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Measurement of the Electron Energy Spectrum and its Moments in Inclusive $B \to Xe\nu$ Decays

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We report a measurement of the inclusive electron energy spectrum for semileptonic decays of B mesons in a data sample of 52 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B-meson factory at SLAC. We determine the branching fraction, first, second, and third moments of the spectrum for lower cut-offs on the electron energy between 0.6 and 1.5 GeV. We measure the partial branching fraction to be $\mathcal{B}(B \to Xe\nu, E_e > 0.6\,\mathrm{GeV}) = (10.36 \pm 0.06(\mathrm{stat.}) \pm 0.23(\mathrm{sys.}))\%$.

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The operator product expansion provides corrections to the relation between the semileptonic B decay rate and the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) [1] matrix element V_{cb} in the free-quark model [2]. The corrections are expressed in terms of non-perturbative quantities that can be extracted from moments of inclusive distributions. We plan to use the precision measurements of moments of the lepton energy spectra presented here and of hadron mass distributions [3] to determine those parameters and thereby to improve the determination of $|V_{cb}|$ [4].

In this paper, we present a new measurement of the inclusive electron energy spectrum from semileptonic B decays, averaged over charged and neutral B mesons produced at the $\Upsilon(4S)$ resonance. After correcting for charmless semileptonic decays, we derive from this spectrum several moments as a function of the minimum electron energy ranging from 0.6 GeV to 1.5 GeV, where lower endpoint is set by the limits of electron identification and prevalence of background. In the B meson rest frame, we define $R_i(E_0, \mu)$ as $\int_{E_0}^{\infty}(E_e - \mu)^i (d\Gamma/dE_e)\, dE_e$, and measure the first moment $M_1(E_0) = R_1(E_0, 0)/R_0(E_0, 0)$, the central moments $M_n(E_0) = R_n(E_0, M_1(E_0))/R_0(E_0, 0)$ for $n = 2$, 3 and the partial branching fraction $\mathcal{B}(E_0) = \tau_B\ R_0(E_0, 0)$, where τ_B is the average lifetime of charged and neutral B mesons.

The measurements presented here are based on data collected by the *BABAR* detector [5] at the PEP-II asymmetric e^+e^- storage ring; they correspond to an integrated luminosity of 47.4 fb^{-1} on the $\Upsilon(4S)$ resonance and 9.1 fb^{-1} at an energy 40 MeV below the resonance (off-resonance), measured in the electron-positron center of mass frame. Where background and efficiency corrections cannot be measured directly from data, we use a full simulation of the detector based on GEANT4 [6]. In the following, all kinematic variables defined in the $\Upsilon(4S)$ rest frame will be annotated with an asterisk.

This analysis is similar to the *BABAR* measurement of the semileptonic branching fraction [7], including use of the same electron identification criteria, but supersedes it by an order of magnitude in integrated luminosity. We identify $B\overline{B}$ events by observing an electron, e_{tag}, with charge $Q(e_{tag})$ and a momentum of $1.4 < p^* < 2.3$ GeV/c in the $\Upsilon(4S)$ rest frame. These electrons make up the tagged sample that is used as normalization for the branching fraction. Each electron e_{sig} with charge $Q(e_{sig})$ for which we require $p^* > 0.5\,\mathrm{GeV}/c$ is assigned to the unlike-sign sample if the tagged sample contains an electron with $Q(e_{tag}) = -Q(e_{sig})$, and to the like-sign sample if $Q(e_{tag}) = Q(e_{sig})$. In events without $B^0\overline{B}^0$ mixing, primary electrons from semileptonic B decays belong to the unlike-sign sample while secondary electrons contribute to the like-sign sample.

Multi-hadron events are selected by either requiring a track multiplicity $N_{ch} \geq 5$, or $N_{ch} = 4$ plus at least two photon candidates with $E_\gamma > 80\,\mathrm{MeV}$. Track pairs from converted photons are not included in N_{ch}, but count as one photon. For further suppression of non-$B\overline{B}$ events we require the ratio of the Fox-Wolfram moments H_2^*/H_0^* to be less than 0.8.

Electrons originating from the same B meson as the tagged electron typically have opposite charge and direction. To reject them we require

$$\cos\alpha^* > 1.0 - p_e^*(\,\mathrm{GeV/c}) \quad \text{and} \quad \cos\alpha^* > -0.2, \qquad (1)$$

where α^* is the angle between the two electrons. This requirement also excludes electron pairs from $J/\psi \to e^+e^-$ decays. To suppress background contributions from $J/\psi \to e^+e^-$ decays to the tagged sample, we require the invariant mass M_{ee} of the tag electron, paired with any electron of opposite charge and $\cos\alpha^* < -0.2$, to be outside the interval $2.9 < M_{ee} < 3.15\,\mathrm{GeV}/c^2$. Here the requirement on $\cos\alpha^*$ does not reduce the efficiency of this veto, but ensures that no signal electron satisfying Eq. 1 is excluded from the unlike-sign sample. The efficiencies of these selection criteria are estimated by Monte Carlo (MC) simulation.

Continuum background is subtracted from the tagged, like- and unlike-sign samples by scaling the off-resonance yields by the ratio of on- to off-resonance integrated luminosities, corrected for the energy dependence of the continuum cross section. In the off-resonance sample, the momenta are scaled by the ratio of the on- and off-resonance energies.

Electron spectra from photon conversions and Dalitz decays are extracted from data, taking into account the pair-reconstruction efficiencies from MC simulation. The relative uncertainty in these efficiencies is estimated to be 13% and 19% for conversion and Dalitz pairs, respectively.

The misidentification rates for pions, kaons, and protons are extracted from data control samples. They rise from 0.05% to 0.12% for pions and fall from 0.4% to 0.1% for kaons as p^* increases from 0.5 to 2.5 GeV/c. The systematic errors are estimated from the control sample purities and from the uncertainties in the π, K and p abundances. The resulting relative uncertainties are less than 40%.

There is a small residual background in the sample of unlike-sign pairs originating from the same B meson and fulfilling the requirement on the opening angle α^* from Eq. 1. It is estimated from a fit to the $\cos\alpha^*$ distribution, separately for each 50-MeV/c-wide bin in p^*. The distribution is flat for signal pairs, while for background pairs it is taken from MC simulation, with a maximum at $\cos\alpha^* = -1$ and gradually decreasing to 0 at $\cos\alpha^* = 1$.

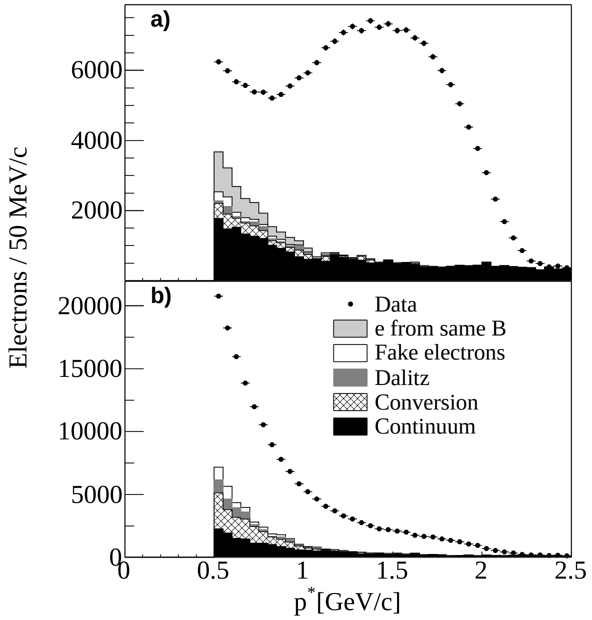

FIG. 1: Measured momentum spectrum (points) and estimated backgrounds (histograms) for electron candidates in (a) the unlike-sign sample, and (b) the like-sign sample.

Fig. 1 shows the electron momentum spectra and the background contributions discussed so far. Further backgrounds arise from decays of τ leptons, charmed mesons produced in $b \to c\bar{c}s$ decays and J/ψ or $\psi(2S) \to e^+e^-$ decays with only one detected e. We also need to correct for cases where the tagged electron does not originate from a semileptonic B decay. These backgrounds are irreducible, and their contributions to the three electron samples are estimated from MC simulations, using the ISGW2 model [9] to describe semileptonic D and D_s meson decays. Assuming $\Gamma(D_s \to Xe\nu) = \Gamma(D \to Xe\nu)$, we obtain $\mathcal{B}(D_s \to Xe\nu) = (8.05 \pm 0.66)\%$. Using 0.84 ± 0.09 [10] for the measured fraction of $B \to D_s X$ decays where the D_s originates from fragmentation of the W Boson, and $\mathcal{B}(B \to D_s X) = (10.5 \pm 2.6)\%$ [11] yields $\mathcal{B}(B^{0,+} \to D_s^+ \to e^+) = (0.71 \pm 0.20)\%$. Assuming equal production rates of D and D^* and using $\mathcal{B}(B \to \overline{D}D^{(*)}X) = (8.2 \pm 1.3)\%$ [10], we arrive at $\mathcal{B}(B^{0,+} \to D^{0,+} \to e^+) = (0.84 \pm 0.21)\%$. To estimate the contribution of electrons from τ decays, we consider the cascades $B \to \tau \to e$ and $B \to D_s \to \tau \to e$, with branching fractions taken from [11]. The rates for the decays $B \to J/\psi \to e^+e^-$ and $B \to \psi(2S) \to e^+e^-$ are also adjusted to [11].

These irreducible background spectra are subtracted from the like-sign and unlike-sign spectra after correction for electron identification efficiency. We determine this efficiency as a function of p^* and the polar angle θ^* using $e^+e^- \to e^+e^-\gamma$ events and then use MC simulation to estimate losses in hadronic events with higher multiplicities. For $p^* > 0.6\,\text{GeV}/c$, the average efficiency is 91% with an uncertainty of 1.5% estimated from the size of the MC correction. A summary of the yields is given in Table I.

TABLE I: Unlike-sign and like-sign pair yields for $0.6 < p^* < 2.5\,\text{GeV}/c$ and their corrections with statistical and systematic errors. Numbers are quoted after all selection criteria.

	e^+e^- sample	$e^\pm e^\pm$ sample
All candidates	183493 ± 434	133842 ± 371
continuum bkgd.	22922 ± 349	15758 ± 290
conversion, Dalitz	$2978 \pm 286 \pm 327$	$10730 \pm 502 \pm 1177$
fake e	$885 \pm 63 \pm 423$	$2229 \pm 182 \pm 966$
e from same B	$3200 \pm 34 \pm 160$	
e yield	$153508 \pm 630 \pm 558$	$105126 \pm 712 \pm 1523$
eff. corr. e yield	$169654 \pm 732 \pm 2235$	$117192 \pm 803 \pm 2510$
irreducible bkgd.	$13912 \pm 92 \pm 1341$	$14512 \pm 97 \pm 2513$
corr. e yield	$155742 \pm 738 \pm 2606$	$102680 \pm 809 \pm 3551$

To account for $B^0\overline{B}^0$ mixing, we determine the number of primary electrons in the i-th p^* bin from the like-sign and unlike-sign pairs as

$$N^i_{b\to c,u} = \frac{1 - f_0\chi_0}{1 - 2f_0\chi_0}\frac{N^i_{e^+e^-}}{\epsilon^i_{\alpha^*}} - \frac{f_0\chi_0}{1 - 2f_0\chi_0}N^i_{e^\pm e^\pm} \qquad (2)$$

where $\chi_0 = 0.186 \pm 0.004$ [11] is the $B^0\overline{B}^0$ mixing parameter and $f_0 = \mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0) = 0.490 \pm 0.018$ [11]. The parameter $\epsilon^{i}_{\alpha^*}$ is the efficiency of the additional requirement for the unlike-sign sample as defined in Eq. 1.

The spectrum obtained from Eq. 2 is corrected for the effects of bremsstrahlung in the detector material using MC simulation. Since this correction significantly impacts the first moments, 3% for $E_0 = 0.6\,\mathrm{GeV}$ and 0.5% for $E_0 = 1.5\,\mathrm{GeV}$, we have verified that the detector material is simulated to better than 3%. Fig. 2 shows the resulting spectrum of primary electrons.

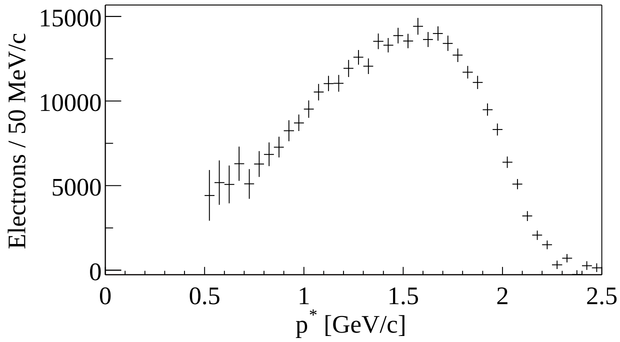

FIG. 2: Electron momentum spectrum from $B \to Xe\nu(\gamma)$ decays in the $\Upsilon(4S)$ frame after correction for efficiencies and bremsstrahlung, with combined statistical and systematic errors.

Charmless semileptonic $B \to X_u e\nu$ decays are modeled as in [12] by a combination of semileptonic decays with resonant and non-resonant hadronic systems. Using $\mathcal{B}(B \to X_u e\nu) = (2.2 \pm 0.5) \times 10^{-3}$ [12] to correct for this background, we determine the moments $\tilde{M}_n = \sum_k p_k^n N^k_{b\to c}/\sum_k N^k_{b\to c}$ where k runs over all bins above the energy E_0 and p_k are the bin centers for $n = 1$ and the bin centers shifted by $\tilde{M}_1$ for $n = 2, 3$. These moments are then transformed into E_e moments M_n by correcting for the movement of the B mesons in the center-of-mass frame. Further biases due to the event selection criteria and binning are estimated from MC simulation. The spectra and moments presented are those of $B \to X_c e\nu(\gamma)$ decays with any number of photons. The moments as a function of E_0 are shown in Fig. 3 and Table II lists the principal systematic errors for $E_0 = 0.6$ and 1.5 GeV. Without subtraction of $B \to X_u e\nu$ decays, we measure $M_1^{b\to x}(1.5\,\mathrm{GeV}) = (1779.0 \pm 1.9 \pm 0.7)\,\mathrm{MeV}$, which is consistent with a recent measurement by CLEO [13]. Measurements with $E_0 = 0\,\mathrm{GeV}$ have been performed by DELPHI [14].

We determine the partial branching fraction as $(\sum_k N^k_{b\to c,u})/(N_{tag}\ \epsilon_{evt}\ \epsilon_{cuts})$, where k runs over all bins with $E_e > E_0$, $N_{tag} = (3616.8 \pm 3.5(\mathrm{stat.}) \pm 21.8(\mathrm{syst.})) \times 10^3$ is the background-corrected number of tag electrons, $\epsilon_{evt} = (98.9 \pm 0.5)\%$ refers to the relative efficiency for selecting two-electron events compared to events with a single e_{tag}, and $\epsilon_{cuts} = (82.8 \pm 0.3)\%$ is the acceptance for the signal electron for $E_0 = 0.6\,\mathrm{GeV}$. The result,

$$\begin{aligned}&\mathcal{B}(B \to Xe\nu(\gamma),\, E_e > 0.6\,\mathrm{GeV})\\ &\qquad = (10.36 \pm 0.06(\mathrm{stat.}) \pm 0.23(\mathrm{syst.}))\%,\end{aligned}$$

is consistent with our previous measurement [7], with the overall error improved by 25%. The partial branching fraction can be extrapolated to $E_0 = 0$ as part of a combined fit of the Heavy Quark Effective Theory (HQET) parameters to the full set of moments [4].

Current theoretical predictions on the lepton energy moments do not incorporate photon emission. Therefore we use PHOTOS [15] to simulate QED radiation and correct the moments for its impact. We verify that radiation that is not included in PHOTOS, e.g. additional hard photons, have no significant effect on the moments. The radiatively corrected moments and the estimated PHOTOS uncertainty [16] are given in Table II. The complete listing of all moments and the full correlation matrix, with and without PHOTOS corrections can be found in Tables III-V. For fitting purposes, a set of tables and matrices with a precision of 5 significant digits can be obtained from the authors.

In summary, we report a measurement of the electron energy spectrum of the inclusive decay $B \to Xe\nu$ and its branching fraction for electron energies above 0.6 GeV, which supersedes our previous result [7]. We have also derived branching fractions, first, second, and third moments of electron energy spectrum from $B \to X_c e\nu$ decays for cut-off energies from 0.6 to 1.5 GeV. This set of moments combined with hadron mass moments [3] will be used for a significantly improved determination of HQET parameters and of $|V_{cb}|$ [4].

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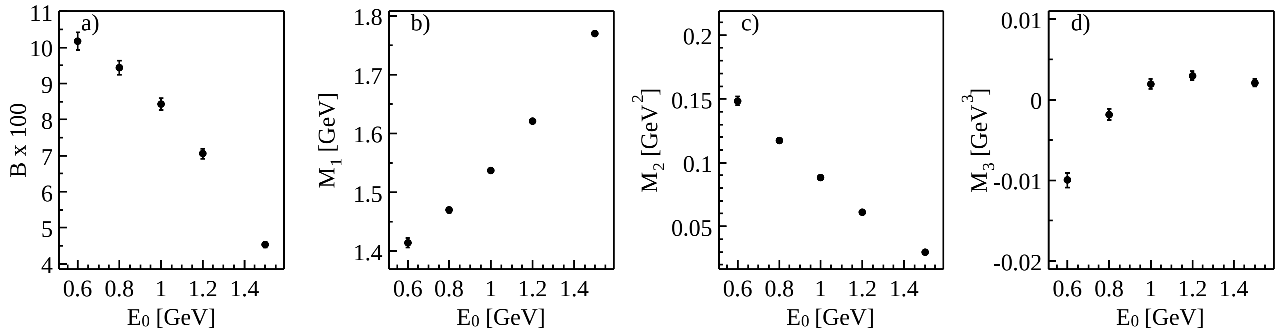

FIG. 3: Measured moments of the inclusive electron energy spectrum of $B \to X_c e\nu(\gamma)$ decays as a function of the cut-off energy, (a) $\mathcal{B}$, (b) M_1, (c) M_2 and (d) M_3.

TABLE II: Results and breakdown of the systematic errors for $\mathcal{B} = \tau_B \int_{E_0}^{\infty} (d\Gamma/dE_e)\, dE_e$, and the moments M_1, M_2, and M_3 for $B \to X_c e\nu$ in the B-meson rest frame for two values of E_0.

	$\mathcal{B}[10^{-2}]$		M_1[MeV]		$M_2[10^{-3}$ GeV^2]		$M_3[10^{-3}$ GeV^3]	
E_0[GeV]	0.6	1.5	0.6	1.5	0.6	1.5	0.6	1.5
conversion and Dalitz pairs	0.029	0.001	1.6	0.02	0.6	0.00	0.06	0.00
e identification efficiency	0.151	0.044	2.5	0.30	0.6	0.07	0.29	0.08
e from same B	0.019	0.000	1.3	0.00	0.6	0.00	0.03	0.00
$B \to D_s \to e$	0.074	0.001	4.1	0.04	1.6	0.00	0.14	0.00
$B \to D \to e$	0.060	0.000	3.8	0.00	1.6	0.00	0.01	0.00
$B \to \tau \to e$	0.032	0.002	1.4	0.05	0.4	0.00	0.13	0.00
e from J/ψ or $\psi(2S)$	0.002	0.001	0.0	0.01	0.0	0.01	0.00	0.00
Secondary tags	0.053	0.011	1.5	0.06	0.5	0.00	0.06	0.00
χ	0.034	0.021	0.8	0.01	0.3	0.00	0.03	0.00
tracking efficiency	0.084	0.033	1.0	0.06	0.3	0.02	0.07	0.00
bremsstrahlung correction	0.011	0.028	1.9	0.43	0.0	0.05	0.19	0.00
event selection	0.052	0.024	0.6	0.14	0.0	0.03	0.07	0.01
$b \to u$ subtraction	0.047	0.030	1.2	1.24	0.6	0.48	0.20	0.17
B momentum correction	0.000	0.005	0.0	0.19	0.1	0.10	0.04	0.02
N_{tag} normalization	0.068	0.030						
Moments	10.17	4.54	1414.3	1769.2	148.5	29.8	-9.97	2.11
±(stat.)	0.06	0.03	3.7	1.8	2.0	0.8	0.79	0.44
±(sys.)	0.23	0.08	7.4	1.4	2.7	0.5	0.48	0.20
Moments with rad. correction	10.30	4.79	1432.8	1774.3	148.0	30.3	-12.05	2.12
±(stat.)	0.06	0.03	3.9	1.9	2.2	0.9	0.88	0.47
±(sys.)	0.24	0.09	7.8	1.4	3.1	0.5	0.46	0.20

TABLE III: Measured moments M_1, M_2, M_3, and $\mathcal{B}$ for five cut-off energies E_0 with first their statistical error and second their systematic error. The moments are given in the B-meson rest frame and are defined to include X_c hadronic states only and to include decays $B \to X_c e\nu\gamma$ with any number of photons.

E_0[GeV]	$\mathcal{B}[10^{-2}]$	M_1[MeV]	$M_2[10^{-3}\text{ GeV}^2]$	$M_3[10^{-3}\text{ GeV}^3]$
0.6	$10.17 \pm 0.06 \pm 0.23$	$1414.3 \pm 3.7 \pm 7.4$	$148.5 \pm 2.0 \pm 2.7$	$-9.97 \pm 0.79 \pm 0.48$
0.8	$9.43 \pm 0.05 \pm 0.19$	$1469.8 \pm 2.4 \pm 3.6$	$117.3 \pm 1.2 \pm 0.9$	$-1.82 \pm 0.60 \pm 0.39$
1.0	$8.42 \pm 0.04 \pm 0.16$	$1537.2 \pm 1.9 \pm 2.1$	$88.3 \pm 0.9 \pm 0.6$	$1.95 \pm 0.53 \pm 0.30$
1.2	$7.05 \pm 0.04 \pm 0.13$	$1621.3 \pm 1.8 \pm 1.6$	$61.2 \pm 0.9 \pm 0.6$	$2.97 \pm 0.49 \pm 0.24$
1.5	$4.54 \pm 0.03 \pm 0.08$	$1769.2 \pm 1.8 \pm 1.4$	$29.8 \pm 0.8 \pm 0.5$	$2.11 \pm 0.44 \pm 0.20$

TABLE IV: Measured moments M_1, M_2, M_3, and $\mathcal{B}$ for five cut-off energies E_0 with first their statistical error and second their systematic error.The moments are given in the B-meson rest frame and are corrected for QED radiative effects.

E_0[GeV]	$\mathcal{B}[10^{-2}]$	M_1[MeV]	$M_2[10^{-3}\text{ GeV}^2]$	$M_3[10^{-3}\text{ GeV}^3]$
0.6	$10.30 \pm 0.06 \pm 0.24$	$1432.8 \pm 3.9 \pm 7.8$	$148.0 \pm 2.2 \pm 3.1$	$-12.05 \pm 0.88 \pm 0.46$
0.8	$9.61 \pm 0.05 \pm 0.20$	$1484.8 \pm 2.6 \pm 3.7$	$117.7 \pm 1.3 \pm 1.0$	$-3.18 \pm 0.64 \pm 0.38$
1.0	$8.65 \pm 0.04 \pm 0.17$	$1548.7 \pm 2.0 \pm 2.2$	$89.1 \pm 1.0 \pm 0.6$	$1.19 \pm 0.57 \pm 0.30$
1.2	$7.31 \pm 0.04 \pm 0.14$	$1629.9 \pm 1.9 \pm 1.7$	$62.1 \pm 0.9 \pm 0.6$	$2.66 \pm 0.52 \pm 0.24$
1.5	$4.79 \pm 0.03 \pm 0.09$	$1774.3 \pm 1.9 \pm 1.4$	$30.3 \pm 0.9 \pm 0.5$	$2.12 \pm 0.47 \pm 0.20$

TABLE V: Correlation matrix of the 20 measured moments. Matrix elements are for the full errors (statistical and systematic added in quadrature) in percent. The superscript i refers to the energy thresholds $E_i = 0.6$, 0.8, 1.0, 1.2, 1.5 GeV for $i = 1$, 2, 3, 4, 5 respectively.

	M_1^1	M_1^2	M_1^3	M_1^4	M_1^5	M_2^1	M_2^2	M_2^3	M_2^4	M_2^5	M_3^1	M_3^2	M_3^3	M_3^4	M_3^5	$\mathcal{B}^1$	$\mathcal{B}^2$	$\mathcal{B}^3$	$\mathcal{B}^4$	$\mathcal{B}^5$
M_1^1	100.0	83.2	64.0	48.3	34.0	-73.6	-26.5	12.3	22.5	23.4	13.5	-9.2	0.7	10.5	15.7	-50.8	-26.4	-11.8	-2.5	8.0
M_1^2		100.0	81.4	66.8	51.5	-35.1	-20.0	27.3	37.8	38.3	-7.3	-0.3	9.7	21.3	27.2	-36.5	-24.1	-7.4	3.3	16.7
M_1^3			100.0	84.0	68.5	-3.5	26.6	40.4	53.9	54.5	5.5	6.6	21.0	34.3	41.1	-16.7	-7.2	-0.8	12.0	27.8
M_1^4				100.0	79.1	15.5	49.0	69.8	61.9	65.7	23.8	28.0	33.9	43.2	51.6	-0.3	6.7	12.1	15.9	35.1
M_1^5					100.0	28.7	63.1	85.6	88.8	79.7	48.7	59.7	64.4	66.4	65.1	17.6	23.4	27.5	31.5	36.3
M_2^1						100.0	66.5	42.8	35.2	33.4	3.9	41.9	38.0	33.4	30.9	66.1	44.1	33.9	29.6	28.0
M_2^2							100.0	75.2	68.9	67.3	59.0	61.0	63.1	61.4	60.6	53.9	51.4	40.3	38.0	41.1
M_2^3								100.0	90.9	88.6	66.7	81.3	79.7	78.9	78.8	36.3	39.4	41.9	39.3	45.1
M_2^4									100.0	94.5	66.3	82.1	87.4	87.3	84.9	30.3	35.3	38.4	41.9	44.0
M_2^5										100.0	67.4	83.8	90.8	94.5	93.6	29.0	34.3	37.3	40.1	45.3
M_3^1											100.0	79.0	76.8	72.2	68.2	31.4	43.7	41.6	38.2	34.4
M_3^2												100.0	95.9	90.5	85.2	47.5	48.3	48.5	44.5	39.5
M_3^3													100.0	97.4	92.8	41.4	44.0	44.8	44.0	40.0
M_3^4														100.0	97.5	33.7	37.4	39.1	40.6	39.5
M_3^5															100.0	28.3	32.4	34.5	36.1	39.3
$\mathcal{B}^1$																100.0	95.4	90.4	86.3	80.1
$\mathcal{B}^2$																	100.0	97.7	95.1	90.1
$\mathcal{B}^3$																		100.0	98.3	94.3
$\mathcal{B}^4$																			100.0	96.5
$\mathcal{B}^5$																				100.0

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