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FAST-NEUTRON TOTAL AND SCATTERING CROSS SECTIONS OF BISMUTH

by

A. B. Smith, J. F. Whalen,
E. Barnard, J. A. M. de Villiers,
and D. Reitmann

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Physics

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ABSTRACT

Total neutron cross sections of bismuth were measured with resolutions of $\gtrsim 1$ keV over the energy range 0.2 to 1.4 MeV. Differential elastic scattering cross sections were determined at intervals $\lesssim 50$ keV from 0.3 to 1.5 MeV with resolutions of ~20 keV. The inelastic neutron excitation of a state at 896 ± 1 keV was observed, and the respective differential excitation cross sections determined with incident resolutions of $\gtrsim 10$ keV. Partially resolved resonance structure was evident in all the measured values. The experimental results were assayed for possible intermediate structure and were compared with the results of optical-model and statistical calculations. The model calculations were cognizant of the fluctuation and correlation of compound-nucleus resonance widths and of the shell closure at N = 126.

I. INTRODUCTION

The heavy and readily available element bismuth is used in reactor systems as a shielding material. This element has been proposed as a primary target material for the production of intense neutron sources using medium-energy positive-ion accelerators. The fast-neutron properties of bismuth are important in these applications. Despite this fact, the reported fast-neutron total cross sections of bismuth are not always consistent in either structure or magnitude. The differential elastic scattering cross sections of bismuth are not well defined, and relatively little is known of the inelastic neutron scattering. Fast-neutron interactions with bismuth are of basic physical interest in the context of intermediate resonance structure and of the optical potential in the region of a neutron shell closure.

The present work was undertaken primarily to provide reliable and internally consistent data to meet the applied need. Further, physical

*The numerical data resulting from this work have been transmitted to the National Neutron Cross Section Center, Brookhaven National Laboratory.

understanding was an objective, particularly where it leads to the reliable calculation of fast-neutron cross sections and the quantitative extrapolation of experimental results.

II. EXPERIMENTAL METHODS

Total neutron cross sections and differential elastic and broad-resolution inelastic scattering cross sections were measured at the Argonne National Laboratory. Detailed fine-resolution inelastic scattering measurements were performed at the Pelindaba Laboratory.

Total neutron cross sections and associated statistical uncertainties were determined from the measured transmissions. Below an incident neutron energy of 475 keV and above 1200 keV, transmission measurements were made using the monoenergetic source method and the source reaction $^7Li(p,n)^7Be$.[1,2] Incident neutron resolutions were 1.5-2.5 keV. The absolute energy scale was determined to within ±5 keV, relative to the known source-reaction threshold. Between incident neutron energies of 475 and 1200 keV, a pseudo-white-source time-of-flight method was used to determine sample transmissions.[3] The time-of-flight resolution was 0.1-0.15 nsec/m. The time-of-flight energy scale was determined relative to the velocity of light and believed known to ±10 keV. For both methods, "in-scattering" corrections were small and sample transmissions were >50%. The monoenergetic and time-of-flight results are in good agreement in a region of overlap from 450 to 500 keV and at selected check points at higher energies.

Broad-resolution (~20 keV) differential elastic and inelastic scattering cross sections were determined using a multiangle time-of-flight system.[4] Measurements were made at eight laboratory scattering angles, typically 28, 38, 53, 69, 85, 115, 129, and 155°. Scattered neutron resolutions were ~1.5 nsec/m, sufficient to resolve elastic neutron groups and inelastic neutron groups resulting from the excitation of known level structure in bismuth.[5] All broad-resolution scattering measurements were made relative to the known differential elastic scattering cross sections of carbon[6] and were corrected for sample attenuation, angular resolution, and multiple scattering effects.[7] The measured differential elastic scattering values were fitted by the method of least squares with the expression

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}\left[1 + \sum_{i=1}^{n} \omega_i P_i(\theta)\right], \qquad (1)$$

where $P_i(\theta)$ are Legendre polynomials expressed in the laboratory coordinate system, and σ and ω_i are derived from the fitting procedure. At lower energies, uncertainties in i = 5 and higher coefficients generally exceeded

their magnitudes, and the series was terminated at n = 4. Above incident energies of approximately 1.0 MeV, n was increased to 5. With these choices of n and with the derived parameters σ and ω_i, Eq. 1 was descriptive of the measured values over the observed angular interval (as shown in Fig. 2 later). The elastic scattering cross sections, σ_{el}, were judged known to ±8%, inclusive of uncertainties in the carbon standard. The standard deviations of the ω_i values were obtained from the fitting procedure. Broad-resolution inelastic-excitation cross sections were determined concurrently with the elastic neutron scattering cross sections. Generally, the observed inelastic scattering angular distributions were symmetric about 90° and nearly isotropic. Inelastic-excitation cross sections were obtained by averaging the observed differential values weighted inversely with the respective fractional solid angles. All the inelastic scattering results were corrected in the same manner as the elastic scattering measurements. Broad-resolution inelastic cross-section uncertainties were determined from counting statistics and estimated systematic uncertainties, including an estimated ~5% uncertainty in the carbon reference cross sections.

Fine-resolution inelastic scattering results were obtained at the Pelindaba Laboratory using a 3.0-MV pulsed Van de Graaff and time-of-flight techniques. Incident neutron resolutions of 10-12 keV were obtained using metallic lithium targets and the source reaction $^7Li(p,n)^7Be$. Scattered neutrons resulting from the inelastic excitation of a state at ~896 keV were observed by means of a well-shielded, 10-cm-diam, conventional proton-recoil scintillator placed between 1.0 and 1.2 m from the sample. The experimental apparatus is described elsewhere.[3]

The fine-resolution measurements were also made relative to the elastic scattering cross section of carbon.[6] Scattering samples of bismuth and carbon were chosen small enough so that the flux-attenuation corrections were <20% at all energies. The results were corrected for flux attenuation in bismuth and carbon and for multiple scattering in bismuth by means of an expression derived from semianalytic considerations and Monte Carlo calculations.[8]

During a given series of fine-resolution measurements, care was taken to avoid shifts in the neutron-energy scale. In particular, accelerator parameters, other than energy, were held constant. To minimize the relative energy shifts between successive series of runs, a region of overlap inclusive of a well-defined reference peak was always ensured.

Angular distributions of inelastically scattered neutrons were measured with fine resolution at selected incident neutron energies and at typical laboratory scattering angular increments of 15° between 30 and 150°. The experimental points were least-squares fitted with an expression of the form of Eq. 1, where $d\sigma/d\omega$ and σ refer to differential and total inelastic scattering cross sections, respectively, and n = 2. The parameters σ, ω_1, and ω_2 were derived from the fitting procedure, with the Legendre polynomials expressed in the laboratory coordinate system.

The errors in the individual fine-resolution data points were inclusive of statistical uncertainties from the integration of bismuth and carbon experimental peaks and a 5% uncertainty in the relative detector sensitivity, but not of systematic uncertainties in the carbon reference-standard cross section. Fine-resolution 90° inelastic-excitation functions were determined with a better precision ($\lesssim$10%) than were data points associated with other angles (10-15%).

III. EXPERIMENTAL RESULTS

A. Total Neutron Cross Sections

The total neutron cross sections of bismuth were determined from 0.2 to 1.40 MeV. The results are summarized in Fig. 1 (see the appendix for numerical tabulation of the results). A great deal of partially resolved resonance structure exists superimposed on a general energy-dependent trend. The energy-averaged behavior of the present results is in good agreement with a number of early determinations of the total cross sections of bismuth.[9-11] The present work extrapolates well to lower-energy results,[12] and the present values are in good agreement with the reported total neutron-scattering cross sections.[6] The major features of the structure observed in the present work agree with those of Ref. 13, and the energy-averaged magnitudes of the two results are reasonably similar. The energy-averaged magnitude, structure, and energy scale of the results of Ref. 14 are not in detailed agreement with those of the present work.

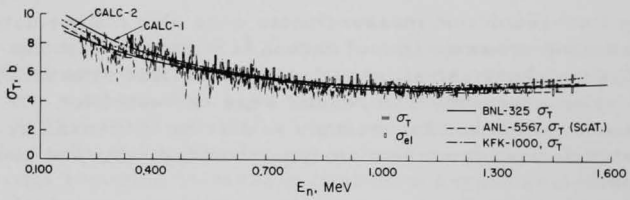

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Fig. 1. Total Neutron Cross Sections of Bismuth. Vertical bars indicate the present results with respective errors. The solid curve is taken from Ref. 10. The dashed curve is the total scattering cross section of Ref. 6. The dotted-dashed curve is the energy average of the total cross sections of Ref. 13. The boxes are elastic scattering results of the present work. The curves noted as CALC-1 and CALC-2 are the result of calculations described in Section IV.

B. Elastic Neutron Scattering

Elastic scattering angular distributions were determined at incident neutron-energy intervals of <50 keV from 0.3 to 1.5 MeV, with resolutions

of ~20 keV. Figure 2 compares a representative measured angular distribution with the fit of Eq. 1 to the experimental results. Figure 3 summarizes the elastic scattering results expressed in the form of Eq. 1. (The corresponding numerical values are given in the appendix.) The present measured elastic scattering and total-cross-section results are reasonably consistent, as illustrated in Fig. 1. The results of the present work are in good agreement with previously reported elastic scattering determinations[15-20] and are consistent with the reported total neutron-scattering angular distributions.[6]

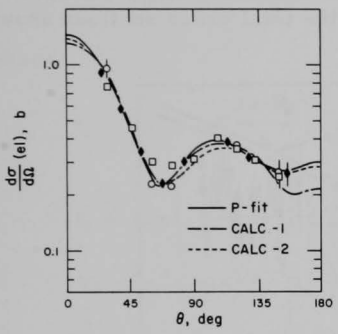

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Fig. 2

Elastic Scattering of 1.0-MeV Neutrons from Bismuth. Solid points are from the present work, open circles from Ref. 16, and open squares from Ref. 17. The solid curve is the result of fitting Eq. 1 to the present results. The dotted and dashed lines are calculated from optical potentials as discussed in Section IV.

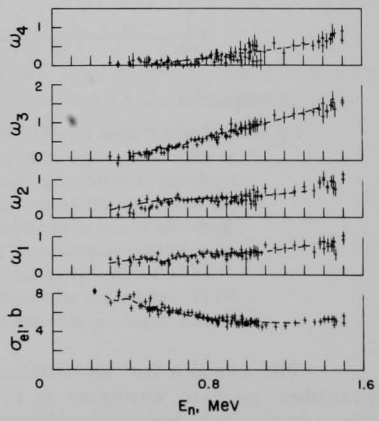

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Fig. 3

Differential Elastic Scattering from Bismuth Expressed in the Format of Eq. 1. Present results are indicated by crosses. ◆ is the value from Ref. 19, ■ from Ref. 17, ● from Ref. 15, and ▼ from Ref. 20. The dashed curve is the total scattering distribution of Ref. 6.

C. Inelastic Neutron Scattering

Neutrons corresponding to the excitation of a single state in bismuth at 896 ± 1 keV were observed. The excitation energy was carefully determined in a supplementary measurement at the Pelindaba Laboratory using a germanium-lithium detector to observe gamma-ray emission following the inelastic neutron process. This observed state

was judged equivalent to the 900-keV, 7/2-level reported in other work.[5] The differential cross sections for the excitation of this state at a laboratory scattering angle of 90° were measured for incident neutron energies between 1020 and 1500 keV at intervals of 5 or 10 keV. Because of the rather low cross section and correspondingly low detector response rates, it was considered too time-consuming to attempt any further improvement in resolution. The experimental results are shown in Fig. 4. These good-resolution results were consistent with the broad-resolution (~20 keV) measured values. (Numerical cross-section values are given in the appendix.) An appreciable amount of structure is present. However, the magnitude of the inelastic cross section is too small to be reflected in the total cross sections shown in Fig. 1.

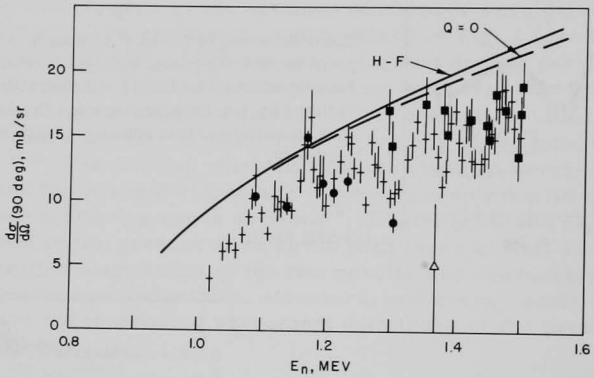

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Fig. 4. Differential Cross Sections for the Excitation of the 896-keV State in Bismuth at a Scattering Angle of 90°. Crosses indicate the results of the present fine-resolution measurements. Solid circles are the result of the angle integral of fine-resolution differential-angular distributions divided by 4π. Solid squares denote the results of broad-resolution measurements. Vertical bars indicate cross-section uncertainties. The triangular datum point indicates the value given in Ref. 22. The solid curve indicates the result of Hauser-Feshbach (H-F) calculations, and the dashed curve, calculated values inclusive of correction factors, as described in Section IV.

The results for inelastic scattering angular distributions measured at incident neutron energies of 1090, 1140, 1170, 1195, 1213, 1233, and 1306 keV are tabulated in the appendix, together with the ω_1 and ω_2 coefficients derived from a fit of Eq. 1 to the measured data. No statistically significant deviation from isotropy could be established.

Previous knowledge of inelastic scattering from bismuth at the energies of the present work is sparse. One reported value[21] at 1.37 MeV is markedly lower than that indicated by the present work, while the results of Beyster et al.[22] are reasonably consistent with the present work near 1.0 MeV.

IV. INTERPRETATION AND DISCUSSION

A. Optical Model and Statistical Calculations

The measured elastic, inelastic, and total cross sections were compared with results of optical model and statistical calculations.[23,24] The point of departure for the calculations was the surface-absorption optical potential of Moldauer,[25]

$$V = V_0 f_1(r) + iW_0 f_2(r) + V_{so}\left(\frac{\hbar}{m_\pi c}\right)^2 \underline{\sigma} \cdot \underline{\ell}\,\frac{1}{r}\frac{df_1}{dr}, \tag{2}$$

where

$$f_1 = \left(1 + \exp\frac{r - R_1}{a_1}\right)^{-1},$$

$$f_2 = \exp\left[-\left(\frac{r - R_2}{a_2}\right)^2\right],$$

$$R_1 = r_1 + r_0 A^{1/3}, \quad R_2 = R_1 + r_2$$

$$r_0 = 1.16\text{F}, \quad r_1 = 0.6\text{F}, \quad r_2 = 0.5\text{F},$$

$$a_1 = 0.62\text{F}, \text{ and } a_2 = 0.5\text{F}.$$

This potential has been shown to be descriptive of neutron interactions with spherical nuclei.[25] In the present application, the real and imaginary strengths (V_0 and W_0) were varied to minimize χ^2, where

$$\left.\begin{aligned} &\chi^2 = \sum_i wt_i\left(B_i^{calc} - B_i^{exp}\right)^2 \\ &\text{and} \\ &B_0 = \frac{\sigma_{el}}{4\pi}, \quad B_i = B_0 \cdot \omega_i \text{ of Eq. 1} \end{aligned}\right\} \tag{3}$$

Thus the potential was adjusted to best describe the observed elastic scattering in the form of Eq. 1. The weighting factor, wt_i, was set to unity or inversely proportional to the estimated uncertainty in B_i with little effect on the choice of optimum V_0 and W_0. Calculations were carried out at each measured elastic scattering energy and included compound elastic and inelastic processes, as determined using the Hauser-Feshbach formalism.[26] The optimum values were V_0 = 45.5 MeV and W_0 = 6.2 MeV and were essentially constant over the measured energy range 0.3-1.5 MeV. The

elastic scattering and total cross sections calculated using these optimum parameters were in good agreement with the present measurements as indicated in Figs. 1, 2, and 5 by curves noted as CALC-1. This potential yields s-wave strength functions of 1.12×10^{-4}, consistent with values reported from resonance measurements.[27] The potential differs appreciably from the general form of Moldauer only in a reduction in the surface absorption by approximately a factor of two. Vonach et al., pointed out that such reduced absorption is characteristic of the region of the double closed shell at A = 208, and the values for the absorption obtained above are similar to those proposed by Vonach et al.[28]

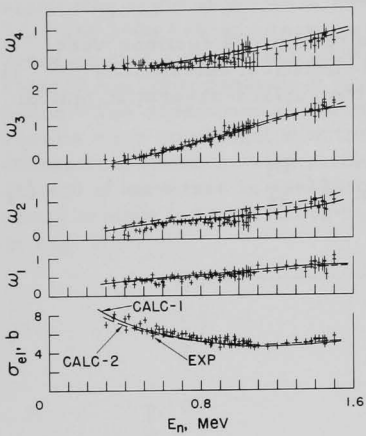

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Fig. 5. Comparison of Measured (crosses) and Calculated (curves) Differential Elastic Scattering Cross Sections of Bismuth. The format is that of Eq. 1. The interpretation of the calculated results is discussed in Section IV.

The above potential differs from some others used in the interpretation of neutron interactions with bismuth at similar energies.[29-31] For example, Cox has achieved good quantitative agreement between calculated and measured differential elastic scattering angular distributions and polarizations near incident energies of 1.0 MeV.[29] His calculated results are indicated by the CALC-2 curve of Fig. 2. Figures 1 and 5 compare results calculated using the Cox potential (CALC-2) and the form derived above (CALC-1) with measured values over a wider energy range. The two potentials give similar agreement with experiment, that derived from the present work being slightly more descriptive of total and scattering cross sections but less appropriate to polarization.

It is of interest to compare results of calculations using the above potentials with reported experiments over a wide energy range. The forces are nonlocal, and the equivalent local parameters will be energy-dependent. Here the energy dependence $V = V_0 - 0.25E$, $W = W_0 - 0.2E$, and a volume absorption $U = 0.125E$ is used as proposed by Engelbrecht and Fiedeldey.[32] Figure 6 compares experimental results to 10.0 MeV with the resulting calculated total cross sections based upon the parameters from the above χ^2 fit (CALC-1) and as given by the potential of Cox (CALC-2).[10] Both potentials give a qualitative description of experiment, but both calculated total cross sections tend to be small in the region of the large optical resonance at 4-5 MeV. Both of the above potentials lead to calculated differential elastic scattering cross sections at 6.0 MeV similar to those experimentally reported, the Cox potential being the more suitable.[33]

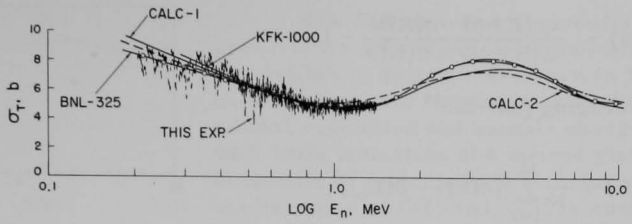

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Fig. 6. Comparison of Calculated and Measured Total Cross Sections of Bismuth over an Extended Energy Range. The present experimental values are indicated by bars. The curve with circular points is from Ref. 10. The curve noted KFK-1000 is from Ref. 13, and the two calculated curves, CALC-1 and CALC-2, are described in Section IV.

The cross sections for the neutron excitation of the single state in bismuth (E_x = 0.896 MeV, 7/2-) energetically attainable in the present experiments were calculated using the above potential determined from the χ^2 fitting procedure and the Hauser-Feshbach formalism. Figure 4 compares the results with the experiment. The qualitative agreement between calculation and experiment is reasonably good, though the calculated values tend to be larger than the experimental quantities. It is known that the statistical result of Hauser-Feshbach is influenced by fluctuations in resonance widths and correlations in resonance spacings. Moldauer[34] discussed these effects extensively and derived a "corrected" transmission coefficient of the form

$$\theta_\alpha = \frac{2}{Q_\alpha}[1 - (1 - Q_\alpha T_\alpha)^{1/2}], \tag{4}$$

where T_α is the statistical transmission coefficient and Q_α is a parameter varying from 0 to 1 (Q_α = 1 for strongly overlapping resonances; Q_α = 0 for isolated resonances). The dashed curves of Fig. 4 indicate the inelastic-excitation cross sections calculated by using the "corrected" transmission and values of Q_α = 0. Values obtained with Q_α = 1 are essentially the same as those resulting from the "uncorrected" calculations. Generally, the "correction" factors tend to lower the calculated inelastic cross sections, particularly for Q_α = 0, and bring them into better agreement with experiment. However, the effect is small in this case, partly due to the relatively large values of the spins involved.

B. Structure and Correlations

The structure evident in the total cross section of bismuth (shown in Fig. 1) has been associated with an "intermediate structure" characterized by widths and spacings much larger than those of the compound nuclei, but small relative to those of the diffraction or single-particle resonance.[14,35] The association is often based on qualitative inspection and can be deceptive.[36,37] A more quantitative assay of the present experimental results has been attempted using the correlation function[37,38]

$$C(\delta) = \frac{\langle\sigma(E+\delta)\cdot\sigma(E)\rangle}{\langle\sigma(E+\delta)\rangle\langle\sigma(E)\rangle} - 1 \tag{5}$$

and the averaging function[39]

$$C(R) = \frac{1}{N}\sum_{i=1}^{N}[\sigma(E_i) - \bar{\sigma}(E_i)]^2, \tag{6}$$

where

$$\bar{\sigma}(E_i) = \frac{1}{R}\int_{E_i-R/2}^{E_i+R/2}\sigma(E)\,dE.$$

Before $C(\delta)$ and $C(R)$ were evaluated from the measured total cross sections, the slow energy dependence of the cross section was removed in one of two ways. In the first method, a cubic energy dependence was least-squares fitted to the measured total cross sections. The resulting cubic expansion of the average energy dependence was subtracted from the measured values and a positive constant added to ensure nonnegative quantities. The results of the cubic fitting procedure were essentially identical to the total cross sections calculated with the optical potential derived in Section A above. The second method employed the "shape" cross section calculated from the optical potential of Eq. 3, using the V_0 and W_0 derived from the fitting procedures. The "shape" cross section was subtracted from the measured total cross section to obtain a remaining "fluctuating" cross section. Both of the above procedures led to very similar $C(\delta)$ and $C(R)$ distributions and resulted in "fluctuating" cross sections retaining intermediate-structure characterized by widths and spacings of $\lesssim$200 keV.

The calculated $C(\delta)$ distributions rapidly decreased with δ in an essentially Lorentzian manner, as shown in Fig. 7. The half-width of the Lorentzian was 2-3 keV, approximately the experimental resolution. For large values of δ, $C(\delta)$ oscillates in a manner and with an rms magnitude characteristic of the finite energy range of the experimental sample.[37] There was little evidence for a second Lorentzian characteristic of an intermediate structure width of 10 to 50 keV. Some tendency for a general slope of the function $C(\delta)$ over an energy interval of >100 keV was probably due to a residual slow energy dependence not fully corrected for in either of the above subtraction procedures.

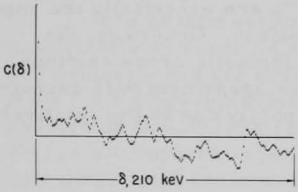

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Fig. 7. $C(\delta)$ of Eq. 5 Evaluated from the Total Cross Section of Bismuth

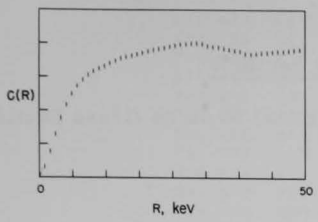

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Fig. 8. C(R) of Eq. 6 Evaluated from the Measured Bismuth Total Neutron Cross Sections

The C(R) function derived from the measured values increases monotonically with R to an oscillatory plateau, as shown in Fig. 8. The behavior is again consistent with the experimental resolution and sample energy range with little indication of a second plateau characteristic of intermediate structure. Generally, the behavior of $C(\delta)$ and $C(R)$ is consistent with known distributions of compound-nucleus resonance widths and spacings, and neither function shows appreciable evidence for an intermediate structure of another nature.[40]

V. SUMMARY REMARKS

The experiments reasonably achieved the objective of providing well-defined total neutron and elastic and inelastic neutron scattering cross sections of bismuth up to incident neutron energies of ~1.5 MeV. The energy-averaged total and elastic scattering cross sections were well described by a surface-absorption optical potential and statistical theory. Best agreement between experiment and calculation was achieved with a surface absorption smaller than found widely applicable in other mass regions. This reduced absorption was believed due to the shell closure at Z = 82 and N = 126 and is consistent with similar effects reported elsewhere. The optical potential and statistical theory led to calculated inelastic scattering cross sections ~20% larger than observed experimentally. Width-fluctuation corrections to the calculated inelastic scattering led to only marginally improved agreement with experiment. The optical potential derived from the present measurements was extended to a wider energy range and found qualitatively descriptive of reported experimental values. However, the potential was not unique. Considerable energy-dependent structure was observed in the measured cross sections. A quantitative assay of the structure observed in the total cross sections led to results consistent with well-known compound-nucleus resonance structure and the available experimental resolution.

APPENDIX

Tabulation of Measured Cross Sections

All data have been transmitted to the National Neutron Cross Section Center, Brookhaven National Laboratory.

```
C
C NATURAL BISMUTH DATA BLOCK
C        FINAL VALUES----8/69
C        TO BE PUBLISHED
C        PELINDABA-REPUBLIC OF SOUTH AFRICA
C                 E. BARNARD-J. DEVILLIERS- D. REITMANN
C        ARGONNE NATIONAL LABORATORY
C                 A. SMITH- J. WHALEN
C
C      ELASTIC SCATTERING CROSS SECTIONS OF BISMUTH
C       FINAL VALUES
C       TIME-OF-FLIGHT METHOD
C          INCIDENT RESOLUTION ABOUT 20 KEV
C          SCATTERED RESOLUTION 1.5 NSEC/M
C       ESTIMATED ERROR IN INTEGRATED X-SEC 8 PERCENT INCLUDING STD.
C       ERROR IN OMEGA COEF. ESTIMATED FROM LEAST SQ. FITTING.
C       FORMAT
C           D X-SEC= (X-SEC/ 4*PI)*(1.+ SUM OMEGA*P)
C                SUM FROM 1-5
C                P=LEGENDRE POLYNOMIAL IN LAB. SYSTEM
C       MEASURED ANGULAR INTERVAL 25-155 DEG. AT EIGHT ANGLES
C       ALL DATA CORRECTED FOR MULTIPLE SCATTERING
C       ALL RESULTS RELATIVE TO DIF. CARBON X-SEC OF ANL-5567(REV)
C       FOLLOWING CARD FORMAT  6X, 2I4, 5(I5,I4) , BCD
C          WHERE RESPECTIVE VALUES ARE,
C                E-N IN KEV
C                X-SEC*100
C                OMEGA-1 *1000
C                D-OMEGA-1*1000
C                ----------
C                OMEGA-5 *1000
C                D-OMEGA-5*1000
C        FOLLOWING THE ABOVE EQUATION
C
      300 699  414  55  318  81  106  66   66  71    0   0
      340 773  415  84   69  81  -72  85   20  85    0   0
      344 813  283  81  267  80   79  88   42  82    0   0
      405 643  322  89  325  86  103  84   30  80    0   0
      400 764  400  88  129  56  211  66   74  91    0   0
      420 787  457  83   98 122  113 146  131 200    0   0
      450 667  309  88  440  60  194  58  173  57    0   0
      460 670  464  58  254  61  144  45  111 .57    0   0
      480 711  448  61  222  75  155  90   79 123    0   0
      490 631  397  78  484 111  190 140   78 152    0   0
      505 748  404  69  254  61  184  68  150  69    0   0
      515 629  424  66  296  64  204  69    0  60    0   0
      540 636  403  66  273  64  262  69   66  60    0   0
      545 581  555  61  489  86  342  41   29 121    0   0
      560 620  332  64  386  66  354  63   -6  69    0   0
      565 684  289  65  365  67  202  66  128  62    0   0
      580 646  303  61  454  61  200  67   33  61    0   0
      600 593  370  68  375  66  262  63  -58  64    0   0
      600 601  389  62  413  64  329  75  123  96    0   0
      600 651  346  69  405  71  275  85   89 117    0   0
      605 600  280  65  358  68  385  64  134  66    0   0
      620 621  494  62  421  67  356  67   45  78    0   0
      640 615  450  68  497  61  360  69   19  68    0   0
      650 599  547  65  589  60  397  64  112  61    0   0
```

660	623	484	62	472	63	418	60	41	64	0	0
680	580	518	68	446	67	353	62	-21	64	0	0
700	596	430	66	461	69	479	66	23	64	0	0
700	598	370	68	438	65	358	62	135	66	0	0
720	601	474	65	470	61	549	61	38	84	0	0
740	571	490	69	466	57	546	69	24	95	0	0
750	556	344	66	412	53	411	67	102	89	0	0
760	578	585	60	513	58	580	69	54	95	0	0
775	551	552	60	409	61	487	67	249	67	0	0
780	549	484	69	476	61	564	68	161	69	0	0
800	546	598	63	525	64	580	67	171	67	0	0
820	521	557	64	440	67	663	68	245	69	0	0
825	511	482	60	507	84	636	107	272	119		0
840	531	461	60	420	59	598	71	65	97	0	0
850	499	609	66	503	60	717	64	165	71	0	0
850	479	535	54	517	80	538	100	292	133	0	0
855	492	498	63	323	64	473	79	319	105	0	0
860	544	507	68	413	56	609	67	158	92	0	0
875	542	595	71	554	101	815	128	130	142	0	0
880	531	553	65	502	67	719	64	291	61	0	0
900	450	403	67	343	62	629	66	207	63	0	0
900	501	469	63	336	63	622	75	60	103	0	0
900	552	409	61	516	66	648	55	51	75	0	0
900	517	520	68	487	56	669	67	227	92	0	0
900	551	388	60	516	60	598	60	61	60	0	0
920	478	494	60	390	60	626	60	204	60	0	0
925	548	585	58	424	85	800	102	341	140	0	0
925	519	674	60	525	160	961	160	217	174	0	0
940	563	564	60	496	60	758	60	138	60	35	60
940	536	575	60	426	60	790	60	233	60	44	67
950	471	561	70	545	70	909	70	341	70	29	70
950	487	549	60	477	88	764	105	337	145	0	50
960	493	500	60	383	60	705	60	115	60	57	72
960	473	524	60	374	60	686	60	120	60	0	60
975	561	653	104	585	100	828	105	242	108	-13	109
975	518	546	91	469	133	856	159	421	218	0	80
980	475	495	100	435	103	866	100	131	101	48	109
980	534	484	109	409	102	782	100	72	109	0	150
1000	508	416	139	452	158	823	169	213	195	0	130
1000	489	545	147	600	170	861	186	422	115	0	170
1000	507	601	70	445	102	908	122	395	168	0	80
1020	515	590	131	615	137	943	131	584	138	0	140
1020	478	529	134	558	136	831	143	184	159	0	160
1025	512	577	98	352	144	827	172	372	236	0	100
1040	496	638	137	715	135	937	130	517	138	108	152
1040	489	587	132	419	135	869	134	99	136	40	135
1050	510	619	113	337	165	935	197	521	271	0	50
1050	475	612	139	536	132	1006	136	391	137	-17	138
1060	465	598	134	557	135	951	142	97	158	0	150
1060	503	524	136	673	138	901	147	500	163	0	150
1080	446	573	60	535	87	1013	104	120	243	0	100
1100	469	775	90	760	127	946	162	345	180	-49	185
1150	453	699	130	606	143	1185	155	575	161	78	162
1200	461	695	127	630	138	1127	148	322	154	-74	155
1250	490	770	129	687	141	1232	156	524	158	-33	160
1300	520	780	136	801	150	1220	164	580	171	-187	173
1350	500	600	160	700	190	1280	100	520	130	-10	120
1380	508	867	131	936	147	1359	155	642	170	138	197
1380	503	807	131	893	147	1337	155	609	170	125	197
1400	537	862	131	981	148	1497	156	708	171	199	199
1400	536	883	131	989	147	1500	155	720	170	200	198
1400	522	688	148	1043	168	1164	187	524	196	-222	199
1420	527	746	138	783	158	1287	168	626	186	-84	120
1420	534	826	135	809	152	1305	165	644	187	0	50
1440	533	804	139	955	134	1462	137	705	132	126	130
1440	531	751	130	941	135	1452	138	677	133	126	32
1450	472	875	122	768	173	1612	221	834	245	282	251

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      1450 535  858 143  942 164 1419  78  783 105    0  50
      1450 533  738 161  925 190 1534 110  795 148    0  40
      1460 506  542 151  739 176 1346 192  839 117  224 160
      1500 565  915 107  995 105 1520 105  903 140    0 100
      1500 493 1033 105 1125 104 1584  82  657  92   39  93

C  BISMUTH  INELASTIC ANGULAR DISTRIBUTIONS ( Q=-896+-1 KEV )
C  INCIDENT RESOUTION 10-12 KEV , X-SEC MB/SR, ANGLE IN DEGREES (LAB)
C                          IN. ENERGY IN KEV
C ANG(LAB)--- 1090.     1140.     1170.     1195.     1213.     1233.     1306.
C ----      --------- --------- --------- --------- --------- --------- --------
   20.                                                12.8+-2.9
   30.      10.1+-1.2  8.2+-1.1 13.6+-3.3 11.5+-1.7  7.9+-0.7 12.2+-0.7  6.7+-0.8
   45.      10.3+-1.2  8.2+-1.0 14.5+-2.6 12.1+-1.5 11.6+-1.1 11.5+-0.9  8.3+-0.7
   60.       9.5+-1.1  9.9+-1.1 15.1+-2.6  6.6+-1.5  8.7+-0.7  6.8+-0.8  7.6+-0.8
   75.       9.1+-1.1  9.8+-1.0 11.3+-1.6  9.8+-1.6 10.3+-0.9 12.0+-0.8  7.3+-0.7
   90.      10.8+-1.0 10.3+-0.9 16.6+-1.7 11.4+-2.1 11.2+-0.7 12.9+-0.7  8.7+-0.8
  105.       8.9+-1.1  9.1+-1.1 16.2+-2.5 12.0+-1.6  9.3+-0.7  9.6+-0.8  8.7+-0.9
  120.       8.4+-1.1 11.7+-1.2 11.8+-2.6 11.3+-1.4 10.5+-0.7 10.9+-0.9
  135.      12.1+-1.3  8.7+-1.1 15.3+-2.8  9.4+-2.0 14.0+-1.4 13.3+-1.3 10.3+-1.1
  145.      12.5+-1.7
  148.                          13.4+-3.2 13.7+-2.3                      7.8+-1.2
  150                   9.8+-1.8                    13.0+-1.0 12.6+-1.1
C
C
C XSEC.     130.4     121.2     185.4     142.3     134.6     146.5       105.9
            +-4.93    +-4.52    +-8.72    +-6.93    +-5.76    +-7.50      +-4.24
C
 OMEGA-1
            -.096     -.101     -.012     -.065     -.176     -.035       -.148
            +-.069    +-.071    +-.091    +-.085    +-.081    +-.094      +-.073
 OMEGA-2
            +.137     -.140     -.139     +.141     +.050     +.059       +.004
            +-.095    +-.097    +-.115    +-.129    +-.098    +-.121      +-.098
C    ABOVE X-SEC IS ANGLE INTEGRAL OF DIFFERENTIAL VALUES IN MB.
C    OMEGA-1 AND 2 ARE RESULT OF P-2 LEGENDRE FIT TO MEASURE VALUES
C    ALL VALUES RELATIVE TO DIFFERENTIAL ELASTIC SCATTERING X-SEC
C         OF CARBON GIVEN IN ANL-5567 (REV)
C    ALL VALUES CORRECTED FOR MULTIPLE SCATTERING
C    ERRORS NOT INCLUSIVE OF UNCERTAINTY IN CARBON STD.
C
C END OF BLOCK
C
C
C
C  CROSS SECTIONS FOR EXCITATION OF 896+-1 KEV STATE IN BISMUTH OBSERVED
C    AT 90 DEGREES, MB/SR, RELATIVE TO CARBON DIFFERENTIAL ELASTIC
C    SCATTERING ( ANL-5567 (REV)), CORRECTED FOR MULTIPLE SCATTERING,
C    ERRORS NOT INCLUSIVE OF UNCERTAINTY IN CARBON STD.
C
C  FORMAT 3E12.6
C    1) ENERGY IN KEV
C    2) 90 DEG. DIF. X-SEC IN MB/SR
C    3) ERROR IN X-SEC IN MB/SR
C
+.102000E+04+.400000E+01+.100000E+01
+.104000E+04+.610000E+01+.700000E+00
+.105000E+04+.670000E+01+.700000E+00
+.106000E+04+.620000E+01+.600000E+00
+.107000E+04+.740000E+01+.600000E+00
+.108000E+04+.880000E+01+.600000E+00
+.108500E+04+.102000E+02+.800000E+00
+.109000E+04+.120000E+02+.900000E+00
+.110000E+04+.910000E+01+.700000E+00
+.111000E+04+.075000E+02+.050000E+01
+.112000E+04+.104000E+02+.120000E+01
+.112500E+04+.094000E+02+.090000E+01
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+.113000E+04+.100000E+02+.120000E+01
+.113900E+04+.099000E+02+.070000E+01
+.114700E+04+.093000E+02+.060000E+01
+.116000E+04+.116000E+02+.090000E+01
+.116500E+04+.144000E+02+.280000E+01
+.117000E+04+.142000E+02+.090000E+01
+.117500E+04+.165000E+02+.210000E+01
+.118000E+04+.125000E+02+.100000E+01
+.118600E+04+.111000E+02+.080000E+01
+.119000E+04+.120000E+02+.160000E+01
+.119500E+04+.114000E+02+.210000E+01
+.120000E+04+.097000E+02+.090000E+01
+.121200E+04+.118000E+02+.070000E+01
+.122200E+04+.131000E+02+.090000E+01
+.123300E+04+.150000E+02+.100000E+01
+.123800E+04+.145000E+02+.090000E+01
+.124300E+04+.126000E+02+.080000E+01
+.1253  E+04+.123   E+02+.08    E+01
+.1262  E+04+.098   E+02+.06    E+01
+.1270  E+04+.146   E+02+.09    E+01
+.1275  E+04+.129   E+02+.09    E+01
+.1280  E+04+.127   E+02+.16    E+01
+.1289  E+04+.116   E+02+.09    E+01
+.1300  E+04+.103   E+02+.07    E+01
+.1307  E+04+.107   E+02+.09    E+01
+.1313  E+04+.110   E+02+.07    E+01
+.1326  E+04+.133   E+02+.10    E+01
+.1333  E+04+.144   E+02+.10    E+01
+.1340  E+04+.162   E+02+.09    E+01
+.1353  E+04+.149   E+02+.11    E+01
+.1366  E+04+.153   E+02+.12    E+01
+.1373  E+04+.135   E+02+.09    E+01
+.1380  E+04+.112   E+02+.08    E+01
+.1386  E+04+.124   E+02+.09    E+01
+.1392  E+04+.161   E+02+.13    E+01
+.1400  E+04+.170   E+02+.10    E+01
+.1405  E+04+.146   E+02+.10    E+01
+.1410  E+04+.133   E+02+.10    E+01
+.1416  E+04+.160   E+02+.14    E+01
+.1420  E+04+.160   E+02+.12    E+01
+.1425  E+04+.132   E+02+.08    E+01
+.1430  E+04+.130   E+02+.11    E+01
+.1440  E+04+.130   E+02+.08    E+01
+.1445  E+04+.134   E+02+.10    E+01
+.1450  E+04+.159   E+02+.09    E+01
+.1455  E+04+.153   E+02+.11    E+01
+.1460  E+04+.148   E+02+.10    E+01
+.1466  E+04+.172   E+02+.11    E+01
+.1470  E+04+.186   E+02+.13    E+01
+.1475  E+04+.187   E+02+.11    E+01
+.1480  E+04+.166   E+02+.11    E+01
+.1485  E+04+.178   E+02+.12    E+01
+.1490  E+04+.157   E+02+.11    E+01
+.1500  E+04+.150   E+02+.16    E+01
C
C  END OF BLOCK
C
C
C  INELASTIC SCATTERING CROSS SECTIONS OF BISMUTH, Q=-896+-1 KEV
C        INTEGRATED ANGULAR DISTRIBUTIONS
C    FORMAT(7E10.4)
C        1. ENERGY IN MEV
C        2. INCIDENT ENERGY SPREAD IN MEV
C        3. Q VALUE IN MEV
C        4. +- ERROR IN Q VALUE
C        5. XSEC IN BARNS
C        6. + XSEC ERROR IN BARNS
```

```
C         7. - XSEC ERROR IN BARNS
C     ALL XSEC RELATIVE TO CARBON AS GIVEN IN ANL-5567 REV
C     ALL VALUES CORRECTED FOR MULTIPLE SCATTERING
C
 .1090E 01 .1000E-01-.8960E 00 .1000E-02 .1304E 00 .4930E-02 .4930E-02
 .1140E 01 .1000E-01-.8960E 00 .1000E-02 .1212E 00 .4520E-02 .4520E-02
 .1170E 01 .1000E-01-.8960E 00 .1000E-02 .1854E 00 .8720E-02 .8720E-02
 .1195E 01 .1000E-01-.8960E 00 .1000E-02 .1423E 00 .6930E-02 .6930E-02
 .1213E 01 .1000E-01-.8960E 00 .1000E-02 .1346E 00 .5760E-02 .5760E-02
 .1233E 01 .1000E-01-.8960E 00 .1000E-02 .1465E 00 .7500E-02 .7500E-02
 .1306E 01 .1000E-01-.8960E 00 .1000E-02 .1059E 00 .4240E-02 .4240E-02
 .1295E 01 .2000E-01-.8960E 00 .1000E-02 .2140E 00 .2160E-01 .2160E-01
 .1300E 01 .2000E-01-.8960E 00 .1000E-02 .1811E 00 .2726E-01 .2726E-01
 .1350E 01 .2000E-01-.8960E 00 .1000E-02 .2220E 00 .2731E-01 .2731E-01
 .1380E 01 .2000E-01-.8960E 00 .1000E-02 .2164E 00 .2597E-01 .2597E-01
 .1387E 01 .2000E-01-.8960E 00 .1000E-02 .1907E 00 .1970E-01 .1900E-01
 .1420E 01 .2000E-01-.8960E 00 .1000E-02 .2046E 00 .2456E-01 .2456E-01
 .1445E 01 .2000E-01-.8960E 00 .1000E-02 .2007E 00 .2000E-01 .2000E-01
 .1450E 01 .2000E-01-.8960E 00 .1000E-02 .1874E 00 .3246E-01 .3246E-01
 .1460E 01 .2000E-01-.8960E 00 .1000E-02 .2293E 00 .2751E-01 .2751E-01
 .1475E 01 .2000E-01-.8960E 00 .1000E-02 .2135E 00 .2562E-01 .2562E-01
 .1495E 01 .2000E-01-.8960E 00 .1000E-02 .1682E 00 .2018E-01 .2018E-01
 .1499E 01 .2000E-01-.8960E 00 .1000E-02 .2104E 00 .2525E-01 .2525E-01
 .1500E 01 .2000E-01-.8960E 00 .1000E-02 .2380E 00 .3600E-01 .3600E-01

C
C     TOTAL CROSS SECTIONS OF BISMUTH
C         MONO-ENERGETIC COURCE METHOD IN THE INTERVALS
C           100-500 KEV AND 1200-1500 KEV. TIME-OF-FLIGHT
C           IN RANGE 500-1200 KEV.  MONO-ENERGETIC RESOLUTION 1.5-2.5
C           KEV. TIME OF FLIGHT RESOLUTION 0.1-0.15 NSEC/M.
C         FORMAT(3E12.6)
C               ENERGY IN KEV
C               XSEC IN BARNS
C               ERROR IN XSEC IN BARNS
C
 .206000E 03 .815500E 01 .105000E 00
 .207000E 03 .822600E 01 .105000E 00
 .208000E 03 .843700E 01 .105000E 00
 .209000E 03 .820800E 01 .105000E 00
 .210000E 03 .814000E 01 .105000E 00
 .211000E 03 .800200E 01 .105000E 00
 .212000E 03 .776800E 01 .105000E 00
 .213000E 03 .730900E 01 .105000E 00
 .214000E 03 .755000E 01 .105000E 00
 .215000E 03 .719300E 01 .105000E 00
 .216000E 03 .696300E 01 .105000E 00
 .217000E 03 .740100E 01 .105000E 00
 .218000E 03 .744400E 01 .105000E 00
 .219000E 03 .737900E 01 .105000E 00
 .220000E 03 .704600E 01 .105000E 00
 .221000E 03 .798600E 01 .105000E 00
 .222000E 03 .884800E 01 .105000E 00
 .223000E 03 .876800E 01 .105000E 00
 .224000E 03 .845000E 01 .105000E 00
 .225000E 03 .858900E 01 .105000E 00
 .226000E 03 .824200E 01 .105000E 00
 .227000E 03 .860900E 01 .105000E 00
 .228000E 03 .849900E 01 .105000E 00
 .229000E 03 .847300E 01 .105000E 00
 .230000E 03 .852300E 01 .105000E 00
 .231000E 03 .830100E 01 .105000E 00
 .232000E 03 .861400E 01 .105000E 00
 .233000E 03 .807300E 01 .105000E 00
 .234000E 03 .782900E 01 .105000E 00
 .235000E 03 .734400E 01 .105000E 00
 .236000E 03 .712400E 01 .105000E 00
 .237000E 03 .731400E 01 .105000E 00
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.238000E 03	.742300E 01	.105000E 00
.239000E 03	.784600E 01	.105000E 00
.240000E 03	.760600E 01	.105000E 00
.241000E 03	.779100E 01	.105000E 00
.242000E 03	.764100E 01	.105000E 00
.243000E 03	.795500E 01	.105000E 00
.244000E 03	.844200E 01	.105000E 00
.245000E 03	.838000E 01	.105000E 00
.246000E 03	.832800E 01	.105000E 00
.247000E 03	.788900E 01	.105000E 00
.248000E 03	.710700E 01	.105000E 00
.249000E 03	.680600E 01	.105000E 00
.250000E 03	.756400E 01	.105000E 00
.251000E 03	.825700E 01	.105000E 00
.253000E 03	.827300E 01	.105000E 00
.254000E 03	.808600E 01	.105000E 00
.255000E 03	.800300E 01	.105000E 00
.256000E 03	.796200E 01	.105000E 00
.257000E 03	.814600E 01	.105000E 00
.258000E 03	.810300E 01	.105000E 00
.259000E 03	.800200E 01	.105000E 00
.260000E 03	.752600E 01	.105000E 00
.261000E 03	.753100E 01	.105000E 00
.262000E 03	.728000E 01	.105000E 00
.263000E 03	.658500E 01	.105000E 00
.264000E 03	.638100E 01	.105000E 00
.265000E 03	.632500E 01	.105000E 00
.266000E 03	.605000E 01	.105000E 00
.267000E 03	.606700E 01	.105000E 00
.268000E 03	.734800E 01	.105000E 00
.269000E 03	.772700E 01	.105000E 00
.270000E 03	.862300E 01	.105000E 00
.271000E 03	.852200E 01	.105000E 00
.272000E 03	.836900E 01	.105000E 00
.273000E 03	.833800E 01	.105000E 00
.274000E 03	.783300E 01	.105000E 00
.275000E 03	.844200E 01	.105000E 00
.276000E 03	.782800E 01	.105000E 00
.277000E 03	.742200E 01	.105000E 00
.278000E 03	.621900E 01	.105000E 00
.276000E 03	.810900E 01	.105000E 00
.278000E 03	.631000E 01	.105000E 00
.279000E 03	.632300E 01	.105000E 00
.280000E 03	.603200E 01	.105000E 00
.281000E 03	.689500E 01	.105000E 00
.282000E 03	.743300E 01	.105000E 00
.283000E 03	.764300E 01	.105000E 00
.284000E 03	.776100E 01	.105000E 00
.285000E 03	.770700E 01	.105000E 00
.286000E 03	.791000E 01	.105000E 00
.287000E 03	.780400E 01	.105000E 00
.287000E 03	.685200E 01	.105000E 00
.288000E 03	.667400E 01	.105000E 00
.289000E 03	.711600E 01	.105000E 00
.290000E 03	.703700E 01	.105000E 00
.291000E 03	.708300E 01	.105000E 00
.292000E 03	.768100E 01	.105000E 00
.293000E 03	.691200E 01	.105000E 00
.294000E 03	.700500E 01	.105000E 00
.295000E 03	.727900E 01	.105000E 00
.296000E 03	.723000E 01	.105000E 00
.297000E 03	.730800E 01	.105000E 00
.298000E 03	.734000E 01	.105000E 00
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