYS79 J. Äystö, D.M. Moltz, M.D. Cable, R.D. von
Dincklage, R.F. Parry, J.M. Wouters, and J. Cerny,
Phys. Lett. 82B, (1979) 43
- AYS81 J. Äystö, M.D. Cable, R.F. Parry, J.M. Wouters,
D.M. Moltz, and J. Cerny, Phys. Rev. C23, (1981)
879
- BAD67 G.D. Badhwar, C.L. Deney, B.R. Dennis, and M.F.
Kaplon, Nucl. Inst. Meth. 57, (1967) 116
- BAR82 V. Barci, J. Gizon, A. Gizon, J. Crawford, J.
Genevey, A. Plochocki, and M.A. Cunningham, Nucl.
Phys. A383, (1982) 309
- BAT76 T. Batsch, M. Nowicki, J. Zylicz, D.D. Bogdanov,
V.A. Karnaukhov, L.A. Pietrov, and A. Plochocki,
Proc. 3rd Int. Conf. Nucl. Far Stab., CERN 76-13,
(1976) 106
- BAY77 G. Baym, Lectures on Quantum Mechanics, (W.A.
Benjamin Inc., Reading Mass., 1977)
- BEC69 E. Beck, Nucl. Inst. Meth. 76, (1969) 77
- BER69 M.J. Berger, S.M. Seltzer, S.E. Chappell, J.C.
Humphreys, and J.W. Motz, Nucl. Inst. Meth. 69,
(1969) 181

- CHO81 P. Chowdhury, U. Garg, T.P. Sjoreen, and D.B. Fossan, Phys. Rev. C23, (1981) 733
- CHO82 P. Chowdhury, W.F. Piel, Jr., and D.B. Fossan, Phys. Rev. C25, (1982) 813
- CUN82 M.A. Cunningham, Nucl. Phys. A385, (1982) 221
- DAU66 J.M. D'Auria, and I.L. Preiss, Nucl. Phys. 84, (1966) 37
- DAU76 J.M. D'Auria, J.W. Gräter, L. Westgaard, G. Nyman, P. Peuser, E. Roeckl, and H. Otto, Proc. 3rd Int. Conf. Nucl. Far Stab., CERN 76-13, (1976) 100
- DAV68 J.P. Davidson, Collective Models of the Nucleus, (Academic Press, New York, 1968)
- DAV79 C.N. Davids, C.A. Gagliardi, M.J. Murphy, and E.B. Norman, Phys. Rev. C19, (1979) 1463
- DES74 A. deShalit and H. Feshbach, Theoretical Nuclear Physics, Volume I: Nuclear Structure, (John Wiley and Sons, Inc., 1974)
- EKS77 C. Ekström, S. Ingelman, G. Wannberg, and M. Skarestad, Nucl. Phys. A292, (1977) 144
- EKS78 C. Ekström, G. Wannberg, and J. Heinemeier, Phys. Lett. 76B, (1978) 565
- EPH79 M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, F. Touchard, and H. Wollnik, Phys. Rev. C19, (1979) 1504
- GAR78 U. Garg, T.P. Sjoreen, and D.B. Fossan, Phys. Rev. Lett. 40, (1978) 831
- GAR79 U. Garg, T.P. Sjoreen, and D.B. Fossan, Phys. Rev.

- C19, (1979) 217
- GEN77 J. Genevey-Rivier, A. Charvet, G. Marguier, C. Richard-Serre, J. D'Auria, A. Huck, G. Klotz, A. Knipper, and G. Walter, Nucl. Phys. A283, (1977) 45
- GOO73 D.R. Goosman and D.E. Alburger, Phys. Rev. C7, (1973) 2409
- HAM81 J.M. Hamilton, Heavy Ion Collisions, (editor, R. Bock, North-Holland Pub. Co., Amsterdam, 1981)
- HAN79 P.G. Hansen, Ann. Rev. Nucl. Part. Sci. 29, (1979) 69
- HOR75 P. Hornshøj, P. Tidemand-Petersson, R. Bethoux, A.A. Caretto, J.W. Grüter, P.G. Hansen, B. Jonson, E. Hagberg, and S. Mattsson, Phys. Lett. 57B, (1975) 147
- JAN76 J. Jänecke, Atomic Data and Nuclear Data Tables 17, (1976) 455
- KEL62 E.L. Kelly, Nucl. Inst. Meth. 18&19, (1962) 33
- KJE70 A. Kjelberg and G. Rudstam (eds): The ISOLIDE Isotope Separator Facility at CERN, CERN 70-3, (1970)
- KON65 E.J. Konopinski and M.E. Rose, (editor, K. Siegbahn, Alpha-, Beta-, and Gamma-Ray Spectroscopy, 1965) Vol. 2, 1327
- KON66 E.J. Konopinski, The Theory of Beta Radioactivity, (Clarendon Press, Oxford, 1966)
- LIR76 S. Liran and N. Zeldes, Atomic Data and Nuclear

Data Tables 17, (1976) 431

- MAP79 C.C. Maples, Jr. and J. Sivak, IEEE Transactions in Nuclear Science NS-26, (1979) 4409
- MOL79a D.M. Moltz, J. Äystö, M.D. Cable, R.D. von Dincklage, R.F. Parry, J.M. Wouters, and J. Cerny, Phys. Rev. Lett. 42, (1979) 43
- MOL80a D.M. Moltz, R.A. Gough, M.S. Zisman, D.J. Vieira, H.C. Evans, and J. Cerny, Nucl. Inst. Meth. 172, (1980) 507
- MOL80b D.M. Moltz, J.M. Wouters, J. Äystö, M.D. Cable, R.F. Parry, R.D. von Dincklage, and J. Cerny, Nucl. Inst. Meth. 172, (1980) 519
- MOL81 D.M. Moltz, J. Äystö, M.D. Cable, R.F. Parry, P.E. Haustein, J.M. Wouters, and J. Cerny, Nucl. Inst. Meth. 186, (1981) 141
- NIL55 S.G. Nilsson, Dan. Mat. Fys. Medd. 29, (1955) No. 16
- OTT79 H. Otto, P. Peuser, G. Nyman, and E. Roeckl, Nucl. Inst. Meth. 166, (1979) 507
- PAU71 J.M. Paul, Nucl. Inst. Meth. 96, (1971) 51
- PLO81 A. Płochocki, J. Zylicz, R. Kirchner, O. Klepper, E. Roeckl, P. Tidemand-Petersson, I.S. Grant, P.M. Saelides, and W.D. Schmidt-Ott, Phys. Lett. 106B, (1981) 285
- PRE62 M.A. Preston, Physics of the Nucleus, (Addison-Wesley Pub. Co., Mass., 1962)
- RAV79 H.L. Ravn, Phys. Rep. 54, (1979) 201

- REH78 D.M. Rehfield, Nucl. Inst. Meth. 157, (1978) 351
- ROB77 R.G.H. Robertson, T.J. Bowles, and S.J. Freedman,
Nucl. Inst. Meth. 147, (1977) 361
- ROG65 P.C. Rogers and G.E. Gordon, Nucl. Inst. Meth. 37,
(1965) 259
- ROS55 M.E. Rose, Beta- and Gamma-Ray Spectroscopy
(editor, K. Siegbahn, North-Holland, Amsterdam,
1955) 273
- SAN76 I.H. Sanders and A.H. Wapstra (eds): Atomic Masses
and Fundamental Constants 5, (Plenum Press, 1976)
- SCH66 H.F. Schopper, Weak Interactions and Nuclear Beta
Decay, (North-Holland Publ. Co., Amsterdam, 1966)
- SCH75 H.M. Schüpferling, Nucl. Inst. Meth. 123, (1975)
67
- SEE76 P.A. Seeger and W.M. Howard, Atomic Data and
Nuclear Data Tables 17, (1976) 428
- SID69 G. Sidenius, in Proceedings of the First
International Conference on Ion Sources, Saclay,
France, (1969) 401
- SMI51 A. Smith, Phys. Rev. 82, (1951) 955
- SOF81 K. Sofia, B.N. Subba Rao, and J.E. Crawford, Phys.
Rev. C24, (1981) 1615
- THI81 C. Thibault, F. Touchard, S. Büttgenbach, R.
Klapisch, M. De Saint Simion, H.T. Duong, P.
Jacquinot, P. Juncar, S. Liberman, P. Pillet, J.
Pinard, J.L. Vialle, A. Pesnelle, and G. Huber,
Nucl. Phys. A367, (1981) 1

- UHL41 G.E. Uhlenbeck and E.J. Konopinski, Phys. Rev. 60,
(1941) 308
- WAP81 A.H. Wapstra and K. Bos, to be published 1983
- WAY54 K. Way and M. Wood, Phys. Rev. 94, (1954) 119
- WES75 L. Westgaard, K. Aleklett, G. Nyman, and E.
Roeckl, Z. Phys. A275, (1975) 127
- WOH72 F.K. Wohn, J.R. Clifford, G.H. Carlson, and W.L.
Talbert, Jr. Nucl. Inst. Meth. 101, (1972) 343
- WOU83 J.M. Wouters, H.M. Thierens, J. Aystö, M.D. Cable,
P.E. Haustein, R.F. Parry, and J. Cerny, to be
published in Phys. Rev. C, (1983)
- WU65 C.S. Wu, O. Kofoed-Hansen, M. Goldhaber, L.
Grodzins, A.W. Sunyar, H. Frauenfelder, R.M.
Steffen, F. Reines, S.P. Rosen, and H. Primakoff,
(editor, K. Siebgahn, Alpha-, Beta-, and Gamma-ray
Spectroscopy, 1965) Vol. 2, 1365

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.