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Original Article

Solvability of certain exponential Lebesgue-Nagell equations $x^2 + p^m = y^n$

Patcharee Wongsason[1] and Sawian Jaidee[2*]

[1] *Department of Mathematics Statistics and Computer, Faculty of Science, Ubon Ratchathani University, Warin Chamrap, Ubon Ratchathani, 34190 Thailand*

[2] *Department of Mathematics, Faculty of Science, Khon Kaen University, Mueang, Khon Kaen, 40002 Thailand*

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Abstract

In this article, we first investigate the exponential Lebesgue-Nagell equation as shown in the title. Eventually, we can establish a necessary and sufficient criterion for having an integer solution to such an equation under the conditions that $p \equiv 3 \pmod 4$ and $n \equiv 1 \pmod 4$. The unique factorization in the ring of Gaussian integers, the existence of primitive divisors of the Lehmer sequences, and also the MAGMA program are the essentials applied in this work.

Keywords: exponential Lebesgue-Nagell equations, Gaussian integers, unique factorization, Lehmer sequences, primitive divisors

1. Introduction

Let C be a nonzero integer and n be an integer greater than 2. The Diophantine equation

$$x^2 + C = y^n \quad (1)$$

is the so-called *generalized Ramanujan-Nagell equation*. There is a very broad literature on studying such an equation, which always has finitely many positive integer solutions (Landau & Ostrowski, 1920). The explorations on finding an integer solution to this equation can be studied more in (Bureaud, Mignotte & Siksek, 2006; Cohn, 1993), and these contain early results in the case when C is a fixed integer. Many authors have been interested over the year in the case $C = p^m$ when p is a fixed prime number (Arif & Muriefah, 1997, 1998, 1999, 2006) or even a general prime number (Arif & Muriefah, 2002; Bérczes & Pink, 2008; Le, 2003; Lin Zhu, 2011; Xiaowei, 2013). More generally, the case of C consisting of a product of prime powers p^m, where p belongs to some fixed finite set of primes, has recently been investigated by several mathematicians (Luca, 2002; Luca & Togbcé, 2008, 2009; Pink, 2007; Pink & Rábai, 2011; Soydan & Tzanakis, 2016; Lin Zhu, Le, & Soydan, 2015).

Our interest in this paper focuses on equation (1) in the case $C = p^m$ when p is a prime number and m is a natural number. This specific equation type is known as *the exponential Lebesgue-Nagell equation*. Now, we will divide our discussion about some results concerning our considered equation into 2 cases, namely for m being odd or even:

Case A: Let $m = 2k + 1$, where k is a positive integer, p be odd such that $p \not\equiv 7 \pmod 8$, and $n > 3$ be an odd integer with $\gcd(n, h) = 1$, where h is the class number of the number field $\mathbb{Q}(\sqrt{-p})$. Arif and Abu Muriefah demonstrated in Arif and Muriefah (1998) that the equation $x^2 + 3^m = y^n$ has the unique positive integral solution given by $n = 3$, $m = 5 + 6N$, $x = 10 \times 3^{3N}$, $y = 7 \times 3^{2N}$ when N is one-third of the highest power of 3 which divides x. In 2002, they also proved that the equation $x^2 + p^{2k+1} = y^n$, where $\gcd(p, x) = 1$ and $n \geq 5$ is not a multiple of 3, has exactly two families of solutions given by

*Corresponding author
Email address: jsawia@kku.ac.th

$$p = 19, n = 5, k = 5M, x = 22434 \times 19^{5M}, y = 55 \times 19^{2M} \text{ and}$$
$$p = 341, n = 5, k = 5M, x = 2759646 \times 341^{5M}, y = 377 \times 19^{2M}$$

when M is one - fifth of the highest power of p which divides x. This work can be found in (Arif & Muriefah, 2002). In addition, all the integer solutions to the equation $x^2 + q^m = y^3$ consist of exactly one solution $(q, k, x, y) = (11, 1, 9324, 443)$ due to (Lin Zhu, 2011).

Case B: Let $m = 2k$, where k is a positive integer. Bérczes and Pink showed in Bérczes and Pink (2008) that all integer solutions to the equation $x^2 + p^{2k} = y^n$ are

$$(x, y, p, n, k) = (11,5,2,3,1), (46,13,3,3,2), (524,65,7,3,1), (2,5,11,3,1),$$
$$(278, 5, 29, 7, 1), (38, 5, 41, 5, 1), (52, 17, 47, 3, 1), (1405096, 12545, 97, 3, 1),$$

where i) x, y, n, k are unknown integers satisfying $x \geq 5$ $y > 1$, $n \geq 3$ is a prime and $k \geq 0$ with $\gcd(x, y) = 1$, and ii) $2 < p < 100$. Observe that the equation $x^2 + p^2 = y^n$ has no integer solution (x, y, p, n) when n is a prime with $p \equiv 3 \pmod 4$ and $n \equiv 1 \pmod 4$ such that $2 < p < 100$.

Being motivated by the works of Bérczes and Pink as mentioned above in the particular case $k = 1$ led us to assert the conjecture that the equation $x^2 + p^2 = y^n$ would have no integer solution when $p \equiv 3 \pmod 4$ and $n \equiv 1 \pmod 4$. Eventually, it turned out that we were able to obtain the following main result.

Theorem 1. Let p and n be a prime number and a natural number greater than 1 satisfying $p \equiv 3 \pmod 4$ and $n \equiv 1 \pmod 4$, respectively. Then the Diophantine equation $x^2 + p^2 = y^n$ has an integer solution (x, y) if and only if

$$-p = \sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (-1)^{n-k-1} b^{2k} \qquad (2)$$

for some even positive integer b such that $b^2 < \left\lceil \frac{\binom{n}{n-3}}{\binom{n}{n-1}} \right\rceil$.

The important tools used to prove this main result are the unique factorization in the ring of Gaussian integers, the existence of primitive divisors of the Lehmer sequences, and the MAGMA program at some points. Indeed, we have explicitly illustrated in (Jaidee & Saosoong, 2022) that the equation $x^2 + p^2 = y^5$ has no integer solution for any prime p with $p \equiv 3 \pmod 4$, without applying the second tool.

2. Preliminaries

In order to complete our main result, let us first give the necessary and sufficient condition for having an integer solution of the Fermat-type equation with signatures $(2,2,n)$ as follows:

Theorem 2. Let n be an integer greater than 1. Then the equation $x^2 + y^2 = z^n$ with $\gcd(x, y) = 1$ has an integer solution if and only if the equation

$$x + yi = u(a + bi)^n \qquad (3)$$

has an integer solution (x, y, a, b) for some $u \in \{\pm i, \pm 1\}$.

To prove Theorem 2, we need Lemma 1 and Lemma 2 below. The first lemma is easily proven by applying the unique factorization in the ring of Gaussian integers. In fact, this lemma is true for any unique factorization domain and also for its advanced analogue in the unique prime ideal factorization appearing in the book written by Alaca and Kenneth (2004).

Lemma 1. Let n be any natural number and α, β and γ be nonzero and nonunit Gaussian integers such that β and γ are coprime. If $\alpha^n = \beta\gamma$, then there exist β_1, γ_1 and unit elements u, v in Gaussian integers for which $\beta = u\beta_1$ and $\gamma = v\gamma_1$ where β_1 and γ_1 are coprime.

Lemma 2. Let n be a natural number greater than 2. If the equation $x^2 + y^2 = z^n$ has an integer solution (x, y) with $\gcd(x, y) = 1$, then $x + yi$ and $x - yi$ are coprime.

The proof of Lemma 2 may be found in Andreescu, Andrica, and Cucurezeanu (2010). Instead of being arbitrary integer y in the necessary condition stated in Theorem 2, we can choose y as a fixed prime p such that $p \equiv 3 \pmod 4$ in order to apply Theorem 2 specifically as illustrated in the following lemma. Its proof may be seen in Jaidee and Wannalookkhee (2020).

Lemma 3. Let n be a natural number greater than 2, and p be a prime number such that $p \equiv 3 \pmod 4$. If the equation $x^2 + p^2 = y^n$ has an integer solution (x, y), then $\gcd(x, p) = 1$.

Let α and β be algebraic integers for which $(\alpha + \beta)^2$ and $\alpha\beta$ are nonzero coprime rational integers, and $\frac{\alpha}{\beta}$ is not a root of unity. For each natural number n , we call

$$\tilde{u}_n = \tilde{u}_n(\alpha, \beta) = \begin{cases} \dfrac{(\alpha^n - \beta^n)}{\alpha - \beta} & \text{if } n \text{ is odd,} \\ \dfrac{(\alpha^n - \beta^n)}{\alpha^2 - \beta^2} & \text{if } n \text{ is even} \end{cases}$$

the Lehmer sequences. A rational prime p is a primitive divisor of $\tilde{u}_n$ if p divides $\tilde{u}_n$ but does not divide $(\alpha^n - \beta^n)^2 \tilde{u}_1 \cdots \tilde{u}_{n-1}$. For instance, if $\alpha = \frac{1+\sqrt{5}}{2}$ and $\beta = \frac{1-\sqrt{5}}{2}$, then the term $\tilde{u}_n$ is the Fibonacci number F_n for any natural number n. These numbers are formed to be the Fibonacci sequence listed as A00045 in the On-Line Encyclopedia of Integer Sequences (OEIS) (Sloane, 2022) begins with

$$F_0 = 0, F_1 = 1, F_2 = 1, F_3 = 2, F_4 = 3, F_5 = 5, F_6 = 8, F_7 = 13, F_8 = 21, F_9 = 34, \ldots.$$

Clearly, F_1, F_2, F_5 and F_6 have no primitive divisors, but F_3, F_4, F_7, F_8 and F_9 have a primitive divisor. The following two theorems taken from (Bureaud, Mignotte, & Siksek, 2006) will play an important key role in the next section.

Theorem 3. For every integer $n > 30$, $\tilde{u}_n(\alpha, \beta)$ has a primitive divisor.

Theorem 4. Let n satisfy $6 < n \leq 30$ and $n \neq 8, 10, 12$. Then all $\tilde{u}_n(\alpha, \beta)$ having no primitive divisors are of the form

$$(\alpha, \beta) = \left(\frac{\sqrt{a} - \sqrt{b}}{2}, \frac{\sqrt{a} + \sqrt{b}}{2}\right),$$

where (a, b, n) are given as follows:

$$(7,1,-7), (7,1,-19), (7,3,-5), (7,5,-7), (7,13,-3), (7,14,-22), (9,5,-3), (9,7,-1), (9,7,-5),$$
$$(13,1,-7), (14,3,-13), (14,5,-3), (14,7,-1), (14,7,-5), (14,19,-1), (14,22,-14), (15,7,-1),$$
$$(15,10,-2), (18,1,-7), (18,3,-5), (18,5,-7), (24,3,-5), (24,5,-3), (26,7,-1), (30,1,-7), (30,2,10).$$

The proof of Theorem 1.

Before showing the proof of Theorem 1, the following facts will be needed.

Theorem 5. There are no natural numbers $a > 1$ and b such that $a \not\equiv b \pmod 2$ and $\gcd(a, b) = 1$ satisfying the equation

$$1 = \sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (a)^{n-2k-1} (-b^2)^k \qquad (4)$$

for any natural number $n > 1$ with $n \equiv 1 \pmod 4$.

Proof. Suppose that there exist natural numbers $a > 1$, b and n such that $a \not\equiv b \pmod 2$ with $\gcd(a, b) = 1$, and $n \equiv 1 \pmod 4$ satisfying the equation (4). Let $\alpha = a + bi$ and $\beta = a - bi$. Following the binomial theorem and the equation (4), we eventually obtain that

$$\alpha^n + \beta^n = 2a = \alpha + \beta.$$

Then we may write

$$\alpha^n + \beta^n = (\alpha + \beta) \left(\frac{\alpha^{2n} - \beta^{2n}}{\alpha^2 - \beta^2}\right) \left(\frac{\alpha - \beta}{\alpha^n - \beta^n}\right).$$

Consequently,

$$\left(\frac{\alpha^{2n} - \beta^{2n}}{\alpha^2 - \beta^2}\right) = \left(\frac{\alpha^n - \beta^n}{\alpha - \beta}\right) \qquad (5)$$

Since α and β are roots of the polynomial equation $X^2 - 2aX + (a^2 + b^2) = 0$, we have that α and β are algebraic integers. Obviously, $(\alpha + \beta)^2$ and $\alpha\beta$ are coprime. We claim that $\frac{\alpha}{\beta}$ is not a root of unity. Suppose that it is a root of unity, that is, $(\frac{\alpha}{\beta})^m = 1$ for some natural number m. Then, it is a root of the polynomial equation $X^m - 1 = 0$. Since we know that

$$X^m - 1 = \prod_{d|m} \varphi_d(X),$$

there exists a natural number d_0 such that $\varphi_{d_0}(\alpha/\beta) = 0$. Note that $\varphi_d(X)$ is the d^{th} cyclotomic polynomial. One can check that $\frac{\alpha}{\beta}$ is a zero of the polynomial

$$p(X) = X^2 - \frac{2(a^2 - b^2)}{\alpha\beta} X + 1.$$

This implies that the polynomial $\varphi_{d_0}(X)$ must divide $p(X)$ as $\varphi_{d_0}(X)$ is always monic and irreducible. Indeed, $p(X)$ cannot be divided by all possibilities of $\varphi_{d_0}(X)$, a contradiction. Hence $\frac{\alpha}{\beta}$ is not a root of unity. Now, we are able to define $\tilde{u}_n(\alpha,\beta)$ as the Lehmer sequence. From (5), we deduce that the Lehmer sequence $\tilde{u}_{2n}(\alpha,\beta)$ has no primitive divisors for any natural number n. Applying Theorem 3 and Theorem 4 together with the condition $n \equiv 1 \pmod 4$, we eventually find that $\tilde{u}_{2n}(\alpha,\beta)$ has a primitive divisor for any natural number n excluding $n = 5$. This leads to a contradiction. It remains to focus on the case $n = 5$ only. By (4), we have $a^4 - 10a^2b^2 + 5b^4 = 1$. By applying the ThueSolve function in **MAGMA** (Bosma, Cannon, & Playoust, 1997), we know that $(x,y) = (\pm 1, 0)$ are only integer solutions of the Thue equation $x^4 - 10x^2y^2 + 5y^4 = 1$. Again, we have a contradiction. Hence, we have completed the proof of the theorem.

Lemma 4. Let n be a natural number greater than 1 with $n \equiv 1 \pmod 4$. Then

$$\sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (-1)^{n-k-1} b^{2k} \geq 0 \tag{6}$$

for any even positive integer b such that $b^2 \geq \left\lceil \frac{\binom{n}{n-3}}{\binom{n}{n-1}} \right\rceil$.

Proof. Let b be an even positive integer such that $b^2 \geq \left\lceil \frac{\binom{n}{n-3}}{\binom{n}{n-1}} \right\rceil$. Rearranging the summation in (6), we obtain that

$$1 + \binom{n}{4} b^4 + \binom{n}{8} b^8 + \cdots + nb^{n-1} - \left[\binom{n}{2} b^2 + \binom{n}{6} b^6 + \cdots + \binom{n}{n-3} b^{n-3}\right]$$
$$> \binom{n}{4} b^2 \left(b^2 - \left\lceil \frac{\binom{n}{2}}{\binom{n}{4}} \right\rceil\right) + \binom{n}{8} b^6 \left(b^2 - \left\lceil \frac{\binom{n}{6}}{\binom{n}{8}} \right\rceil\right) + \cdots + nb^{n-3} \left(b^2 - \left\lceil \frac{\binom{n}{n-3}}{\binom{n}{n-1}} \right\rceil\right) \geq 0$$

Now, we are ready to prove Theorem 1.

Proof. Let p and n be a prime number and a natural number greater than 1 satisfying $p \equiv 3 \pmod 4$ and $n \equiv 1 \pmod 4$, respectively. For the necessary condition, let us assume that the equation $x^2 + p^2 = y^n$ has an integral solution (x,y), and suppose that the equation (2) is not true for any even positive integer b such that $b^2 < \left\lceil \frac{\binom{n}{n-3}}{\binom{n}{n-1}} \right\rceil$. Applying Lemma 3 and Theorem 2 together with the fact that $u = u^n$ for any $u \in \{\pm i, \pm 1\}$, we eventually obtain that $p + xi = (a+bi)^n$ for some $a, b \in \mathbb{Z}$. Observe that $p - xi = (a - bi)^n$ and recall that $\gcd(x,p) = 1$ and y is odd. Then we have

$$y^n = x^2 + p^2 = (p+xi)(p-xi) = (a^2+b^2)^n,$$

which implies that $y = a^2 + b^2$. If $a \equiv b \pmod 2$, then we have that y is even, which is a contradiction. So, a and b have an opposite parity. Now, we consider

$$p + xi = \left(\sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (-1)^k a^{n-2k} b^{2k}\right) + \left(\sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k+1} (-1)^k a^{n-1-2k} b^{2k+1}\right) i.$$

Then, we have

$$p = a \sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (-1)^k a^{n-2k-1} b^{2k},$$

which implies that $a = \pm 1$ or $a = \pm p$. If $a = 1$, then b must be even.
Since $n \equiv 1 \pmod 4$, it follows that

$$p = 1 - \binom{n}{2} b^2 + \binom{n}{4} b^4 - \cdots + nb^{n-1} \equiv 1 \pmod 4,$$

which is a contradiction. If $a = -1$, then we have that

$$-p = \sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (-1)^{n-k-1} b^{2k},$$

which is impossible by reference to Lemma 4 together with the assumption. If $a = -p$, then b must be even. As $n \equiv 1 \pmod 4$ and $\gcd(4,p) = 1$, we eventually obtain that

$$-1 = p^{n-1} - \binom{n}{2} p^{n-3} b^2 + \binom{n}{4} p^{n-5} b^4 - \cdots + nb^{n-1} \equiv 1 (\text{mod } 4),$$

which is a contradiction. Applying Theorem 5 to the other case leads us to get a contradiction as well. For the sufficient condition, suppose that there exists an even positive integer b_0 for which ${b_0}^2 < \left\lfloor \frac{\binom{n}{n-3}}{\binom{n}{n-1}} \right\rfloor$ and

$$p = -\sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k} (-1)^{n-k-1} a^{n-2k} {b_0}^{2k}.$$

Then we choose

$$x_0 = -\sum_{k=0}^{\frac{n-1}{2}} \binom{n}{2k+1} (-1)^{n-k-1} {b_0}^{2k+1}.$$

It is not hard to see that $(p, x_0, -1, b_0)$ satisfies equation (3) in Theorem 2 for some $u \in \{\pm i, \ \pm 1\}$. Hence, we have completed the proof.

3. Concluding Discussion

According to Tables 1 and 2 below together with applying Theorem 1, we conclude that for any prime p with $p \equiv 3 \ (\text{mod } 4)$ and a natural number $1 < n \leq 49$ with $n \equiv 1 \ (\text{mod } 4)$, the Diophantine equation $x^2 + p^2 = y^n$ has no integer solution (x, y). For each fixed natural number $1 < n \leq 49$ with $n \equiv 1 \ (\text{mod } 4)$, this result generalizes the works of Bérczes and Pink mentioned in the case B for only the particular case $k = 1$ and $p \equiv 3 \ (\text{mod } 4)$. There are infinitely many primes of the form $4k + 3$, listed as A002145 in the On-Line Encyclopedia of Integer Sequences (OEIS) (Sloane, 2022). We, moreover, conjecture that our considered equation has no integer solution for any natural number $n > 1$ with $n \equiv 1 \ (\text{mod } 4)$ and for any prime p with $p \equiv 3 \ (\text{mod } 4)$.

Table 1. The values of the sum in (2)

n	b	Values of the sum in (2)	Remark
5	all even	≥40	positive
9	2	-1199	composite
13	2	-8839	prime $\equiv 1 \ (\text{mod } 4)$
	4	-4291039	composite
17	2	873121	positive
	4	-24553864319	composite
	6	7005476875681	positive
21	2	-6699319	composite
	4	-7547952442399	composite
	6	-9382001116577399	composite
25	2	-451910159	composite
	4	-379677384665279	composite
	6	-33413277960843515279	composite
	8	1500111128083892163841	composite
29	2	10513816601	positive
	4	508156418079387041	positive
	6	-546561263566978653459559	composite
	8	-868307314095250733575673559	composite
	10	28714774144970063639717469401	positive
33	2	135250416961	positive
	4	195337401466191394561	positive
	6	-55544682746808341439157439	composite
	8	-671582932652885722310459458559	composite
	10	-173156776127815926903091558852799	composite
	12	178179625643608687570320730917646081	positive
37	2	-8464641213079	composite
	4	20456911077705143997281	positive
	6	-17653223669804406176810517719	composite
	8	-3437192033013175861274046101509759	composite
	10	-6243764616905212012976446882123616599	composite
	12	631477325821592776208040048198094984801	positive
	14	135174135846655757423281431224261441223268	positive

Table 2. The values of the sum in (2)

n	b	Values of the sum in (2)	Remark
41	2	33973466382481	positive
	4	-9727649740836715098004799	composite
	6	65933408587323941845688405725201	positive
	8	-13536412949968925749002920977371720959	composite
	10	-99376498767324043660260758523750875381999	composite
	12	-53665717085918221112725250796920790368950079	composite
	14	23525696254572342402118496445124787158685773201	positive
	16	13932512484569015094869100053411051281882786483201	positive
45	2	4814772228819641	positive
	4	-4840884886670433593354451679	composite
	6	175633012692018657955115709876643321	positive
	8	-39165376532163420253440671987199758092159	composite
	10	-1218748280038458927839876515654580684070148999	composite
	12	-2412142537849669341564627051505411745844937390559	composite
	14	-283668767912640307359465836370366577155604220340679	composite
	16	546467594673009682304230256786294510968059831519224321	positive
49	2	-88640227692525599	composite
	4	-746301899503456335359674623359	composite
	6	2561487504687167123255029365909544286	positive
	8	-49208654712806503603755163905249327148623359	composite
	10	-1257374684957935908101711595079174190553509735759959	composite
	12	-72150053530469629308059274221073511792264518509408639	composite
	14	-565611735929982524628863778424017901863350099446791009	composite
	16	9168771727839287761217425376646039689426830969756505303041	positive
	18	14244515680539506494265991915655837682633397745431493110682081	positive

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