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PQ/T Composite Schemes for OpenPGP using NIST and Brainpool Elliptic Curve Domain Parameters

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Abstract

This document defines PQ/T composite schemes based on ML-KEM and ML-DSA combined with ECDH and ECDSA algorithms using the NIST and Brainpool domain parameters for the OpenPGP protocol.

About This Document

This note is to be removed before publishing as an RFC.

Status information for this document may be found at https://datatracker.ietf.org/doc/draft-ietf-openpgp-nist-bp-comp/.

Discussion of this document takes place on the WG Working Group mailing list (mailto:openpgp@ietf.org), which is archived at https://mailarchive.ietf.org/arch/browse/openpgp/. Subscribe at https://www.ietf.org/mailman/listinfo/openpgp/.

Source for this draft and an issue tracker can be found at https://github.com/openpgp-pqc/draft-ehlen-openpgp-nist-bp-comp.

Status of This Memo

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Table of Contents

1. Introduction

This document defines PQ/T composite schemes based on ML-KEM and ML-DSA combined with ECDH and ECDSA using the NIST and Brainpool domain parameters for the OpenPGP protocol. It is an extension of [I-D.draft-ietf-openpgp-pqc], which introduces post-quantum cryptography in OpenPGP using hybrid KEMs and digital signatures combining ML-KEM and ML-DSA with ECC algorithms based on the Edwards Curves defined in [RFC7748] and [RFC8032].

Due to their long-standing and wide deployment, there are well-tested, secure, and efficient implementations of ECDSA and ECDH with NIST-curves [SP800-186]. The same applies to Brainpool curves [RFC5639] which are recommended or required in certain regulatory domains, for instance in Germany [TR-03111]. The purpose of this document is to support users who would like to or have to use such hybrid KEMs and/or signatures with OpenPGP.

1.1. Conventions used in this Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

In wire format descriptions, the operator "||" is used to indicate concatenation of groups of octets.

1.1.1. Terminology for Multi-Algorithm Schemes

The terminology in this document is oriented towards the definitions in [RFC9794]. Specifically, the terms "multi-algorithm", "composite" and "non-composite" are used in correspondence with the definitions therein. The abbreviation "PQ" is used for post-quantum schemes. To denote the combination of post-quantum and traditional schemes, the abbreviation "PQ/T" is used. The short form "PQ(/T)" stands for PQ or PQ/T.

1.2. Post-Quantum Cryptography

This section describes the individual post-quantum cryptographic schemes. All schemes listed here are believed to provide security in the presence of a cryptographically relevant quantum computer.

1.2.1. ML-KEM

ML-KEM [FIPS-203] is based on the hardness of solving the Learning with Errors problem in module lattices (MLWE). The scheme is believed to provide security against cryptanalytic attacks based on classical as well as quantum algorithms. This specification defines ML-KEM only in composite combination with ECDH encryption schemes in order to provide a pre-quantum security fallback.

1.2.2. ML-DSA

ML-DSA [FIPS-204] is a signature scheme that, like ML-KEM, is based on the hardness of solving the Learning With Errors problem and a variant of the Short Integer Solution problem in module lattices (MLWE and SelfTargetMSIS). Accordingly, this specification only defines ML-DSA in composite combination with ECDSA signature schemes.

1.3. Elliptic Curve Cryptography

The ECDH encryption is defined here as a KEM.

All elliptic curves for the use in the composite combinations are taken from [RFC9580].

For interoperability this extension offers ML-* in composite combinations with the NIST curves P-384, P-521 defined in [SP800-186] and the Brainpool curves brainpoolP384r1, brainpoolP512r1 defined in [RFC5639].

1.4. Applicable Specifications for the use of PQC Algorithms in OpenPGP

This document is to be understood as an extension of [I-D.draft-ietf-openpgp-pqc], which introduced PQC in OpenPGP, in that it defines further algorithm code points. All general specifications in [I-D.draft-ietf-openpgp-pqc] that pertain to the ML-KEM and ML-DSA composite schemes or generally cryptographic schemes defined therein equally apply to the schemes specified in this document.

2. Preliminaries

This section provides some preliminaries for the definitions in the subsequent sections.

2.1. Elliptic curves

2.1.1. SEC1 EC Point Wire Format

Elliptic curve points of the generic prime curves are encoded using the SEC1 (uncompressed) format as the following octet string:

B = 04 || X || Y

where X and Y are coordinates of the elliptic curve point P = (X, Y), and each coordinate is encoded in the big-endian format and zero-padded to the adjusted underlying field size. The adjusted underlying field size is the underlying field size rounded up to the nearest 8-bit boundary, as noted in the "Field size" column in Table 3, Table 4, or Table 7. This encoding is compatible with the definition given in [SEC1].

2.1.2. Measures to Ensure Secure Implementations

In the following measures are described that ensure secure implementations according to existing best practices and standards defining the operations of Elliptic Curve Cryptography.

Even though the zero point, also called the point at infinity, may occur as a result of arithmetic operations on points of an elliptic curve, it MUST NOT appear in any ECC data structure defined in this document.

Furthermore, when performing the explicitly listed operations in Section 5.1.1.1 it is REQUIRED to follow the specification and security advisory mandated from the respective elliptic curve specification.

3. Supported Public Key Algorithms

This section specifies the composite ML-KEM + ECDH and ML-DSA + ECDSA schemes. All of these schemes are fully specified via their algorithm ID, that is, they are not parametrized.

3.1. Algorithm Specifications

For encryption, the following composite KEM schemes are specified:

ID	Algorithm	Requirement	Definition
100	ML-KEM-768+ECDH-NIST-P-384	MAY	Section 5.2
101	ML-KEM-1024+ECDH-NIST-P-521	MAY	Section 5.2
102	ML-KEM-768+ECDH-brainpoolP384r1	MAY	Section 5.2
103	ML-KEM-1024+ECDH-brainpoolP512r1	MAY	Section 5.2

Table 1: KEM algorithm specifications

For signatures, the following composite signature schemes are specified:

ID	Algorithm	Requirement	Definition
104	ML-DSA-65+ECDSA-NIST-P-384	MAY	Section 6.2
105	ML-DSA-87+ECDSA-NIST-P-521	MAY	Section 6.2
106	ML-DSA-65+ECDSA-brainpoolP384r1	MAY	Section 6.2
107	ML-DSA-87+ECDSA-brainpoolP512r1	MAY	Section 6.2

Table 2: Signature algorithm specifications

3.1.1. Experimental Codepoints for Interop Testing

[Note: this section to be removed before publication]

The use of private/experimental codepoints during development are intended to be used in non-released software only, for experimentation and interop testing purposes only. An OpenPGP implementation MUST NOT produce a formal release using these experimental codepoints. This draft will not be sent to IANA without every listed algorithm having a non-experimental codepoint.

4. Algorithm Combinations

4.1. Composite KEMs

The ML-KEM + ECDH public-key encryption involves both the ML-KEM and an ECDH KEM in a non-separable manner. This is achieved via KEM combination, that is, both key encapsulations/decapsulations are performed in parallel, and the resulting key shares are fed into a key combiner to produce a single shared secret for message encryption.

4.2. Composite Signatures

The ML-DSA + ECDSA signature consists of independent ML-DSA and ECDSA signatures, and an implementation MUST successfully validate both signatures to state that the ML-DSA + ECDSA signature is valid.

4.3. Key Version Binding

All PQ/T asymmetric algorithms defined in this document are to be used only in v6 (and newer) keys and certificates.

5. Composite KEM Schemes

5.1. Building Blocks

5.1.1. ECDH KEM

In this section we define the encryption, decryption, and data formats for the ECDH component of the composite algorithms.

Table 3 and Table 4 describe the ECDH KEM parameters and artifact lengths.

	NIST P-384	NIST P-521
Algorithm ID reference	100	101
Field size	48 octets	66 octets
ECDH KEM	ECDH-KEM Section 5.1.1.1	ECDH-KEM Section 5.1.1.1
ECDH public key	97 octets of SEC1-encoded public point	133 octets of SEC1-encoded public point
ECDH secret key	48 octets big-endian encoded secret scalar	66 octets big-endian encoded secret scalar
ECDH ephemeral	97 octets of SEC1-encoded ephemeral point	133 octets of SEC1-encoded ephemeral point
ECDH key share	48 octets	66 octets

Table 3: NIST curves parameters and artifact lengths

	brainpoolP384r1	brainpoolP512r1
Algorithm ID reference	102	103
Field size	48 octets	64 octets
ECDH KEM	ECDH-KEM Section 5.1.1.1	ECDH-KEM Section 5.1.1.1
ECDH public key	97 octets of SEC1-encoded public point	129 octets of SEC1-encoded public point
ECDH secret key	48 octets big-endian encoded secret scalar	64 octets big-endian encoded secret scalar
ECDH ephemeral	97 octets of SEC1-encoded ephemeral point	129 octets of SEC1-encoded ephemeral point
ECDH key share	48 octets	64 octets

Table 4: Brainpool curves parameters and artifact lengths

The SEC1 format for point encoding is defined in Section 2.1.1.

The various procedures to perform the operations of an ECDH KEM are defined in the following subsections. Specifically, each of these subsections defines the instances of the following operations:

(ecdhCipherText, ecdhKeyShare) <- ECDH-KEM.Encaps(ecdhPublicKey)

and

(ecdhKeyShare) <- ECDH-KEM.Decaps(ecdhCipherText, ecdhSecretKey)

To instantiate ECDH-KEM, one must select a parameter set from Table 3 or Table 4.

5.1.1.1. ECDH-KEM

The operation ECDH-KEM.Encaps() is defined as follows:

1. Generate an ephemeral key pair {v, V=vG} as defined in [SP800-186] or [RFC5639] where v is a random scalar with 0 < v < n, n being the base point order of the elliptic curve domain parameters

2. Compute the shared point S = vR, where R is the recipient's public key ecdhPublicKey, according to [SP800-186] or [RFC5639]

3. Extract the X coordinate from the SEC1 encoded point S = 04 || X || Y as defined in section Section 2.1.1

4. Set the output ecdhCipherText to the SEC1 encoding of V

5. Set the output ecdhKeyShare to X

The operation ECDH-KEM.Decaps() is defined as follows:

1. Compute the shared Point S as rV, where r is the ecdhSecretKey and V is the ecdhCipherText, according to [SP800-186] or [RFC5639]

2. Extract the X coordinate from the SEC1 encoded point S = 04 || X || Y as defined in section Section 2.1.1

3. Set the output ecdhKeyShare to X

5.1.2. ML-KEM

ML-KEM features the following operations:

(mlkemCipherText, mlkemKeyShare) <- ML-KEM.Encaps(mlkemPublicKey)

and

(mlkemKeyShare) <- ML-KEM.Decaps(mlkemCipherText, mlkemSecretKey)

The above are the operations ML-KEM.Encaps and ML-KEM.Decaps defined in [FIPS-203]. Note that mlkemPublicKey is the encapsulation and mlkemSecretKey is the decapsulation key.

ML-KEM has the parametrization with the corresponding artifact lengths in octets as given in Table 5. All artifacts are encoded as defined in [FIPS-203].

	ML-KEM-768	ML-KEM-1024
Algorithm ID reference	100, 102	101, 103
Public key	1184 octets	1568 octets
Secret key	64 octets	64 octets
Ciphertext	1088 octets	1568 octets
Key share	32 octets	32 octets

Table 5: ML-KEM parameters and artifact lengths

To instantiate ML-KEM, one must select a parameter set from the column "ML-KEM" of Table 5.

5.2. Composite Encryption Schemes with ML-KEM

Table 1 specifies the following ML-KEM + ECDH composite public-key encryption schemes:

Algorithm ID reference	ML-KEM	ECDH-KEM curve
100	ML-KEM-768	NIST P-384
101	ML-KEM-1024	NIST P-521
102	ML-KEM-768	brainpoolP384r1
103	ML-KEM-1024	brainpoolP512r1

Table 6: ML-KEM + ECDH composite schemes

The ML-KEM + ECDH composite public-key encryption schemes are built according to the following principal design:

* The ML-KEM encapsulation algorithm is invoked to create an ML-KEM ciphertext together with an ML-KEM symmetric key share.

* The encapsulation algorithm of an ECDH KEM is invoked to create an ECDH ciphertext together with an ECDH symmetric key share.

* A Key-Encryption-Key (KEK) is computed as the output of a key combiner that receives as input both of the above created symmetric key shares, the ECDH ciphertext, the ECDH public key, and the protocol binding information.

* The session key for content encryption is then wrapped as described in [RFC3394] using AES-256 as algorithm and the KEK as key.

* The PKESK packet's algorithm-specific parts are made up of the ML-KEM ciphertext, the ECDH ciphertext, and the wrapped session key.

5.2.1. Key Combiner

For the composite KEM schemes defined in this document the procedure multiKeyCombine that is defined in Section 4.2.1 of [I-D.draft-ietf-openpgp-pqc] MUST be used to compute the KEK that wraps a session key.

5.2.2. Key Generation Procedure

The implementation MUST generate the ML-KEM and the ECDH component keys independently. ML-KEM key generation follows the specification in [FIPS-203], and the artifacts are encoded as fixed-length octet strings whose sizes are listed Section 5.1.2. ECDH key generation follows the specification in [SP800-186] or [RFC5639], and the artifacts are encoded as fixed-length octet strings whose sizes and format are listed in Table 3 or Table 4.

5.2.3. Encryption Procedure

The procedure to perform public-key encryption with an ML-KEM + ECDH composite scheme is as follows:

1. Take the recipient's authenticated public-key packet pkComposite and sessionKey as input

2. Parse the algorithm ID from pkComposite and set it as algId

3. Extract the ecdhPublicKey and mlkemPublicKey component from the algorithm specific data encoded in pkComposite with the format specified in Section 5.3.2.

4. Instantiate the ECDH-KEM and the ML-KEM depending on the algorithm ID according to Table 6

5. Compute (ecdhCipherText, ecdhKeyShare) = ECDH-KEM.Encaps(ecdhPublicKey)

6. Compute (mlkemCipherText, mlkemKeyShare) = ML-KEM.Encaps(mlkemPublicKey)

7. Compute KEK = multiKeyCombine(mlkemKeyShare, ecdhKeyShare, ecdhCipherText, ecdhPublicKey, algId) as defined in Section 5.2.1

8. Compute C = AESKeyWrap(KEK, sessionKey) with AES-256 as per [RFC3394] that includes a 64 bit integrity check

9. Output the algorithm specific part of the PKESK as ecdhCipherText || mlkemCipherText || len(C, symAlgId) (|| symAlgId) || C, where both symAlgId and len(C, symAlgId) are single octet fields, symAlgId denotes the symmetric algorithm ID used and is present only for a v3 PKESK, and len(C, symAlgId) denotes the combined octet length of the fields specified as the arguments.

5.2.4. Decryption Procedure

The procedure to perform public-key decryption with an ML-KEM + ECDH composite scheme is as follows:

1. Take the matching PKESK and own secret key packet as input

2. From the PKESK extract the algorithm ID as algId and the wrapped session key as encryptedKey

3. Check that the own and the extracted algorithm ID match

4. Parse the ecdhSecretKey and mlkemSecretKey from the algorithm specific data of the own secret key encoded in the format specified in Section 5.3.2

5. Instantiate the ECDH-KEM and the ML-KEM depending on the algorithm ID according to Table 6

6. Parse ecdhCipherText, mlkemCipherText, and C from encryptedKey encoded as ecdhCipherText || mlkemCipherText || len(C, symAlgId) (|| symAlgId) || C as specified in Section 5.3.1, where symAlgId is present only in the case of a v3 PKESK.

7. Compute (ecdhKeyShare) = ECDH-KEM.Decaps(ecdhCipherText, ecdhSecretKey)

8. Compute (mlkemKeyShare) = ML-KEM.Decaps(mlkemCipherText, mlkemSecretKey)

9. Compute KEK = multiKeyCombine(mlkemKeyShare, ecdhKeyShare, ecdhCipherText, ecdhPublicKey, algId) as defined in Section 5.2.1

10. Compute sessionKey = AESKeyUnwrap(KEK, C) with AES-256 as per [RFC3394], aborting if the 64 bit integrity check fails

11. Output sessionKey

5.3. Packet Specifications

5.3.1. Public-Key Encrypted Session Key Packets (Packet Type ID 1)

The algorithm-specific fields consist of the output of the encryption procedure described in Section 5.2.3:

* A fixed-length octet string representing an ECDH ephemeral public key in the format associated with the curve as specified in Section 5.1.1.

* A fixed-length octet string of the ML-KEM ciphertext, whose length depends on the algorithm ID as specified in Table 5.

* A one-octet size of the following fields.

* Only in the case of a v3 PKESK packet: a one-octet symmetric algorithm identifier.

* The wrapped session key represented as an octet string.

Note that like in the case of the algorithms X25519 and X448 specified in [RFC9580], for the ML-KEM composite schemes, in the case of a v3 PKESK packet, the symmetric algorithm identifier is not encrypted. Instead, it is placed in plaintext after the mlkemCipherText and before the length octet preceding the wrapped session key. In the case of v3 PKESK packets for ML-KEM composite schemes, the symmetric algorithm used MUST be AES-128, AES-192 or AES-256 (algorithm ID 7, 8 or 9).

In the case of a v3 PKESK, a receiving implementation MUST check if the length of the unwrapped symmetric key matches the symmetric algorithm identifier, and abort if this is not the case.

Implementations MUST NOT use the obsolete Symmetrically Encrypted Data packet (Packet Type ID 9) to encrypt data protected with the algorithms described in this document.

5.3.2. Key Material Packets

The composite ML-KEM + ECDH schemes defined in this specification MUST be used only with v6 keys, as defined in [RFC9580], or newer versions defined by updates of that document.

5.3.2.1. Public Key Packets (Packet Type IDs 6 and 14)

The algorithm-specific public key is this series of values:

* A fixed-length octet string representing an ECC public key, in the point format associated with the curve specified in Section 5.1.1.

* A fixed-length octet string containing the ML-KEM public key, whose length depends on the algorithm ID as specified in Table 5.

5.3.2.2. Secret Key Packets (Packet Type IDs 5 and 7)

The algorithm-specific secret key is these two values:

* A fixed-length octet string of the encoded ECDH secret key, whose encoding and length depend on the algorithm ID as specified in Section 5.1.1.

* A fixed-length octet string containing the ML-KEM secret key in seed format, whose length is 64 octets (compare Table 5). The seed format is defined in accordance with Section 3.3 of [FIPS-203]. Namely, the secret key is given by the concatenation of the values of d and z, generated in steps 1 and 2 of ML-KEM.KeyGen [FIPS-203], each of a length of 32 octets. Upon parsing the secret key format, or before using the secret key, for the expansion of the key, the function ML-KEM.KeyGen_internal [FIPS-203] has to be invoked with the parsed values of d and z as input.

6. Composite Signature Schemes

6.1. Building Blocks

6.1.1. ECDSA-Based Signatures

To sign and verify with ECDSA the following operations are defined:

```
(ecdsaSignatureR, ecdsaSignatureS) <- ECDSA.Sign(ecdsaSecretKey,
                                                 dataDigest)
```

and

```
(verified) <- ECDSA.Verify(ecdsaPublicKey, dataDigest,
                           ecdsaSignatureR, ecdsaSignatureS)
```

Here, the operation ECDSA.Sign() is defined as the algorithm in Section "6.4.1 ECDSA Signature Generation Algorithm" of [SP800-186-5], however, excluding Step 1: H = Hash(M) in that algorithm specification, as in this specification the message digest H is a direct input to the operation ECDSA.Sign(). Equivalently, the operation ECDSA.Sign() can be understood as representing the algorithm under Section "4.2.1.1. Signature Algorithm" in [TR-03111], again with the difference that in this specification the message digest H_Tau(M) appearing in Step 5 of the algorithm specification is the direct input to the operation ECDSA.Sign() and thus the hash computation is not carried out. The same statement holds for the definition of the verification operation ECDSA.Verify(): it is given either through the algorithm defined in Section "6.4.2 ECDSA Signature Verification Algorithm" of [SP800-186-5] omitting the message digest computation in Step 2 or by the algorithm in Section "4.2.1.2. Verification Algorithm" of [TR-03111] omitting the message digest computation in Step 3.

The public keys MUST be encoded in SEC1 format as defined in section Section 2.1.1. The secret key, as well as both values R and S of the signature MUST each be encoded as a big-endian integer in a fixed-length octet string of the specified size.

The following table describes the ECDSA parameters and artifact lengths:

	NIST P-384	NIST-P-521	brainpoolP384r1	brainpoolP512r1
Algorithm ID reference	104	105	106	107
Field size	48 octets	66 octets	48 octets	64 octets
Public key	97 octets	133 octets	97 octets	129 octets
Secret key	48 octets	66 octets	48 octets	64 octets
Signature value R	48 octets	66 octets	48 octets	64 octets
Signature value S	48 octets	66 octets	48 octets	64 octets

Table 7: ECDSA parameters and artifact lengths

6.1.2. ML-DSA Signatures

Throughout this specification ML-DSA refers to the default pure and hedged version of ML-DSA defined in [FIPS-204].

ML-DSA signature generation is performed using the default hedged version of the ML-DSA.Sign algorithm, as specified in [FIPS-204], with an empty context string ctx. That is, to sign with ML-DSA the following operation is defined:

```
(mldsaSignature) <- ML-DSA.Sign(mldsaSecretKey, dataDigest)
```

ML-DSA signature verification is performed using the ML-DSA.Verify algorithm, as specified in [FIPS-204], with an empty context string ctx. That is, to verify with ML-DSA the following operation is defined:

```
(verified) <- ML-DSA.Verify(mldsaPublicKey, dataDigest, mldsaSignature)
```

ML-DSA has the parametrization with the corresponding artifact lengths in octets as given in Table 8. All artifacts are encoded as defined in [FIPS-204].

	ML-DSA-65	ML-DSA-87
Algorithm ID reference	104, 106	105, 107
Public key	1952 octets	2592 octets
Secret key	32 octets	32 octets
Signature	3309 octets	4627 octets

Table 8: ML-DSA parameters and artifact lengths

6.2. Composite Signature Schemes with ML-DSA

6.2.1. Key Generation Procedure

The implementation MUST generate the ML-DSA and the ECDSA component keys independently. ML-DSA key generation follows the specification in [FIPS-204] and the artifacts are encoded as fixed-length octet strings whose sizes are listed in Section 6.1.2. ECDSA key generation follows the specification in [SP800-186] or [RFC5639], and the artifacts are encoded as fixed-length octet strings whose sizes are listed in Section 6.1.1.

6.2.2. Signature Generation

To sign a message M with ML-DSA + ECDSA the following sequence of operations has to be performed:

1. Generate dataDigest according to Section 5.2.4 of [RFC9580]

2. Create the ECDSA signature over dataDigest with ECDSA.Sign() from Section 6.1.1

3. Create the ML-DSA signature over dataDigest with ML-DSA.Sign() from Section 6.1.2

4. Encode the ECDSA and ML-DSA signatures according to the packet structure given in Section 6.3.1

6.2.3. Signature Verification

To verify an ML-DSA + ECDSA signature the following sequence of operations has to be performed:

1. Verify the ECDSA signature with ECDSA.Verify() from Section 6.1.1

2. Verify the ML-DSA signature with ML-DSA.Verify() from Section 6.1.2

As specified in Section 4.2 an implementation MUST validate both signatures, that is, ECDSA and ML-DSA, successfully to state that a composite ML-DSA + ECDSA signature is valid.

6.3. Packet Specifications

6.3.1. Signature Packet (Packet Type ID 2)

The composite ML-DSA + ECDSA schemes MUST be used only with v6 signatures, as defined in [RFC9580], or newer versions defined by updates of that document.

The algorithm-specific v6 signature parameters for ML-DSA + ECDSA signatures consist of:

* A fixed-length octet string of the big-endian encoded ECDSA value R, whose length depends on the algorithm ID as specified in Table 7.

* A fixed-length octet string of the big-endian encoded ECDSA value S, whose length depends on the algorithm ID as specified in Table 7.

* A fixed-length octet string of the ML-DSA signature value, whose length depends on the algorithm ID as specified in Table 8.

A composite ML-DSA + ECDSA signature MUST use a hash algorithm with a digest size of at least 256 bits for the computation of the message digest. A verifying implementation MUST reject any composite ML-DSA + ECDSA signature that uses a hash algorithm with a smaller digest size.

6.3.2. Key Material Packets

The composite ML-DSA + ECDSA schemes MUST be used only with v6 keys, as defined in [RFC9580], or newer versions defined by updates of that document.

6.3.2.1. Public Key Packets (Packet Type IDs 6 and 14)

The algorithm-specific public key for ML-DSA + ECDSA keys is this series of values:

* A fixed-length octet string representing the ECDSA public key in SEC1 format, as specified in section Section 2.1.1, whose length depends on the algorithm ID as specified in Table 7.

* A fixed-length octet string containing the ML-DSA public key, whose length depends on the algorithm ID as specified in Table 8.

6.3.2.2. Secret Key Packets (Packet Type IDs 5 and 7)

The algorithm-specific secret key for ML-DSA + ECDSA keys is this series of values:

* A fixed-length octet string representing the ECDSA secret key as a big-endian encoded integer, whose length depends on the algorithm ID as specified in Table 7.

* A fixed-length octet string containing the ML-DSA secret key in seed format, whose length is 32 octets (compare Table 8). The seed format is defined in accordance with Section 3.6.3 of [FIPS-204]. Namely, the secret key is given by the value xi generated in step 1 of ML-DSA.KeyGen [FIPS-204]. Upon parsing the secret key format, or before using the secret key, for the expansion of the key, the function ML-DSA.KeyGen_internal [FIPS-204] has to be invoked with the parsed value of xi as input.

7. Security Considerations

The following security considerations given in [I-D.draft-ietf-openpgp-pqc] equally apply to this document:

* the security aspects of composite signatures (Section 9.1 in [I-D.draft-ietf-openpgp-pqc]),

* the arguments for the security features of the KEM combiner given in Section 9.2 of [I-D.draft-ietf-openpgp-pqc], as also the NIST and Brainpool curves represent nominal groups according to [ABH_21],

* the considerations regarding domain separation and context binding for the KEM combiner (Section 9.2.1 in [I-D.draft-ietf-openpgp-pqc]),

* the use of the hedged variant of ML-DSA (Section 9.3 in [I-D.draft-ietf-openpgp-pqc]),

* the minimum digest size for PQ/T signatures (Section 9.4 in [I-D.draft-ietf-openpgp-pqc]),

* the use of symmetric encryption in SEIPD packets (Section 9.5 in [I-D.draft-ietf-openpgp-pqc]),

* and key generation for composite schemes (Section 9.6 in [I-D.draft-ietf-openpgp-pqc]).

When implementing or using any of the algorithms defined in this specification, the above referenced security considerations should be noted.

8. IANA Considerations

IANA is requested to add the algorithm IDs defined in Table 9 to the existing registry OpenPGP Public Key Algorithms. The field specifications enclosed in brackets for the ML-KEM + ECDH composite algorithms denote fields that are only conditionally contained in the data structure.

[Note: Once the working group has agreed on the actual algorithm choice, the following table with the requested IANA updates will be filled out.]

ID	Algorithm	Public Key Format	Secret Key Format	Signature Format	PKESK Format	Reference
TBD	ML-KEM-768+ECDH-NIST-P-384	97 octets ECDH public key (Table 3), 1184 octets ML-KEM-768 public key (Table 5)	48 octets ECDH secret key (Table 7), 64 octets ML-KEM-768 secret key (Table 5)	N/A	97 octets ECDH ciphertext, 1088 octets ML-KEM-768 ciphertext, 1 octet remaining length, [1 octet algorithm ID in case of v3 PKESK,] n octets wrapped session key (Section 5.3.1)	Section 5.2
TBD	ML-KEM-1024+ECDH-NIST-	133 octets	64 octets	N/A	133 octets ECDH	Section 5.2

	P-521	ECDH public key (Table 3), 1568 octets ML-KEM-768 public key (Table 5)	ECDH secret key (Table 3), 64 octets ML-KEM-1024 secret key (Table 5)		ciphertext, 1568 octets ML-KEM-1024 ciphertext, 1 octet remaining length, [1 octet algorithm ID in case of v3 PKESK,] n octets wrapped session key (Section 5.3.1)	
TBD	ML-KEM-768+ECDH-brainpoolP384r1	97 octets ECDH public key (Table 4), 1184 octets ML-KEM-768 public key (Table 5)	48 octets ECDH secret key (Table 4), 64 octets ML-KEM-768 secret key (Table 5)	N/A	97 octets ECDH ciphertext, 1088 octets ML-KEM-768 ciphertext, 1 octet remaining length, [1 octet algorithm ID in case of v3 PKESK,] n octets wrapped session key (Section 5.3.1)	Section 5.2
TBD	ML-KEM-1024+ECDH-brainpoolP512r1	129 octets ECDH public key (Table 4), 1568 octets ML-KEM-768 public	64 octets ECDH secret key (Table 4), 64 octets ML-KEM-1024 secret key	N/A	129 octets ECDH ciphertext, 1568 octets ML-KEM-1024 ciphertext, 1 octet remaining length, [1 octet algorithm ID in case of	Section 5.2

		key (Table 5)	(Table 5)		v3 PKESK,] n octets wrapped session key (Section 5.3.1)	
TBD	ML-DSA-65+ECDSA-NIST-P-384	97 octets ECDSA public key (Table 7), 1952 octets ML-DSA-65 public key (Table 8)	48 octets ECDSA secret key (Table 7), 32 octets ML-DSA-65 secret key (Table 8)	96 octets ECDSA signature Table 7 , 3309 octets ML-DSA-65 signature (Table 8)	N/A	Section 6.2
TBD	ML-DSA-87+ECDSA-NIST-P-521	133 octets ECDSA public key (Table 7), 2592 octets ML-DSA-87 public key (Table 8)	66 octets ECDSA secret key (Table 7), 32 octets ML-DSA-87 secret key (Table 8)	132 octets ECDSA signature Table 7 , 4627 octets ML-DSA-87 signature (Table 8)	N/A	Section 6.2
TBD	ML-DSA-65+ECDSA-brainpoolP384r1	97 octets ECDSA public key (Table 7), 1952 octets	48 octets ECDSA secret key (Table 7), 32 octets ML-	96 octets ECDSA signature Table 7 , 3309 octets ML-DSA-65 signature (Table 8)	N/A	Section 6.2

		ML-DSA-65 public key (Table 8)	DSA-65 secret key (Table 8)			
TBD	ML-DSA-87+ECDSA-brainpoolP512r1	129 octets ECDSA public key (Table 7), 2592 octets ML-DSA-87 public key (Table 8)	64 octets ECDSA secret key (Table 7), 32 octets ML-DSA-87 secret key (Table 8)	128 octets ECDSA signature Table 7 , 4627 octets ML-DSA-87 signature (Table 8)	N/A	Section 6.2

Table 9: IANA updates for registry 'OpenPGP Public Key Algorithms'

IANA is asked to add the following note to this registry:

> The field specifications enclosed in square brackets for PKESK Format represent fields that may or may not be present, depending on the PKESK version.

9. Changelog

This section gives the history of changes in the respective document versions. The order is newest first.

9.1. draft-ietf-openpgp-nist-bp-comp-02

* Updated algorithm selection and assigned experimental code points 100-107.

* Added test vectors.

9.2. draft-ietf-openpgp-nist-bp-comp-01

* Editorial alignment to [I-D.draft-ietf-openpgp-pqc].

9.3. draft-ietf-openpgp-nist-bp-comp-00

* Changed draft title.

9.4. draft-ehlen-openpgp-nist-bp-comp-02

* Completed the IANA table.
* Added "Security Considerations" section.
* Alignment of various technical details to [I-D.draft-ietf-openpgp-pqc].
* Various editorial alignments to [I-D.draft-ietf-openpgp-pqc].

9.5. draft-ehlen-openpgp-nist-bp-comp-01

* Replaced the explicit description of the KEM combiner with a reference to [I-D.draft-ietf-openpgp-pqc].

10. Contributors

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11.1. Normative References

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Appendix A. Test Vectors

A.1. Sample ML-DSA-65+ECDSA-NIST-P-384 with ML-KEM-768+ECDH-NIST-P-384 Data

A.1.1. Transferable Secret Key

Here is a Transferable Secret Key consisting of:

* A v6 ML-DSA-65+ECDSA-NIST-P-384 Private-Key packet
* A v6 direct key self-signature
* A User ID packet
* A v6 positive certification self-signature
* A v6 ML-KEM-768+ECDH-NIST-P-384 Private-Subkey packet
* A v6 subkey binding signature

The primary key has the fingerprint a3f3ea658b8324df76694581f4f6fede3e15bb0b67c7520255d2f7868208d756.

The subkey has the fingerprint 16addcbd549eb8c4153c9626b6aa4dac17adeac4f79c54dfcbe4aabaa28aba1b.


```
-----BEGIN PGP PRIVATE KEY BLOCK-----

xcecBmkMvEloAAAIAQT0a2nu+EbqUwOY2HhES+b5S+JyET4F2T3HBwn7W4NIhAWEv6b26yV0WCix
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apjGA9F1QQEkqTZKiiN3bw9gdHeI0HUAFCOHpKVFMVvjVzVWrMTFsII/GoRvZePL/gmftMqCOglo
urGYYElZAf6FZCUfucsgM+mUKDvZE1ghk+hFiXTUAkLnWaI5Q5idQ1FgysrlxQnG5pGxwz6YM+Zy
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```

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A.1.2. Transferable Public Key

Here is the corresponding Transferable Public Key for Appendix A.1.1 consisting of:

* A v6 ML-DSA-65+ECDSA-NIST-P-384 Public-Key packet

* A v6 direct key self-signature

* A User ID packet

* A v6 positive certification self-signature

* A v6 ML-KEM-768+ECDH-NIST-P-384 Public-Subkey packet

* A v6 subkey binding signature

-----BEGIN PGP PUBLIC KEY BLOCK-----

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=Ntbm
-----END PGP PUBLIC KEY BLOCK-----
```


A.1.3. Encrypted and Signed Message

Here is a signed message "Testing\n" encrypted to the certificate Appendix A.1.2 and signed by the secret key Appendix A.1.1:

* A v6 PKESK

* A v2 SEIPD

The hex-encoded mlkemKeyShare input to multiKeyCombine is 26da669cc569a460708f96b0e4132488c2f990b931a7fa4e02625f3f4293e7b5.

The hex-encoded ecdhKeyShare input to multiKeyCombine is b1564c7701bd f47ac5825908aac109cd4fafa0c528beefe73be02248dff8f2665e8e01d38fd17424a f32c8acaabdfe17.

The hex-encoded output of multiKeyCombine is ea93bb3825128c37f318018d74867cdb451317ae3fa6b64da0eca7931cd8bd7c.

The hex-encoded session key is
0c251def2936896735f8903bf6382d822e6aa3791104b1a2da02e142a10dc38f.

-----BEGIN PGP MESSAGE-----

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-----END PGP MESSAGE-----
```

A.2. Sample ML-DSA-87+ECDSA-NIST-P-521 with ML-KEM-1024+ECDH-NIST-P-521 Data

A.2.1. Transferable Secret Key

Here is a Transferable Secret Key consisting of:

* A v6 ML-DSA-87+ECDSA-NIST-P-521 Private-Key packet

* A v6 direct key self-signature

* A User ID packet

* A v6 positive certification self-signature

* A v6 ML-KEM-1024+ECDH-NIST-P-521 Private-Subkey packet

* A v6 subkey binding signature

The primary key has the fingerprint
e3674a3dcbfc35fcc24b1cd7f55213a3866d17b6081c3ad5933af3d78e8c8bce.

The subkey has the fingerprint
c22c679c40289df8111fda26f1cc8eca6c08dcbc8e20ceaac7e6b7ddd3b040bb.

-----BEGIN PGP PRIVATE KEY BLOCK-----

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-----END PGP PRIVATE KEY BLOCK-----
```


A.2.2. Transferable Public Key

Here is the corresponding Transferable Public Key for Appendix A.2.1 consisting of:

* A v6 ML-DSA-87+ECDSA-NIST-P-521 Public-Key packet

* A v6 direct key self-signature

* A User ID packet

* A v6 positive certification self-signature

* A v6 ML-KEM-1024+ECDH-NIST-P-521 Public-Subkey packet

* A v6 subkey binding signature

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-----BEGIN PGP PRIVATE KEY BLOCK-----
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=3uab
-----END PGP PRIVATE KEY BLOCK-----

A.2.3. Encrypted and Signed Message

Here is a signed message "Testing\n" encrypted to the certificate Appendix A.2.2 and signed by the secret key Appendix A.2.1:

* A v6 PKESK

* A v2 SEIPD

The hex-encoded mlkemKeyShare input to multiKeyCombine is cd8a9216c981c151843d48ce17a30cb69f01373c35032d313ce34244cbaa0e35.

The hex-encoded ecdhKeyShare input to multiKeyCombine is 016ca7330ea0 a216376803717001269aeb8a94083b20bb3a1a709f8aeb322219759d9ff7872bab303 e357f78507d423f59d3e2206e67537aba75280ca7937e250b5b.

The hex-encoded output of multiKeyCombine is 6c514547454fbb8ff7308c80d79f59d1cde7d99a2fe2a2a1ac4e31114906b186.

The hex-encoded session key is 371de99d254c0a0d4ee2c1b63d2a4956bbfe84cdafa4b264dcc59b80ece9d8f4.

-----BEGIN PGP MESSAGE-----

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-----END PGP MESSAGE-----

A.3. Sample ML-DSA-65+ECDSA-brainpoolP384r1 with ML-KEM-768+ECDH-brainpoolP384r1 Data

A.3.1. Transferable Secret Key

Here is a Transferable Secret Key consisting of:

* A v6 ML-DSA-65+ECDSA-brainpoolP384r1 Private-Key packet

* A v6 direct key self-signature

* A User ID packet

* A v6 positive certification self-signature

* A v6 ML-KEM-768+ECDH-brainpoolP384r1 Private-Subkey packet

* A v6 subkey binding signature

The primary key has the fingerprint
6a498c10ff01ddfb1c28d0af05afe75d4c0e625d73fe8ab3cca227bd162d57b7.

The subkey has the fingerprint
408b08b20df93c6abdefb25d87a642766e6455caac621e8ca8204234de7bdedb.

-----BEGIN PGP PRIVATE KEY BLOCK-----

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-----END PGP PRIVATE KEY BLOCK-----
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A.3.2. Transferable Public Key

Here is the corresponding Transferable Public Key for Appendix A.3.1 consisting of:

* A v6 ML-DSA-65+ECDSA-brainpoolP384r1 Public-Key packet
* A v6 direct key self-signature
* A User ID packet
* A v6 positive certification self-signature
* A v6 ML-KEM-768+ECDH-brainpoolP384r1 Public-Subkey packet
* A v6 subkey binding signature

-----BEGIN PGP PRIVATE KEY BLOCK-----

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rZ5Qfsk3X3/gLqPwcrZ4p5S/JghARSW4fNTkIlBj7/d/bctGf4tIEbLsvoNY51ghZ3tFiylqTMo9
KKC/XsCsm5hli2w/Bgayzrvu6cFOeY2utKwR9QY7ZItFMuTduTnQZQPZhDvRiUxFudmVKKOd35jn
YGJBjn+3TTwCHGxWUfWTqN7XtXk8pyH71j+EV5OasV0/6rEZQTn7zrJf+AqjvgroT6u54CuJQBH/
LCOLjbhtmMw8dLYOFm0ewwD23TYngy1rFRQtLtZYjL73A1LXKPP2FVoOzsaZb1mnm9c2UoD1bF6y
qDD1KD0Kwrh3XQNjAdMk8Uji7VFX/gbh3y/VGCaPR5jdES0/XWxMipdHYgfpfCWASUI/dSj7wzDB
8+RyrFUagCL5spzJi/FEIv7mThHJs8ofUX7nSIXKU459TztNzW/9yJ4Rx5eEZObYcs9B6oZzam+4
iA5VchGK474m2soC6tWZFNsdis6hP0ctU/m+JcyyXatl9ShTFI/IvjnBfJg2Bz6zxNYjN8du4uCV
gBhoFH6n+y7JDfO3pSoZnYDozeneV1eM+lNaIBTwGZ+REf7VXDrFGfRLIpXauBG90Zr5XCGMB0co
OD1jlZC7cPXeeqYPklGxfkufI6Cox0y4XNu6JlmUkqRXGtt7BAH+eo0uVVJBbHogi107kWKnGGdG
pOLc096j095tTQ6FhHUCIyWnew1urATgTPxMDBsn8nhfSoXXCHdDo5u+RVzHkUt+2bjmcQg2ohoV
RAKuf9hRXApLe6bMouHPuhrigmoiEynbW4RqECHR2JpaG/EgMaC1vNVatYrzAOG3XRJlwcFWd5Q8
rhsK+wxEuFAGT9XFoiJLpp+1ItLOHtxuDTmT1mePdV0tyjN1prpjADAXcx4M8WZUGVnkmbbzHN2V
BqXIze5FW9Rbt7VmdpeBo3yTJGmXGOQJEOtv+1cGTqn16le27VGi7zG+uhW07nVVGB0uUxMo/jCr
gTtaaOmTlyZUGz46CBkgPMpG7+59aQto6IC345nNklXlU7PqDg5/vVh0/oElzQjt1Qw18U+olTVb
4g1QQdDY/jdTsI3L/5ieFR12yOceldCo51FHU41bAoALXlq/xu2ESpDbqyXB5fG9lVeUegpGkzSK
XzfTaifQ2VI8NARjnmxzQxLXru9vnGGoXi04TKWkuEOhpKEdURQdV+IS7V9ynLa8zfgZNOX9Nz5O
auwgRHKA8/kVI4Wn81JjZ8sAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAABgoPFRoe
=uvYO
-----END PGP PRIVATE KEY BLOCK-----
```


A.3.3. Encrypted and Signed Message

Here is a signed message "Testing\n" encrypted to the certificate Appendix A.3.2 and signed by the secret key Appendix A.3.1:

* A v6 PKESK

* A v2 SEIPD

The hex-encoded mlkemKeyShare input to multiKeyCombine is 1eaa02a4cd82d01573d84c6e1326c19fe8d3cc6bca297e6525a7d84faff68cdf.

The hex-encoded ecdhKeyShare input to multiKeyCombine is 0521a1adda54 0cc7b8589dc9cbe360d51139b3b1fc58f6b4a452baa2ec16022027b3495c04c4abb34 e8bbd603d0ebeb7.

The hex-encoded output of multiKeyCombine is ed4010d69f98dc64db6df1d9d59331708057b8027ea0336c03bad6ea3990b25a.

The hex-encoded session key is
b89c0629753f9e849a2bb176ba564fb7c674aecbe1f9c1d7f71001533871c20b.


```
-----BEGIN PGP MESSAGE-----

wcQuBiEGQIsIsg35PGq977Jdh6ZCdm5kVcqsYh6MqCBCNN573ttmBBFZqGpSy8S5nQFvq+HGrEBG
Gh22tXYqADb0i0aUjIEmGccFwTJWNr1K2vfccIZebIuYSt0dCfvepP3WTe5FVr2ReGBs7nUva6yH
vmf2QqZoOXRzHVQiRqh8KnAx/MH2dVew3mHiIBAZN/lQAj0irDrju1Jftql13ruHYytUNsfVqVMq
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+ZBPX2MdYXvH8jMgxn3pZuM7r+n1A6kz9qWlkLLR2/CvzGaP89i7b04YnrEK4Jw1IyqnxVVBMgQh
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P2GO0zuTFkdnKv/Nszl07ucl2R/kb1G0gT2pHhLDISRoCi8z5rJYpvhbttEhO3YLN3skdCl+K3Mc
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```

```
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bEDZ98gj5+nxo7Bg7QMceYE5n390x2mNMRK63xxUdei/HAum2nxphtlSOy2ZoKcONiiLUzSiBQYR
DXU9vHl8R0tl4F2BR5xFA77x85d8UaTGsD/GCkPZinmefQYlWsJVzJ4tFIiSX4f59H54QiownjK2
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BTMhovEZSUJtKQn/cKHDu+D0FWh9kKCm8agBbpyyKcoIu8V6nqa3yL0rbZKbyW3VhQ/3QNafA1gG
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sDWg3p1v1sN4e2Vp4M2+x4IKRjY3zrmiyl5mub+c+GBT5T/UEMEUji8fUfAAnyPyGKqHC0TBBjEC
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=gXse
-----END PGP MESSAGE-----
```

A.4. Sample ML-DSA-87+ECDSA-brainpoolP512r1 with ML-KEM-1024+ECDH-brainpoolP512r1 Data

A.4.1. Transferable Secret Key

Here is a Transferable Secret Key consisting of:

* A v6 ML-DSA-87+ECDSA-brainpoolP512r1 Private-Key packet

* A v6 direct key self-signature

* A User ID packet

* A v6 positive certification self-signature

* A v6 ML-KEM-1024+ECDH-brainpoolP512r1 Private-Subkey packet

* A v6 subkey binding signature

The primary key has the fingerprint b89e98c38b82bf6f859e7d259bc4d4526c7e6f3448a0b82d0dbe580e3278dba3.

The subkey has the fingerprint 033fa728eb4a55a4d59a0496e51c90b67f70846de0ed3cdfb8f28124ec90d3fd.

-----BEGIN PGP PRIVATE KEY BLOCK-----

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-----END PGP PRIVATE KEY BLOCK-----
```


A.4.2. Transferable Public Key

Here is the corresponding Transferable Public Key for Appendix A.4.1 consisting of:

* A v6 ML-DSA-87+ECDSA-brainpoolP512r1 Public-Key packet

* A v6 direct key self-signature

* A User ID packet

* A v6 positive certification self-signature

* A v6 ML-KEM-1024+ECDH-brainpoolP512r1 Public-Subkey packet

* A v6 subkey binding signature

-----BEGIN PGP PRIVATE KEY BLOCK-----

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-----END PGP PRIVATE KEY BLOCK-----

A.4.3. Encrypted and Signed Message

Here is a signed message "Testing\n" encrypted to the certificate Appendix A.4.2 and signed by the secret key Appendix A.4.1:

* A v6 PKESK

* A v2 SEIPD

The hex-encoded mlkemKeyShare input to multiKeyCombine is 66c0163a0f68f7b783b58cae6feeb4d2d6ad9b99cd2a7ac311fb78fdc42055c8.

The hex-encoded ecdhKeyShare input to multiKeyCombine is 83662068efed 595bbf0f3857bf2d31b4b1c85c1252803761758979819cbb060b0576cef35b3784913 bf5a6fed92641bf0fd726f0dac4b137a7830a23e6adc070.

The hex-encoded output of multiKeyCombine is ee6aa72fb27d4a5b6399761610ea0b52aadc391ead369656e3f5d136752d0bb9.

The hex-encoded session key is 3fed681f8c216acbf665591f8b4618b455f8652c31f329664127a26b7677263e.

-----BEGIN PGP MESSAGE-----

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